Lecture Notes in Mechanical Engineering

Kari T. Koskinen · Helena Kortelainen
Jussi Aaltonen · Teuvo Uusitalo
Kari Komonen · Joseph Mathew
Jouko Laitinen *Editors*

Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)

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Foreword

The 10th World Congress on Engineering Asset Management, WCEAM 2015, was held in Tampere Hall, Tampere, Finland, from 28 to 30 September 2015. It was organised by the Technical University of Tampere (TUT) and VTT Technical Research Centre of Finland. A total of just over 130 delegates participated in this year's congress comprising academics, practitioners and scientists from 22 countries, who contributed over 90 papers and workshop sessions. The event comprised a pre-congress welcome reception followed by the full congress programme which included six keynote addresses, breakout sessions and panel discussions, a gala dinner and a closing session on the final day.

The objective of WCEAM is to bring together leading academics, industry practitioners and research scientists from around the world to:

- Advance the body of knowledge in engineering asset management;
- Strengthen the link between industry, academia and research;
- Promote the development and application of research; and
- Reinforce the critical need for our assets to deliver more sustainable outcomes.

The WCEAM2015 congress slogan was Keep and Grow value. "Value" is one of the key concepts in asset management. The recent international standard ISO 55000 states that asset management supports the realisation of value while balancing financial, environmental and social costs, risks, quality of service and performance related to assets. Thus value can take different forms—in addition to monetary value, the motivations for better management of assets may arise from environmental or social factors, from skills and competence development, from mitigation or adaptation to climate change or from sustainability targets. The various dimensions of value were addressed in panel discussions and in workshops, and in several conference papers.

For asset intensive businesses, Infrastructure and Asset Management is a high cost function whose optimisation is necessary to maximise the performance of assets to deliver profitability and long-term sustainability. There is a realisation that superior performance can be delivered through enhanced strategic and operating decisions made by the board, the executive, and engineering personnel given their access to high quality information. Recent surveys indicate that 60 % of asset managers are not confident that the information that is available to them fulfils this criterion. So decisions made based on this information are also questionable. It is clear that by improving information availability and quality decision makers (operational and strategic) are far better equipped to arrive at informed decisions and therefore better placed to manage profitability and long-term business continuity.

The management of assets is a complex sequence of tasks now being pivoted on information systems. We live in the age of the information revolution which continues through the “Internet of Things”, Industrial Internet, “Internet of Services”, “Industry 4.0” and “Big Data”, where systems integration and connectivity and products providing asset intelligence are being contemplated for adoption by owner operators of asset intensive organisations.

Most organisations aspire to predict asset performance and gear their strategies and operations in accordance with the plant’s (predictability) profile. Few organisations have reached this stage of maturity, nevertheless it remains a nirvana for leading visionaries and a key to long-term competitive success. The information required to manage asset predictability is complex and deep. Industrial Internet could provide a novel, promising platform in managing assets at this level and its early establishment would be critical in the journey to a predictable asset performance state. A number of this year’s congress presentations largely reflect this theme. We acknowledge the generous contributions of the following keynotes and closing speaker at this year’s event:

- Dr. Kari Komonen, Finnish Maintenance Society (Promaint), “Some fundamental issues within strategic physical asset management”
- Prof. Jayantha P. Liyanage, University of Stavanger, Norway, “Assets under uncertain conditions: trends and scenarios”
- Dr. Jari Hämäläinen, Cargotec, Finland, “Future of Engineering Asset Management”
- Prof. Ming Jian Zuo, University of Electronic Science and Technology, China, “Dynamic modelling of mechanical systems for fault diagnosis and health management”
- Dr. Johannes Gutleber, CERN, Switzerland, “Particle accelerators—pushing the frontiers of science and technology”
- Ype Wijnia, Asset Resolutions BV, Netherlands, “The asset management process reference model for infrastructures”
- Darren Covington, Mainpac, Australia, “Delivering Operational Effectiveness in Asset Intensive Industries through Asset Intelligence”

This year's congress hosted two panel sessions both of which were convened by Profs. Kerry Brown, Curtin University and Robyn Keast, Southern Cross University, Australia. They were:

- ISO 55000 Asset Management, "Provocation or Promise"
- Serious Gaming.

Panellists for the ISO 55000 Panel comprised Dr. Kari Komonen, Finnish Maintenance Society; Dr. Christoph Heinz, University of Applied Sciences, Switzerland; Dr. Erik Helmns Nielsen, CEO of Reliasset Denmark; Mr. Alistair Crombie, GexCon Norway; Ing. Irene Roda Ph.D. student, Politecnico di Milano, Department of Management, Economics and Industrial Engineering, Italy and Prof. Joe Amadi-Echendu, Engineering and Technology Management University of Pretoria.

Questions that were directed to the panel included:

- Do the ISO Asset Management Standards require a new way of working?
- Are the ISO Standards capable of being a blueprint for action?
- What does the future for asset management under ISO 55000 look like?"

Together with Assistant Prof. Rob Schoenmaker, Delft Technical University, Profs. Brown and Keast convened the session on Serious Games: Simulation & Learning for Asset Management "Learning to Fish the Common Pool". Learning through Games, the session allowed participants to explore big issues through experiential activities such as:

- Expanding skill sets beyond technical expertise;
- Integrating operational and managerial systems elements;
- Identifying and operationalising changed emphasis from hard assets to service delivery through assets;
- Highlighting human dimensions and behaviour, power dynamics, coalition building, diversity of stakeholder perspectives and agile responses.

The congress also hosted the European Federation of National Maintenance Societies (EFNMS) workshop on Physical asset management. EFMNS has developed a workshop programme which helps participants to understand the requirements of asset management system and the requirements of physical asset management at a practical level. This workshop was led by Erik Helms Nielsen from Reliasset in Denmark and Dr. Kari Komonen from the Finnish national maintenance society.

The Gala Dinner was held at the Tampere Hall which facilitated added networking amongst conference delegates. The best paper award was presented to Prof. Lin Ma, Dr. Michael Cholette and Dr. Fengfeng Li, of Queensland University of Technology, Australia for their paper titled, "Reliability modelling for electricity transmission networks using maintenance records".

Best Paper Award ceremony. From *Left*, Joe Mathew, Michael Cholette, Helena Kortelainen, Lin Ma, Kari T. Koskinen. *Photo* Jyrki Latokartano, 2015

This year's Lifetime Achievement Award for exceptional dedication and contribution to advancing the field of Engineering Asset Management was presented to Dr. Kari Komonen of Finnish Maintenance Society (Promaint). ISEAM's Lifetime Achievement Award recognizes and promotes individuals who have made a significant contribution to research, application and practice of a discipline or in engineering asset management over a continued period of time. This contribution may be a new innovation, new knowledge or ways to improve professional practice in excess of the norm and have a lasting impact in the field. The recipient must have exhibited leadership and inspired others on a national or international level. Dr. Komonen is the third ever recipient of the award which was presented at the Gala Dinner of the 10th WCEAM.

Dr. Komonen receiving the award from Joe Mathew, ISEAM Chair. *Photo* Jyrki Latokartano, 2015

Another highlight of the evening was the performance of “The Professors’ Band” made up of six professors of the TUT, who entertained the delegates at the congress dinner. The illustrious band was led by the Congress Chair.

The Professors Band. *Photo* Jyrki Latokartano, 2015

Three post-conference workshops were also held at the VTT premises in Tampere to discuss “Transformation towards service business in technology-centric firms” and “Digitization and business models for asset service delivery”. The post-conference workshops were attended by 100 participants.

All full papers submitted for review, have been refereed by specialist members of a peer review panel for technical merit and will be published in the Congress proceedings by Springer Verlag in early 2016.

The Chairs are indebted to the Congress Organising Committee (OC) for the success of this congress. In particular, we would like to thank Jussi Aaltonen, Teuvo Uusitalo, Kari Komonen, Jouko Laitinen and Annukka Tiensuu for their splendid efforts in organising a very successful event.

WCEAM 2015 is the tenth in the annual series of peer-reviewed conferences hosted under the auspices of the International Society of Engineering Asset Management (ISEAM) as its forum for exchange of information on recent advances in engineering asset management. After the inaugural WCEAM in July 2006 in the Gold Coast, Australia, through the support of various international bodies, ISEAM has hosted WCEAM 2007 in Harrogate, UK, Beijing, China in 2008, Athens, Greece in 2009, Brisbane, Australia in 2010, Cincinnati, USA in 2011, Daejeon City, Korea in 2012, Hong Kong in 2013 and Pretoria in 2014.

The next WCEAM which will be the 11th in the series, will be held in conjunction with the 2016 QR2SME from 25 to 28 July 2016 in Jiuzhaigou, Sichuan China, while WCEAM 2017 will be held in Australia. Details will become available at www.wceam.com in due time.

Prof. Kari T. Koskinen
Congress Chair
Prof. Seppo Virtanen
Co-chair
Helena Kortelainen
Co-chair
Adj. Prof. Joseph Mathew
Co-chair

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Development of Industrial Internet-Related Asset Management Services with Customers

Toni Ahonen, Tiina Valjakka, Inka Lappalainen and Maaria Nuutinen

Abstract An increasing number of product and service providers aim to gain a competitive advantage through new services enabled by the Industrial Internet. In order to develop and successfully provide Industrial Internet-related services, a company needs to build up related capabilities and construct a strong value proposition in line with real customer needs. This customer and service perspective of the Industrial Internet has so far been rather little studied. Supporting conceptual tools are required. The development of the services relies on how well customers' business and production environments and management of assets are understood, and therefore this paper proposes a framework that creates necessary new knowledge for the development of new Industrial Internet-related services.

1 Introduction

There is a wide ongoing debate on the new opportunities related to the Industrial Internet. While the Industrial Internet is claimed to change businesses radically, many companies are still only trying to get first ideas of what the Industrial Internet means for them. From an asset management perspective, there is also an acknowledged need to create more thorough understanding about the full potential of the Industrial Internet in different domains, and to further understand how customers are willing to manage their assets, and what they are ready to pay for and to start developing collaboratively related services. While effective use of data for

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customers' decision-making is in the core of the development needs, there are many sources of complexity and requirements stemming from the customers' business environment that need to be understood well. The success factors relating to collaboration and better understanding of the customer's business processes have actually increased in significance stressed in service research (e.g. Edvardsson et al. 2007; Vargo and Lusch 2008; Lappalainen et al. 2014).

While companies see many new possibilities to create value for the customer, certain matters are also hindering the service development. One reason for unsuccessful trials in the past has been that the services have not been sufficiently integrated into customers' decision-making processes and the results of the development work have not been easy to adopt.

The Industrial Internet is expected to result in a significant productivity leap with new business models created. Productivity gains equivalent to 2.5–5 % are considered possible from Internet of Things (IoT) applications in discrete and process manufacturing industries and IoT applications are expected to spread to more than 80 % of manufacturing by 2025 (Manyika et al. 2013). However, Porter and Heppelmann (2014) state that it is a dangerous oversimplification to suggest that the Internet of Things "changes everything". They note that the rules of competition and competitive advantage still apply. Companies need to find their own perspective for the Industrial Internet and develop solutions that fit the concrete needs of their customers. In order to do this, the service solution needs to be adapted to the customer's business drivers and situation. In order to be useful, the service needs to properly integrate into customers' production and business processes and their management. The means to understand value in use for beneficiaries have been studied rather lot in the service literature (e.g. Edvardsson et al. 2012; Toivonen and Sundbo 2011). However, related practical conceptual tools are called for supporting more collaborative Industrial Internet service development.

In this paper we aim to construct a framework to define customers' business drivers for the Industrial Internet and the related value-capturing points.

2 Industrial Internet and Related Services as Value Creators

Porter and Heppelmann (2014) present ten questions that a company should answer when altering its strategy in a smart connected world. With respect to the topic of this paper, two of them are the most focal questions: "which set of smart, connected product (and service) capabilities and features should the company pursue" and "what data must the company capture, secure, and analyse to maximise the value of its offering?". In this brief literature review we discuss these topics in the light of recent studies on the Industrial Internet and service research.

2.1 Exploration of the Value Creation Potential

The initial business case to justify the adoption of the Industrial Internet is often based on incremental results in increased revenues or savings. Early adopters have started creating solutions for predictive maintenance and remote asset management, and new means for improving worker productivity, safety and working conditions. However, there seems to be a common understanding of a need to make visions of how new revenue streams can be created through new products, services, differentiated customer experiences and totally new business models.

Today's Industrial Internet solutions are only the beginning of digitalisation that will go through different industrial systems and enable a productivity leap with all industrial resources (Owens 2014). However, companies need to adopt thorough approaches to understanding alternative value creation logics and constructing related business models based on data. A large installed base with a great amount of data provides a potential for productivity improvements by, for instance, identifying productivity gaps through benchmarking across industries (Kunttu et al. 2011). However, the integration of data coming from different sources and tacit knowledge often dispersed across the organisation is a challenge. For instance, data collected by maintenance management systems is, in many cases, underexploited for decision-making at different hierarchical levels of the asset systems. The potential for different types of data may be studied at operational, tactical and strategic levels, and thus within different time horizons (Kortelainen et al. 2015).

Furthermore, it is essential to note that when the value creation logic changes, the mutual roles of business parties in terms of limited-strong dependency also change. In our recent study we defined four alternative provider's strategic value propositions, which also describe different customer relationships as follows (1) functionality and the provision of resources on demand with either short- or long-term contracts, (2) availability-driven partnering with more integrated decision-making with the customer, (3) performance partnering with the focus on the overall efficiency of the customer's business (e.g. Overall Equipment Efficiency), and (4) strategic partnerships or value partnering where the focus is moved to the customers' business and innovative solutions in a holistic or value network manner. The deepened service relationships increasingly focus on sustainability aspects alongside overall efficiency, and adopt a broader and more integrated perspective on value creation (Lappalainen et al. 2014; cf. Vargo and Lusch 2008).

2.2 Customer Involvement and Capabilities Around Data

Customer involvement in new service development is increasingly important. In service research, where the topic has been studied broadly (e.g. Edvardsson et al. 2012), roles such as ideator, designer, tester and innovator are typically identified.

Considering the idea generation phase of new service development, as our main focus, according to Alam and Perry (2002), for instance, customer involvement is characterised as follows: state needs, problems and their solution, criticise existing service; identify gaps in the market; provide a wish list (service requirements); state new service adoption criteria. Since customers have trouble imagining and giving feedback about something that they have not experienced (Matthing et al. 2004), product and service developers need to assume a more active role in finding the relevant information. Matthing et al. state that involving the customer in the development process of a service helps in learning about the customer's latent needs. On the other hand, identifying the customer's existing strategic needs can be supported by systematic methods for learning about the customer's business, for instance through a value chain analysis or applications of uncertainty management (Crain and Abraham 2008; Ahonen et al. 2011).

Furthermore, evidence-based decision-making and the development of new services around data requires totally new capabilities in the organisation. Companies need to have scientists who can process the data, find patterns, and translate them into useful business information (McAfee and Brynjolfsson 2012). Companies also need to have a clear strategy for how to use data and analytics to compete, and how to deploy the right technology architecture and capabilities such as analytics tools (Barton and Court 2012).

Based on our brief literature review, we state that there is a need to construct new approaches to analyse more systematically and collaboratively customer needs, specifically related to Industrial Internet-related asset management services and related value-capturing points.

3 Research Design

A qualitative case study approach was selected in order to understand the dynamics and requirements related to the collaborative development of asset management services enabled by the Industrial Internet (Yin 2009). Furthermore, we adopted a constructive research approach in order to structure a framework for gathering relevant customer understanding.

Our case company is an SME, a family-owned company providing machines, robotic solutions and equipment with lifecycle service to ensure sustainable production for their customers. Highly automatised production equipment with digitalization has enabled new service development to optimise customer performance in a more advanced manner.

Thematic interviews with representatives from the case company and one of their key customers were applied as the main data collection method. Interviewees from the case company represented all organisational levels and key roles, such as owners, development/operation managers, sales and maintenance. In addition, the owner and CEO of one their key customer was interviewed. The customer was selected due to their long-term relationship and their strong interest in the collaborative and innovative development of services enabled by the Industrial Internet. Altogether, six interviews were conducted between April and June 2014. Interviews took approximately one and half hours and were conducted in mixed pairs of authors to ensure multidisciplinary views. In addition to notes, they were recorded and later transcribed.

The qualitative analysis was conducted according to five main themes (Table 1). Then, based on empirical findings we structured a framework for supporting the construction of mutual understanding between the provider and customer regarding the needs and potential for Industrial Internet-enabled asset management.

Table 1 Case specific findings

Theme	Findings
Possibilities for common growth	Uncertainty in economy has been recognised to hinder the investment opportunities among customers, and thus the hardened competition also requires that a company's value proposal needs to stand out in a new way. The growth opportunities are seen to be realised in close collaboration with the most innovative customers with whom it is valuable to study new business opportunities
Customers' value expectations	When considering customers' culture related to asset management, corrective maintenance is often emphasised, decision-making is cost-driven and the value of preventive and condition-based maintenance is still not fully understood. However, forerunners are already far ahead with respect to strategic asset management
	Lifecycle thinking is still to be developed and the total cost of ownership is still not widely considered and understood. Forerunners and larger companies with more capital-intensive production take better into account provider's feedback and are more systematically considering the management of the assets
Customer readiness and expectations towards the Industrial Internet	Customers vary greatly in their preferences and it seems that the potential customers for Industrial Internet-related services are those with great volume and high availability performance requirements. These customers are well aware of the methodology for managing the assets and currently seek easiness in analysing the production performance and are expecting more automation for the analytics

(continued)

Table 1 (continued)

Theme	Findings
Capabilities in own organisation for collaborative development	The most focal issue is how to discuss, further explore, and affect the factors behind the real problems experienced by the customers. The ways to collaboratively analyse the costs and profits in terms of daily decisions and working methods are still lacking
	The steps towards the Industrial Internet will take place incrementally, and the case organisation needs to be ready to develop the offering in line with the identified steps that the customer is ready to take. Finding the relevant personnel at different levels of the customer organisation is crucial. Commitment of the management is the key issue since the value of the solutions needs to be derived from the business aspects as the starting point for the development. The involvement of field personnel seems important; while the technical expertise needs to be exploited, the role in the identification of weak signals related to how customers are willing to manage their production assets is regarded as increasingly important
Collection of information about the customer in daily operations	Currently field operations include a variety of opportunities to more widely and proactively discuss the problems and potentials of the customer production performance. Experienced field workers already receive much information by walking through the production lines, with respect to, for example, how the assets are being maintained and utilised. In long-term relationships, the experienced field workers are also very much trusted by the customers. Still, a systematic approach for further analysing and elaborating collaboratively the identified potential needs to be developed

4 Framework for Developing Industrial Internet Enabled Asset Management Services

4.1 Case Specific Findings and Implications for the Framework

Table 1 presents the findings from our case study with regards to the five themes related to the development of Industrial Internet-related services.

Based on empirical findings, it can be concluded that discussions on the value of preventive and predictive maintenance services provide a relevant basis for building mutual understanding for deepened collaboration possibilities enabled by the Industrial Internet. Furthermore, we conclude that lifecycle management issues need to be addressed carefully in the discussions. There seems to be a great potential related to, together, increasing understanding of the criticality of customers' assets, identifying the bottlenecks and creating a mutual strategy of how overall equipment efficiency can be improved.

4.2 Identification of the Required Information and Knowledge

At the very early stage of the development a service provider should define which sorts of strategic and operational issues are relevant with respect to the targeted Industrial Internet service and related customer relationship. The following sections propose a framework for a collaborative discussion with the customer, directing further service development.

We have chosen two drivers for rough segmentation of customers' business drivers for industrial internet, namely: (1) productivity management and (2) quality and innovativeness. Quality assurance and cost-efficiency represent low-hanging fruits of interest for a large number of companies at the moment. More holistic productivity management and innovativeness for sustainable value creation represent larger opportunities where a company may gather and utilise data from various sources to make significant changes in its value proposal and better integrate into the customers' businesses. Table 2 shows an example of the segmentation with respect to high-level drivers for managing the assets.

In order to identify the customer's position, and specify the value-capturing points and further investigate the specific needs, capabilities and prerequisites of the customer, we suggest contemplation of the following issues with the customer. Here, our empirical results are supplemented with previous studies on asset management (e.g. Kunttu et al. 2011).

- **High-level asset management drivers**: More thorough knowledge of the business drivers will support in the identification of the elements emphasised in the service solutions. The customers may vary with respect to drivers for e.g. capacity, cost efficiency, quality, safety resource efficiency and non-failure policies. Table 2 proposes a depiction of the high-level drivers. Customer specific drivers related to safety, availability, quality, capacity and sustainable value creation need to be well understood.
- **Risks**: Management of the safety and environmental risks related to the customers' operational environment need to be understood thoroughly in order to provide solutions.
- **The most focal phenomena related to production**: The information-based service needs to be integrated with customers' operations and decision-making. Increased understanding of the relevant decision-making points enables a focus on the provision of information in purposeful forms, to be directly integrated into operative practices.

Table 2 An example of segmentation of customers' Industrial Internet business drivers

	Cost-efficiency	Productivity management
Quality optimisation and innovations towards sustainable value creation	Capital intensive production with high demand for quality, combined with flexibility of the production system to adapt to market changes and new innovative product and service concepts that align with the increasing demand for sustainable solutions. The techno-economic questions and availability performance requirements are focused on delivery time requirements and energy and resource efficient management of the assets	Capital intensive production with high utilisation rate and high generic requirement for system availability, combined with tight competition with respect to quality. Total cost of ownership issues and predictive operations and maintenance are emphasised. The most focal techno-economic questions to be addressed are related to effective technology-supported dependability management practices (with reliability, maintainability and maintenance support performance aspects) throughout the system lifecycle. The goals for sustainability, with economic, environmental and societal aspects in balance are of major importance and driven by the market
Quality ensurance	Cost-driven production with a focus on specialised products with ensured quality. Companies are seeking ways to operate with high energy and resource efficiency	Capital intensive production for basic products with high volume demand, under heavy competition. Good understanding of the lifecycle costs and profits, with demand for effective optimisation of those with the help of enabling technologies and well-allocated services. Demand for high availability performance of the production assets with a focus on critical system parts supported by enhanced technologies

- **Life cycles of the customer's assets**: Asset management emphasises an integrated approach, with asset development (capacity and investments), operation and upkeep of assets. The lifecycles of the customers' assets need to be known for profitable value creation opportunities.
- **Criticality and production structure**: The criticality of the equipment considered from the perspective of production efficiency is dependent e.g. on the redundancy, integration level and reliability structure of the system and the value of failure-based production losses. All three aspects of availability performance should be considered here, namely reliability, maintainability and

maintenance support performance. As the utilisation rate (operating rate) of the production system grows, the pressure to retain high availability typically increases. Avoidance of unexpected failures causing significant downtime may be an important driver for predictive solutions and remote monitoring within capital intensive industries with high value for a production hour (and downtime) and high demand for utilisation rates and availability. However, there is variation across industries and customers with respect to value creation potential. Therefore, a thorough risk and criticality analysis in collaboration with the customer may serve as an effective way to form mutual understanding. Thereby, assets can be monitored and analysed with a more careful focus on the potential targets with the most significance for the customer.
- **Failure behaviour of the assets and needs for different maintenance strategies**: The failure behaviour of production systems is affected by various factors, such as the lifecycle phase of the production equipment, maintenance and investment history, stress and process conditions (for instance, temperature and humidity) and overloads. This information makes it possible to plan a balanced maintenance programme. To develop an effective maintenance programme, requirements based on the customer's objectives, the characteristics of the environment, stresses caused by production, and the technology used all need to be known.
- **Complexity of maintenance and opportunities to carry out maintenance activities**: The required maintenance activities required depend on the complexity of the equipment, its structure, the technology, inherent causes for delay and maintainability. The analysis of complexity may reveal new opportunities for innovative solutions.

5 Conclusions

Manufacturing companies are increasingly investing in developing industrial services and seeking new opportunities in a more customer value-oriented way. The Industrial internet is seen as an enabler of new intelligent industrial services around the large amount of data collected from the assets and integrated with other relevant data and knowledge. However, based on literature review and empirical study, both scientific and managerial debate about the value creation potential of the Industrial Internet and related services are still rather coarse even though certain topics, such as predictive maintenance, have received a lot of attention. Industrial Internet makes it possible for companies to comprehensively manage and develop the performance of complex production systems. To reveal the full potential, companies need to adopt novel ways to collaborate with the customers.

This paper addresses the need for better understanding of customers' business when developing Industrial Internet services which seems rather little studied in the IoT scientific debate. Two main scientific contributions were made by combining approaches on service research with recent studies on asset management and the Industrial Internet. Firstly, based on theoretical and empirical exploration the framework for segmentation of customers' business drivers for industrial internet, namely (1) productivity management and (2) quality and innovativeness, was constructed to define alternative possibilities for deeper collaboration. Secondly, the framework was supplemented by relevant strategic and operative issues necessary to specify the value-capturing points and further investigate the specific needs, capabilities and prerequisites of the customer.

As the managerial implication the segmentation framework supplemented with key dimensions for optimising complex production system performance (from an asset management perspective) provides practical tools for providers and customers.

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Maintenance in Real Estate and Manufacturing Industries: Differences, Problems, Needs and Potentials - Four Case Studies

Basim Al-Najjar, Anders Ingwald and Mirka Kans

Abstract It is about 50 % of the activities in the housing sector in the EU region are related to maintenance. According to several publications, building management systems are still quite rare and efficient methodologies for service life prediction of building parts still need to be developed. Also, recent studies show difficulties in finding comprehensive answers concerning, e.g. identifying risks and preventive maintenance actions. Incomplete information can easily lead to incorrect maintenance actions. The problem addressed is: How to improve performance and cost-effectiveness of the maintenance applied on real estate facilities especially buildings to reduce maintenance and management costs and increase company profit? The study's objectives are to analyse maintenance; techniques, costs, weaknesses and potentials, and compare it with manufacturing industry experience. Also, to investigate whether there is a need for a DSS for planning and follow up cost-effective CBM. The major results of four case studies are; (1) Preventive and breakdown maintenance are mainly used and actions are funded from different accounts. (2) The concept of cost-effectiveness is applied occasionally. (3) Lack of CBM-DSS for planning, follow up and evaluate maintenance profitability, and cost-effective improvements of company business and tenant living quality. (4) The profit generated by continuous heating of building thanks efficient maintenance is about 2.332 million SEK. The major conclusion; there is a reasonable opportunity to reduce buildings' management and maintenance costs.

Keywords Maintenance techniques in real estate facilities · Cost-effectiveness · Comparison between maintenance in manufacturing and real estate industries · CBM · Decision support system

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1 Introduction

It is reported that about 50 % of the activities in the housing sector in the EU region are related to maintenance, and slightly lower for the “non” housing sector (Silva et al. 2009). From everyday experience, some of the economic losses that occur in real estate arise out of acute problems or unnecessary replacements of building components, such as refrigerators, roofs, windows, doors. To reduce these losses, maintenance actions may be planned for a building component based on its state instead of calendar time or age. But, these actions cannot effectively be accomplished if the strategy of condition-based maintenance (CBM) is not implemented. In general, by applying proper CBM, it is possible to utilise larger part of a component life cost-effectively without increasing the risk of urgent problems. Research results emphasis that the return on investment in CBM in manufacturing industry is 5–10 times the invested capital (Al-Najjar 2007). Implementing CBM provides; effective data management, proper measurements analysis, planning and executing actions cost-effectively in convenient times (Al-Najjar 2012). Therefore, a profitable maintenance is that which; ensures a right action is done at right component/equipment, right time, in a right way and at a right cost which is less than the losses trigged that action. That there is a strong link between maintenance on one hand and company profitability and competitiveness on the other hand has been shown by many authors (Pulselli et al. 2006; Al-Najjar 2007, 2009; Kans 2008; Ingwald 2009). About 30–40 % of all natural resources utilised in industrialised countries are used in the real estate/construction industry (Pulselli et al. 2006). It is thus highly relevant to introduce CBM strategy to the real estate industry. Facilities Management is a source management that combines people, property and management expertise to provide vital services in support of the organisation (Nik-Mat et al. 2011; Chen et al. 2013). It is also emphasised that the aim of Facilities Management should not be limited to simply reducing the operating expenses of a built facility, but it should focus on enhancing efficiency of the facility as well. According to Garrido et al. (2012), building management systems are still quite rare, and efficient methodologies for service life prediction of building materials still need to be developed. Also, according to Bhavnani (2005), recent studies show difficulties in finding comprehensive answers for how to identify risks and preventive actions, because incomplete information can easily lead to incorrect maintenance operations. Therefore, the problem addressed is: How to improve performance and cost-effectiveness of the maintenance applied on real estate facilities especially buildings to reduce maintenance and management costs and increase company profit? The main objectives of the study are to:

1. Map, identify and analyse maintenance techniques, weaknesses and potentials.
2. Investigate maintenance costs in specific companies within the real estate industry.
3. Compare maintenance experience from real estate industry and that from manufacturing industry.

4. Investigate if there is a need for a decision support system (DSS) for facilitating the implementation of cost-effective CBM and follow up its performance from technical and economic perspectives.

For reviewing the past research, a survey in ScienceDirect showed no hits when we searched for how maintenance is planned and funded in real estate companies; which maintenance strategies were used; and how to achieve cost-effective CBM in building. Also, the search gave zero result when we searched for CMB system or intelligent CBM system for real estate facilities.

2 Phases of the Study and Description of Case Companies

In this study, we use the system theory approach. It aims to specify possible courses of actions together with their risks, costs and benefits. This is why we consider a building as a system that can be divided into different subsystems and components, such as cooling system, pumps and roof. The management system can also be divided into subsystems, such as maintenance, administration, IT and economic. The partition of a building in this manner facilitates the data gathering and analysis to identifying and localising problems, and interactions between sub-systems, e.g. pump performance, maintenance processes and funding. It also facilitates identification of similarities/differences between companies, and estimation of the transactions between sub-systems. The study was planned in the following phases; mapping maintenance activities; identifying existing maintenance techniques, i.e. strategies, polices, methodologies and philosophies; and analysing of maintenance; weaknesses, potentials in four companies within real estate in the City of Växjö, Sweden. We also investigate the need for more advance technologies, e.g. CBM, to provide more cost-effective maintenance. Maintenance in the case companies is analysed to, among others, investigate and consequently judge whether there is a need for an intelligent CBM-DSS to achieve: (1) Better use of resources. (2) Fewer urgent maintenance actions, e.g. repair. (3) Lower maintenance costs. (4) Greater involvement of buildings' users in maintenance. (5) Greater satisfaction for the tenants. In order to achieve the objectives of the study, we analysed companies' activities in maintaining buildings' quality to identify, describe and classify the maintenance techniques applied. It is done with attention is given to maintenance planning, execution and follow up. The study is conducted through: (1) Identifying a person of relevant authority and experience, e.g. maintenance chef, from every company to represent his/her company in the project. (2) Data gathering from personnel (interviews according to 1 above) and maintenance systems. (3) Data analysis with respect to maintenance performance, maintenance cost-effectiveness and experience, opportunities for applying CBM and the need for advanced DSS. (4) Reporting of analysis results and recommendations. (5) Seminars to discuss the methodology and results, and to disseminate knowledge and experience. (6) A workshop to describe and estimate the economic role of maintenance in company business. Exploratory principal objectives for this study are to identify, map and analyse current maintenance techniques and their performance in four real estate companies that owning about 65 % of the rental buildings in the City of Växjö. These companies are: (1) Hyresbostäder and Växjöhem own about 240,000 and 460,000 m^2 resp., mainly residential buildings and partly buildings for geriatric care. (2) Videum owns about 115,000 m^2 housing area and about 80,000 m^2 is devoted for Linnaeus University (offices, classes, laboratories, libraries). (3) VöFAB owns about 270,000 m^2 mainly is business area on Växjö communal buildings.

3 Data Gathering

In order to achieve the exploratory objectives, an interview template including the following questions was developed to be answered by the case companies:

1. How maintenance is defined? What maintenance strategies have been used? Maintenance needs, planning, budget, performance, follow up and improvements?
2. What are the resources, e.g. skills, materials, time, required for doing maintenance actions? If these resources are not available, how long is the waiting time?
3. What are the problems that handled by maintenance and can be classified as; general, regular and rare but costly problems?
4. What are the reasons behind these problems; management, construction, use, others?
5. What are the maintenance actions that the company take for various reasons and why?
6. What are the costs that usually considered in maintenance budget?
7. How much does maintenance cost annually for the past 3–5 years?
8. Are the maintenance economic data accessible for analysis?
9. Does/how a company plan to use/already use, the concept of cost-effective maintenance? If not, why?
10. Does/how the existing systems fit for planning, follow up and improvement of maintenance? Otherwise, what is missing? Does the company need a DSS to facilitate applying cost-effectiveness CBM?

Four interview sessions were conducted with a person from each of the case companies. The interviewed persons were responsible of maintenance (and/or management) of buildings in respective case company. They possess sound knowledge, experience and understanding of maintenance. The interviews were conducted by two persons and recorded to ensure the correctness and quality of the information that were gathered during the interviews.

4 Data Analysis

The information gathered from the case companies was analysed considering the similarity and differences between companies (and also the differences between the case companies and manufacturing industry) in planning, budgeting, execution, follow up and improving maintenance performance. The analysis consider also experience and knowledge that are important in the establishing and running cost-effective maintenance.

4.1 Comparison Between Case Companies

The case companies have some of maintenance features in common, and the differences are:

- Case companies fund maintenance activities differently from preventive maintenance (PM), operation/management, repair, damage to property or/and land management accounts. PM and operation accounts were mostly used.
- Maintenance actions are executed using either company own personnel, external resources or both.
- The data used for planning maintenance actions; in Videum, measurements from technical equipment were used. The rest of the case companies use previous experience.
- The major problems that maintenance handle were also different. Design problems were usual at Hyresbostäder. But, the most usual problems at Videum were technical equipment problems, e.g. pumps, compressors, sensors, temperature, fans.
- The causes behind these problems were also dissimilar. At Hyresbostäder, construction problems were obvious, but at Videum the equipment deterioration was the major cause, aging was behind the problems at VöFAB.
- Total annual maintenance cost and maintenance cost per m^2 were also different. The cost of maintenance per m^2 varied between; 130–273 SEK/m^2 and the total annual maintenance cost varied between 6.5 and 91 million SEK.

4.2 Maintenance Strategies in Manufacturing and Real Estate Industries

IT applications have proven effective in the maintenance of constructed facilities (Ko 2009; Shen et al. 2010). Duarte et al. (2013) claims that maintenance activities represent an increasingly high cost in any manufacturing system or in different types of structures. Also, in order to reduce production cost, minimise downtime and ensure reliability levels, DSSs should be able to optimise maintenance plans and ensuring companies meeting their strategic goals. In the real estate industry, a building is usually partitioned into a number of components/parts, and maintenance work is scheduled for these components in different time ranges.

The case companies define maintenance: the activities needed to maintain building quality. They use preferably:

(a) PM; the maintenance actions planned and budgeted annually to reduce the likelihood of emergencies.
(b) The rest of the activities, i.e. activities that cannot be predicted and planned in advance, e.g. repairs and replacements associated with emergencies/failures or based on fault/inspection reporting.

The expenses of the rest of the activities is directly influenced by PM budget and quality. Although PM reduces the risk of emergencies and accidents, but it typically leads to two losses due to: acute problems (breakdowns) than happen before maintenance actions are done, or loss of a part of the life of the component when it is replaced before its useful life has been exhausted (Al-Najjar 2012). Consequently, economic losses are generated because of costly failures and unnecessary early replacements of building components. But, according to Al-Najjar (1997), maintenance activities in industry are conducted with regard taken to different strategies:

- At failure by restoring the machine to the same as before (Breakdown maintenance).
- Using models for regular planning of maintenance actions regardless of real needs and previous events.
- Based on the machine state, i.e. do nothing until it is really needed. Such maintenance action is done to avoid disruption when symptoms reflecting deterioration type and its severity are measurable.

In the first two strategies there is a clear similarity between maintenance experience from real estate and manufacturing industries. But, the third differs appreciably. In this paper, we define cost-effective maintenance actions as the actions that result in less acute problems, prolonged component life cycle and shortening repair time, i.e. reducing owning and operating costs more than what maintenance actions cost. It is always important to select the most cost-effective maintenance (Ingwald and Al-Najjar 2012). The selection depends on some parameters. In real estate industry these parameters can be; building component type and its state, cost and benefits of maintenance actions, energy consumption, personnel competence, housing satisfaction and age. To make this selection properly, it demands relevant and high quality technical and economic data (Ibid).

4.3 Maintenance Budgeting, Execution and Follow up in Manufacturing and Real Estate Industries

In manufacturing industry, using CBM, it becomes easier to identify damage in the monitored equipment, assess its severity and identify-prioritise the components that must be addressed for maintenance. Therefore, it is possible to plan actions effectively so that the equipment/components that suffer from wear and tear can be replaced or repaired in right time, e.g. at a planned downtime (Al-Najjar 2000). From everyday experience, the determination of time until a maintenance action can be done using analysis system, individual experience or just subjectively, i.e. based on instinctive/emotional feelings. In this study, we consider the factors of high importance in selecting the more profitable maintenance time to be: (1) The size of the capital tied up in equipment. (2) Existing state of the equipment and the causes behind deterioration. (3) Rate of deterioration of the equipment. (4) Probability of failure of the machine given a particular damage under development. (5) Statistical remaining lifetime when this damage is under progress. (6) Failure consequences. To continuously enhance company profitability, the main objective of conducting efficient maintenance should be to enhance maintenance cost-effectiveness. Feedback from maintenance applications helps to prevent recurrence of the same or similar problems, which in turn improves the cost-effectiveness of maintenance and its results and reduces maintenance direct cost (Ingwald and Al-Najjar 2012). Maintenance direct cost can, in general, be divided into: (1) Man-hours for the repair/replacement of units. (2) Physical inspection. (3) Consuming material, tools, equipment, etc. (4) Outsourcing of maintenance. (5) Overhead costs, such as equipment, offices, management, etc. (6) Invested capital in training, new analysis software program or system (Al-Najjar 2007).

In the case companies, maintenance budget is planned by prioritising maintenance actions for the greatest benefit especially when it concerns reducing energy consumption, because it can be measured and followed up. In most cases the companies use their own personnel to repair building components, such as water pipes, building facade or component colour. Maintenance personnel also serve as a source of information when they report every fault they notice during their visits to companies properties. At two of the four case companies, maintenance activities' costs are shared between PM budget and operation/management. In one company, maintenance activities' costs are shared between PM budget, operation/management and repair, and in the fourth company maintenance activities' costs are shared between five accounts: (1) PM-budget; funding the annually planned maintenance activities. (2) Operating/management budget is to fund the activities that cannot be predict, e.g. repair of urgent problems. (3) Repair account; in certain companies repair account is separated from the other activities that are explained above. (4) Damage account; it is for funding all injuries occurring on the buildings. (5) Land-care account; it is for funding the expenses required for land management. While in manufacturing industry all machines maintenance is funded from one maintenance budget. External services that bought by companies are quality checked using special standard. The quality of smaller maintenance projects within the company are controlled by the project manager. Staff experience and knowledge are used for follow up maintenance project activities and improving maintenance performance. But, the case companies lack of a system for systematic and documented project execution, control and follow-up that is required for achieving profitable and continuously improved maintenance performance, quality control and quality assurance of maintenance work, detect anomalies and prevent repetitive problems.

4.4 Maintenance Cost-Effectiveness

In general, companies strive to reduce costs without compromising on quality and safety. In this study, a maintenance investment is considered cost-effective if it generates savings in production costs larger than the invested capital, i.e. increases the value added. This can be achieved by reducing unplanned downtimes through identifying and eliminating causes behind downtimes which converts maintenance from a cost- to a profit-centre (Al-Najjar 2007). This is could not be visualised by using available accountancy systems and software program because they cannot describe and assess more than maintenance costs, such as maintenance saving, results, losses. The major reason; maintenance in the available accountancy systems is considered cost and only cost. In many cases, when several quotations for the same maintenance project are applied, a quotation is selected based on; (1) Personnel experience. (2) Amount of energy savings when it is possible to estimate the savings. (3) Personnel instinctive/emotional feelings at lack of experience, or (4) Quotation cost, i.e. looking for the cheapest. But, a quotation demands more investment does not need to be poor option, and not the one that costs less investment is the best option. Cost-effectiveness of an investment should be estimated (considering the factors that affect or are affected by the investment) on the long term, i.e. over the entire amortisation period. Therefore, it is possible that the alternative quotation costs higher investment can be the most profitable maintenance investment. In the case companies, there was no document describing what cost-effectiveness means when it comes to maintenance projects. But, the practice is not lacking and maintenance personnel try to do as much as possible within the budget framework. Also, cost-effectiveness is used as a guideline for selecting what they call a good! quotation. But, lack of tools and systems required for easy, certain and effective application and follow up made the cost-effectiveness concept is occasionally used, e.g. in the projects when it is possible to increase the benefits through pressing down project costs. Another example, if a company gets two quotations for one maintenance/operation project but of different costs and lead to different operation/management costs, the company chooses the quotation that saves more costs. Also, the case companies select the equipment of larger tied up capital if it yields less energy consumption justifying the increment in the purchasing cost. Observe! no one knows if it was really economically worthwhile selection or not, because it usually cannot be followed up to examine the claim of cost-effectiveness. But, is it really possible to know with high certainty whether what is planned or performed is cost-effective without using a reliable model, effective tool or system for this purpose? The answer is most likely NO (Al-Najjar et al. 2004). The case companies did not follow up a project and assess whether it was cost-effective or not due to the lack of such functions in the currently available systems. However, some companies follow up energy savings. Also, in some of the investigated companies, the concept cost-effectiveness is applied through: (a) Identify how the problem has been initiated and how to prevent its recurrence. (b) Make sure that the solution does not create changes in the structure, and (c) The project cost is justified by the results quality. This approach represents a way to reduce maintenance cost as claimed by the case company. Applying this approach, it is assumed that the identification and elimination of the causes behind high cost are successfully done, and the result justifies the costs incurred in conducting maintenance tasks.

It would appear from both quantitative and qualitative data that the case study company may not be adhering to a systematic approach to making decisions to replace circuit breakers and isolators. The lack of corroboration between historical data and respondent narratives suggest that replacement decisions were not consistent between 1999 and 2013. It is puzzling as to why detailed assessments were not carried to establish the condition of the substations. Instead, the historical data and responses strongly suggest that the decisions to replace switchgear were made on ad hoc basis. This brief paper illustrates the suboptimal nature of equipment replacement decisions, and how this can be exacerbated by inconsistent data and information.

Maintenance work in the case companies lacks of a systematic way to pre-evaluate quotations for the same maintenance task/project, and compare them to choose the most profitable maintenance investment. According to their experience, what is missing is a system for planning, budgeting, execution and follow up cost-effective maintenance, and estimating maintenance economic impact. Currently, the follow-up and evaluation of maintenance investment cost-effectiveness is based entirely on personal experience. It is done through comparing a new project with previous one in a subjective way. But, when these people are retired or moved to another companies, it will be almost impossible to carry out even such subjective follow up and evaluation.

4.5 Example: Cost-Effectiveness of Energy Pumps Maintenance

In the case companies, there was no specific information describing the economic impact of the maintenance of energy pumps although the heating system is running almost continuously without problems with highest load during autumn and winter. In this section, we assess maintenance economic importance for energy pumping responsible of distributing heat to buildings. Hyresbostäder is select due to the easiness of data gathering concerning maintenance of energy pumps. The company has 51 energy pumps of type Wilo, Stratos D40. In this example, we did not give attention to the relationships between the heat providing company (VEAB) and the case company purchasing heat for their tenants. Also, we have excluded the impact of discontinuity of building heating. This is because these issues were irrelevant for the case company and outside the context of this paper. In order to estimate the economic benefit of maintenance work on energy pumps, we need to know: average costs, revenue and profits per property, and maintenance and heating expenses at least for 2012. We aware of it can be a rough estimation if we consider the average costs and revenue per property, because properties surface areas varies between 1000 m^2 to over 20,000 m^2. But as long as there is no more data available, it however, will give an indication of the economic importance of maintaining energy pumps, and to motivate companies to gather more relevant data in future. In Hyresbostäder:

1. The rental housing were 41 buildings at the end of 2012.
    - Heating cost of all buildings during year 2012 was in total 23.6 million SEK. Average revenue per building was 6.402 million SEK, and from all 41 buildings was 262.482 million SEK, where the heating cost is approximately 9 % of the revenue.
    - Average profit per building in 2012 was 0.455 million SEK as the year results (excluding property sales). The total profit for 41 building was 18.655 million SEK.
    - Operating, maintenance and management cost in 2012 was on average 4.593 million per building. This includes costs of building management, repairs, heating, administration, maintenance, taxes and depreciation. But due to the lack of information, it does not include the central administration costs and interest rates that also can be significant costs. The total cost of 41 buildings was 188.313 million SEK.
2. The economic importance of maintaining the heating system is estimated in the following manner:
    (a) Divide the total heating cost (23.6 million SEK) to the operating/management cost in 2012 (188.313 million SEK) yields 12.5 %.
    (b) If we multiply 12.5 % with the revenue in 2012, we get the revenue generated by providing heat equal to 32.81 million SEK. It means 1 h unplanned stoppage of the heating system costs about 3745 SEK losses in revenue. A failure of the heating system may cost the company between 22,470 and 134,820 SEK based on which time in the year (winter or summer), because in winter it takes longer time. The losses per 1 h stoppage of one pump can then be 441-2643 SEK, depending on the failure and timing.
    (c) Total salary cost of maintenance personnel responsible of the stations of energy pumps is 0.475 million SEK per year 2012. Heating profit becomes then: 32.81 (revenue) − 23.6 (heating cost) − 0.475 (maintenance) = 8.7 million SEK (1)

Note that spare parts costs, central administration, interest rates and overhead costs are not included.

(d) We can assess heating profit alternatively through; the average profit per building in 2012 is 0.455 million SEK (for 41 building, it is then 18.655 million SEK). It means (roughly) that the profit due to heating is: 0.125 * 18.655 = 2.332 million SEK (2)

(e) The difference between the two assessed heating profits in Eqs. (1) and (2) is probably due to the difference in the cost factors shown in (c) and (d), respectively. In (c) some expenses are excluded where are they included in (d). Unfortunately, it was not possible to exactly assess the missing expenses.

The number of energy pumps failures during 2012 was negligibly small, and avoiding these failures keeps heating process running without disturbances and economic losses. Therefore, the profit generated due to a continuous building heating is in the first hand a merit of maintenance staff because they had maintained the heating process running without failures.

4.6 CBM and DSS to Plan, Execute and Follow up Maintenance Cost-Effectively

Chew and De Silva (2003), argue that early feedback on poor building maintenance and construction could prevent recurrence of problems. According to Motawa and Almarshad (2013), decisions for building maintenance require various types of information and knowledge created by different members of construction teams, e.g. maintenance records, work orders, causes and failure consequences. To assess reliability of a part in a building, the distribution function for the expected time to failure, mean time to repair and decision time should be properly studied according to Myrefelt (2004). It demands the same requirements even if we assessing the reliability of a component in a producing machine. But, the major problems facing this assessment is the availability of high quality failure data which are not easy to find, and also possibility of making realistic assumptions at modelling. In many cases, these two difficulties reduce the certainty in the model appreciably (Al-Najjar 2012). To reduce economic losses, maintenance activities can be planned based on the condition of each component in the building, i.e. using proper and well accommodated CBM for building components. This means that the maintenance will be done only when a real need exists, and not according to a fixed schedule (British standard BS 3811:1993). Application results of CBM would lead to better use of resources, smaller number of emergency actions, lower maintenance costs, greater involvement of building utilizers in maintenance strategy and greater comfort for the residents, and consequently more profit is generated (Al-Najjar 2007). It possible to find publications introduce systems for integrating different activities related to maintenance of buildings, but the major focus of these systems is on integrating databases, data gathering and performance measure assessment

(Ko 2009). In Shen et al. (2010), the authors present an agent-based, service-oriented approach for integrating data, information and knowledge during the entire facility lifecycle. The same thing can be said about (Nik-Mat et al. 2011), the authors focus on functional, technical and image aspects of maintenance. In the case companies, the concept cost-effectiveness is occasionally applied because it is not easy and manageable to apply if there is no system helps in planning, execution and follow up cost-effectiveness of maintenance projects. Such system can also be used for more efficient execution of cost-effective and continuous improvement of maintenance performance. The improvement is now done based entirely on personal learning process. Therefore, case companies demand is an efficient system that combines personal experience and intelligent CBM-DSS for applying concept cost-effectiveness continuously. The experience of maintenance personnel is great and extensive, but it is not documented. Development of such experience is costly for the companies and has taken many years to build up. In order to keep this experience in house, it demands a reliable knowledge-base for preserving the available experience and make it accessible for all personnel. Maintenance costs represent a large sum of budget in the case companies. The sum varies among companies between about 7 and 91 million SEK annually. But at the same time, big maintenance budget may also mean an additional source to increase the company revenue. The latter can be achieved through applying a cost-effective maintenance that reduces maintenance and operating/management costs, and an intelligent system for planning, follow up and evaluating maintenance activities and its contribution in a company profit (Holmberg et al. 2009). But, a successful application of this idea is necessary to confirm this hypothesis in real estate industry.

5 Results, Conclusions and Discussions

Based on the data gathered from the case companies, the analysis results are summarised as:

(a) Maintenance is well defined in all the case companies but not documented.
(b) PM is mainly implemented to reduce the number of acute problems and repairs.
(c) Repairs of the acute problems are prioritised based on their consequences and benefits.
(d) Maintenance activities are funded from two to five different accounts (PM budget, operation/management, repair, damage/vandalism and land management).
(e) The funding way of maintenance makes benchmarking of maintenance in the case companies impossible.
(f) Maintenance work is carried out with the help of internal and external resources.
(g) Maintenance personnel have good and extensive experience but it is not documented.

(h) Cost-effectiveness concept is not documented and it is only used occasionally and in certain projects.
(i) There is lack of a system required to detect anomalies, prevent repetitive problems, control and assure quality of maintenance projects, cost-effective and continuous improvement of maintenance performance.
(j) The profit generated by non-stop heating of building thanks efficient maintenance is in minimum about 2.332 million SEK.
(k) There is a reasonable opportunity to reduce buildings' management and maintenance costs.

The planning and execution of maintenance in the real estate industry is somewhat different compared with the industrial view on maintenance, but the basic needs are the same. The main notable differences are the way of funding maintenance actions and the level of technology application. While industry today, apply advanced CM technology and DSSs, which are not utilised by the case companies. This, among others, results in experiences and knowledge not being documented, and decision making with low support from information technology.

It is obvious that carrying on maintenance in the way described in the case companies will make it very difficult to know whether maintenance performance was cost-effective or not. Thus, studies to re-arrange maintenance funding accounts, re-define and determine clearly maintenance activities are demanded. These studies are important to ease the follow up of maintenance effectiveness and assess its costs, savings and results. Experience from manufacturing industry is advantageous to utilise for improving maintenance in real estate companies. Implementing a cost-effective maintenance and intelligent systems for planning, follow up, evaluation of maintenance performance and estimation of maintenance financial contributions provides a real opportunity for real estate companies to reduce costs and gain more revenue. Maintenance performance, tools for follow up and evaluation of maintenance should continuously be enhanced with respect to job quality, cost minimisation and delivery accuracy. This is a necessity in order to continuously improve maintenance profitability and increase company profit. Also, it will motivate maintenance staff to demonstrate the usefulness of their maintenance work especially economically. The profit generated by continuous heating of building thanks efficient maintenance is in minimum about 2.332 million SEK. Therefore, there is a reasonable opportunity to reduce buildings' management and maintenance costs. CBM may not be suitable for all building components from the first moment of application, because it is not possible to confirm availability of the technologies required for such CM. Therefore, a special study to investigate available techniques, develop new techniques and implement CM tools and systems to monitor the condition of specific components will be the next step. Applying accommodated CBM-DSS for buildings, it may be possible to overcome the constraints detected in planning, and executing profitable maintenance.

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Reducing the Delivery Time in Food Distribution SMEs Using a Multi-agent System

Fahed Algassem, Qingping Yang and Yuen Au

Abstract The service industry worldwide has been facing unprecedented challenges in terms of delivering products at low cost and with fast delivery speeds. These pressures have had an even greater impact upon SMEs. The use of multi-agent systems (MAS) is increasingly being considered as a practical method of handling the mounting complexity within the supply-chain system which are a result of competing priorities, multiple options, and issues connected with decision-making in real time. Such systems offer a real opportunity to improve lead times, reduce operational costs and therefore enhance business competitiveness. This study aims to investigate the implementation of MAS within the supply chain using the empirical case study of a food distribution SME in Saudi Arabia. The case study indicates that this combination approach can offer considerable performance improvement in SMEs.

1 Introduction

The food industry is characterised by a large proportion of SMEs carrying out food-related activities (Mangina and Vlachos 2005). Food distribution firms act as conduits between food manufacturers and end consumers. These service-based firms combine activities relating to ‘food’ and ‘service’ (Nabhani and Shokri 2007) which include procurement, inventory, warehousing, order processing, and customer service (Nabhani and Shokri 2009) in order to add value to the product for the customer. In the competitive environment of the food distribution industry,

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efficient and effective supply chain management is vital. The supply chain consists of the flow of activities and information from the time materials are sourced until they are transformed into finished products which are then supplied to customers. The optimal performance of a supply chain requires the effective coordination of its functions. Essential to the performance of supply-chain management is the principle of 'right quantities to the right locations at the right time' to reduce unnecessary cost and achieve the required levels of customer satisfaction. The market pressure is constantly driving shorter product life cycles which require real time supply-chain coordination (Rady 2011; Dennis et al. 2008). An enabling platform that provides real time connectivity and sharing of information and tasks can allow an SME to achieve rapid agility and global competitiveness, whilst also enabling it to expand its operational reach and range (Srinivasan et al. 2010). Therefore an MAS-enabling platform of independent, cooperative agents is proposed that can assist the SME in reducing its lead times, managing complexity, and delivering an enhanced service.

2 Literature Review

2.1 Multi-agent System in the Supply Chain

The increasing worldwide complexities of supply chains strain the capability of current enterprise information systems to support the collaborative planning and control needed in the supply chain (Li and Lau 2005). MAS is an emergent technology which uses an intelligent agent-based approach to provide a more natural way to address the complexity of these factors and variables inside a food distribution operation of an SME. According to Di Marzo Serugendo et al. (2011, p. 111), an MAS consists of a group of independently acting agents in a common environment. Each agent is delegated individual responsibilities based on their respective roles in the business process (Ren and Anumba 2004; Park 2005). Therefore an agent can be assigned with a unique function, for example procurement, inventory, or warehousing. Each unique agent can then initiate and complete the tasks and activities within the processes of that function, whilst at the same time cooperating with another functional agent to complete sets of inter-related or common tasks. This can be of significant assistance to SMEs which have to cope with the same level of operational management complexity as a larger provider, especially in relation to navigating the on-going comparison of price policies, inventory policy management, and prioritising the multiple distribution of orders and such related changing factors associated with fast moving production and inventory (Srinivasan et al. 2010).

2.2 Lead-Time

Time is the most important aspect of performance when addressing the flow of goods and information (Lamming 1996). Additionally, as Tummala et al. (2006) state, the concept of delivering "on time" as one of the three most important measures that affect the quality of supply-chain management. Therefore, reducing the elapsed time from beginning to end has a significant positive impact on the operational management and quality of service, and improves customer satisfaction (Nabhani and Shokri 2009). This positive combination enhances the company's competitiveness (Arnheiter and Maleyoff 2005), a quality which is vital for a food distribution SME.

3 Case Study

The case study is of a SME food distribution company in Saudi Arabia. The company's activities includes manufacturing their own products, which have a short life cycle, making warehousing management a time-critical operation (Mangina and Vlachos 2005), and sourcing a range of products for final delivery to food outlets. Initial data collected from warehouse manager reports and driver delivery reports and investigating a sample of 36 customer complaints identified a series of issues; these included the high cost of service, late delivery, product quality issues, and partial and incorrect deliveries, with incorrect billing and inaccurate invoices. Using Six Sigma, and DMAIC (Define, Measure, Analyse, Improve and Control) to obtain a root cause analysis of the poor quality of service, several sources were identified. These included incomplete allocation or incorrect delivery to customers as a result of poor loading plans, accompanied by consistent late delivery, which resulted in high costs for the SME. These were identified as the most significant issues to be addressed. Applying a number of operational improvements to the entire operation reduced defects by 95 % and average delivery time by 27.8 %, with a subsequent 40 % fall in the number of customer complaints.

Furthermore, the cost per defect was reduced by 48 %. However, the most significant problem remained; late delivery of orders. The first step was to collect and measure the beginning to end cycle time (CT) of the food supply chain (FSC) process using a SIPOC diagram (see Fig. 1). A random sample of 100 orders were collected daily during a four-week period. The cycle time measured for each activity in the SIPOC diagram was recorded in minutes (shown in the truncated Table 1).

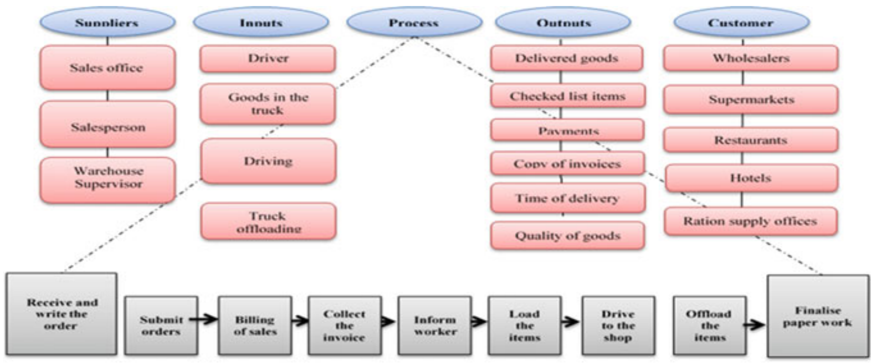

Fig. 1 FSC SIPOC diagram

From this table, the average cycle times for the critical observations of these 100 operational processes (SIPOC) are presented in Fig. 2.

The average length of the delivery time calculated for these 100 transactions was initially 1380 min; approximately 23 h elapsed between receipt of the order from the customer, through submission to the sales administration, and delivery to the customer, so effectively a whole working day was lost just here alone. Once the order had been received by the administration, the time taken to fulfil it was 213 min. The Sales office then processed the “billing of sales” which is then collected by the warehouse supervisor; the stock is extracted, packed, loaded and delivered to the customer. The most significant delay was the average of 1162.32 min from the receipt of the order by the sales person to its submission for processing. Changing the official office working hours initially provided a temporary fix (during the DMAIC stage), producing a 29 % improvement in this time; this, however, was not sustainable. A more permanent solution to overcome the operational inefficiencies that resulted from the elapsed time is needed. It was suggested that information technology could be a potential solution (Andersen 2001; Stratopoulos and Dehning 2000; Zhang and Lado 2001). Nevertheless, within SMEs, IT raises concerns regarding cost and complexity. However, the emergence of alternate technologies such as the Multi-Agents System introduces a potential solution that may address these concerns, as it offers, at a lower cost, the ability to facilitate collaboration and intelligent decision-making in complex dynamic environments (Nissen 2001; Swaminathan 1998).

Table 1 FSC cycle time data collection (100 orders) truncated

Order no	Receive and write the order	A new customer?	Approvals	Submit orders	Customer exceed the credit limit?	Is the quantity available	Billing of sales	Waiting time	Collect the invoices	Is the order available	Inform workers	Load the items	Drive to the shop	Offload the items	Finalize paper work
1	5	No	Y	1291	No	Y	2	49	4	Y	1	27	84.8	16	4
2	5	No	Y	1075	No	Y	1	48	5	Y	1	25	69	26.6	5

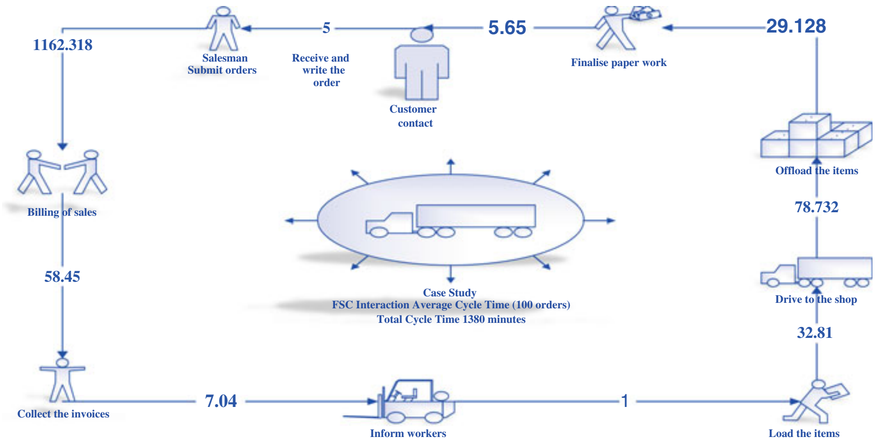

Fig. 2 The case study FSC interaction average cycle time total CT 1380 min

4 Planning

The next step was to identify whether this software, MAS, with its intelligent agents, could provide the visibility and flexibility to address this issue of Late Delivery. Assessment showed that an agent-based option is in fact the most appropriate solution tool and can support SMEs with its low cost, ease of application, ease of use, low maintenance costs, and speed of delivery. The system can be written in many programming languages which means it is more easily available to SMEs and is more customisable for them than the various other costly packaged specialised systems. In order to meet the specific needs of the SME, detailed planning is required as an essential step in properly modelling and simulating the system.

The relationships between customers, salespersons, sales office and warehouse needed to be thoroughly mapped (see Fig. 3). From these findings and analysis, the initial design and coordination protocols were developed. In this case study, the decision was made to set up the application for the analysis in JADE using Java programming.

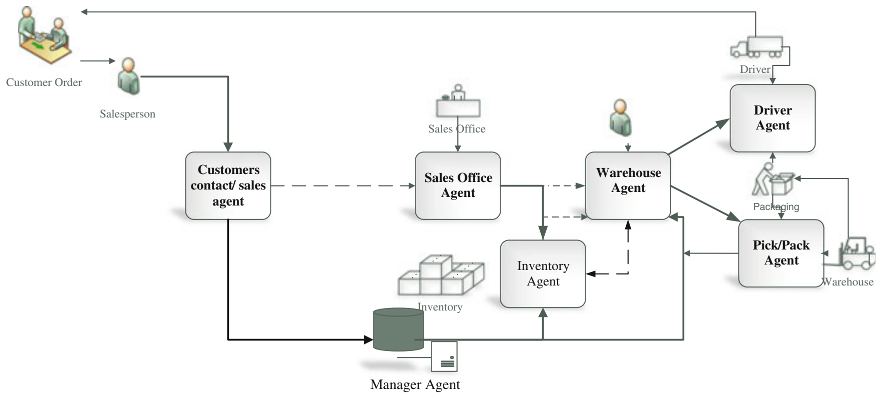

Fig. 3 The case study FSC interaction average

5 Analysis

The analysis phase aims to clarify the problem without any (or minimal) concern for the solution. Nikraz et al. (2006) used the proposed methodology in their work on the Telecom Italia Lab (TILAB); with it, the analysis phase took place using a number of systems ('use cases'), this being one of the best ways to describe the

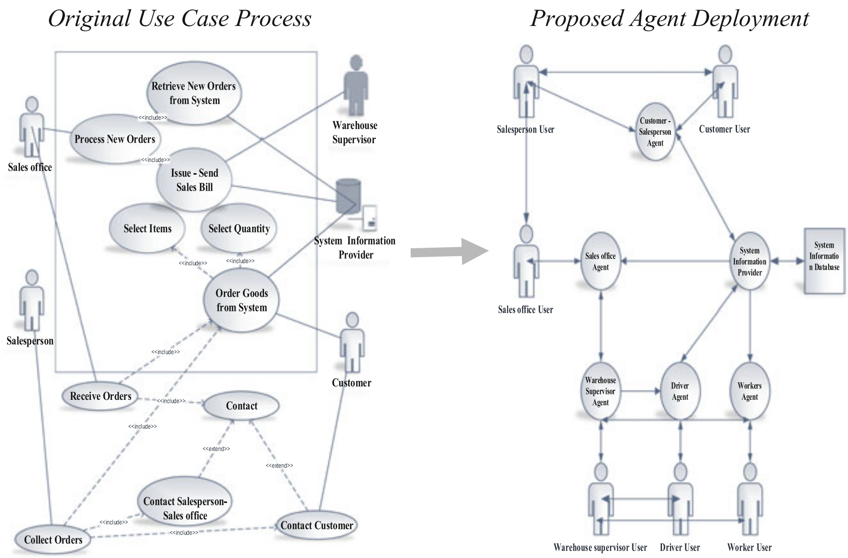

Fig. 4 Use Case showing original to final agent deployment proposed scenario

functional requirements of a new system. Use case diagrams were used to describe the interaction of operational participants ('agents'), and a step-by-step sequence of their actions (Helming el al. 2010) for each separate business process, for example ordering, warehousing etc. In this step, an initial list of the main responsibilities for each identified agent is modelled to produce the responsibility table or diagram. The diagram below shows a use case with only two groups to reduce the complexity. The first group consists of the Salesperson Agent, Customer Agent and Sales Office Agent (Fig. 4). The second group consists of the Warehouse Supervisor Agent, Worker Agent and Driver Agent. Each identified agent type (termed 'acquaintances') demonstrates the communication links/interactions that exist (Fig. 4) and how the agents are connected with one or more interaction. These links and responsibilities produce the final 'agent deployment diagram'. The analysis process is shown in Fig. 4.

6 Design

The 'Agent Deployment Diagram' provides the map for the design phase, but further detail is needed before the generation of the code. Decisions here have a direct impact on implementation (Xu and Shatz 2003). To avoid the duplication of tasks among agents that must use the same information or need access to the same resources to complete their tasks, one essential step is to merge or split the tasks. Splitting the activities of agents can reduce system complexity and improve system efficiency as each agent is deployed on a single computer. This next step produced the interaction table for each agent type with the relevant trigger conditions that indicates the coding instructions from the "Message Tem-plate" required to express the behaviours needed to receive incoming messages. The agents' behaviour then needs to be modelled from the responsibilities identified in the analysis phase along with the key objectives; this determines how the agent will act and react based on the sequence of orders in the process-algorithm (Nikraz et al. 2006). This behaviour change for food distribution responsibilities is described in a "state transition diagram" which is presented in (Fig.5).

7 Implementation

Thus, the food distribution chain of the SME has been software engineered to eliminate the identified problems and improve the system. The system can now be programmed. In practice, as the agents exist in different locations, they will be programmed in different containers on different platforms to represent the actual situation. However, in this case study the system was only simulated on one

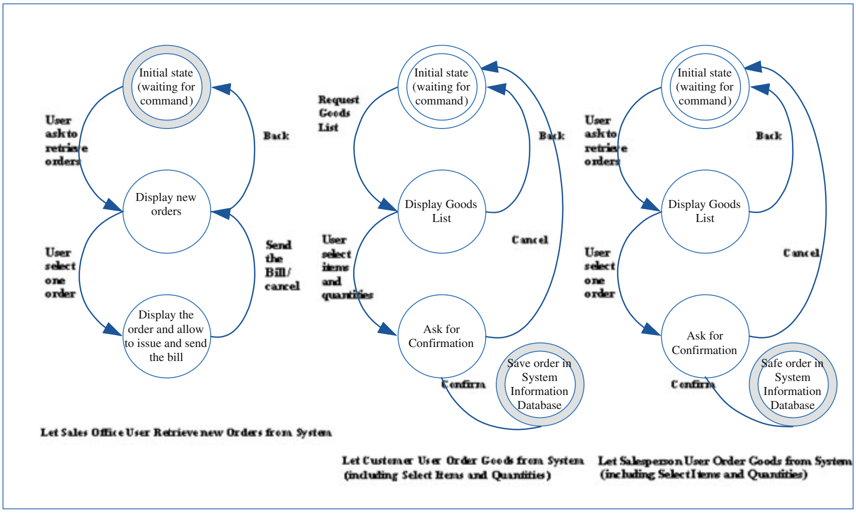

Fig. 5 State transition diagrams for food distribution responsibilities

computer and all the agents located on the same platform. In addition, each transaction was manually entered into the system by the researcher to replicate the real life process in the MAS system, and a full inventory database was populated to represent the exact state at the time. However, it is not possible to replicate constraints that relate to the finite capacity of human and machine resources available, scheduling to compete for specific machines that have other software loaded within the firm, and job routings, daily demands and due dates. Furthermore, the inherent conflicts and delays that may occur between applications installed on desktops in real life systems are not replicated. However, time buffers have been placed at each stage of the process to compensate for these.

8 Results

Using only this multi agent system programme, over 100 simulations of orders were performed; the results were obtained and compared with the original times. Results in Table 2 demonstrate a significant reduction in the cycle time required to deliver orders to customers during official working hours from a total of 1380 to 145.36 min. In principle, this demonstrates a 9-fold improvement in the total time. There was a reduction in elapsed time from approximately 23 to 2 h for the entire cycle, which is 10.31 % of the time that was initially taken. Such a considerable improvement in delivery time would result in a direct measurable improvement in customer satisfaction and cost.

Table 2 Reduction in cycle time in FSC with MAS simulation (minutes)

Process	Receive and write the order	Submit orders	Billing of sales	Collect the invoices	Inform workers	Processing time	Load the items	Drive to the shop	Offload the items	Finalise paper work	Total
MAS Simulation	*	*	*	*	*	*				*	
Before improvement	5	1162.318	58.45	7.04	1	–	32.81	78.732	29.128	5.65	**1380**
After improvement	1.39	0.1	0.1	0.1	0.1	2.7	32.81	78.732	29.128	0.2	**145.36**

9 Conclusion

Food distribution SMEs face the same wide range of operational difficulties in managing their supply chains as larger firms but without the scale of resources and finances. The case study demonstration of a real life issue indicates that in principle the use of MAS in food distribution SMEs could substantially improve the operational communication performance in relation to the multiple and complex input/output of information, and the corresponding sequence of decisions and actions to reduce the cycle time and delivery time, thereby increasing customer satisfaction. The significant improvements demonstrate the effectiveness of the multi-agent system in this SME food distribution chain. The scale of the improvement achieved after the DMAIC is a strong demonstration of this. It is important to note that this is only a demonstration, albeit using real life data, and that an agent-based system is not necessarily a 'one size fits all' solution within an SME in food distribution. However, in view of the scale of improvement seen and success of this methodology in this specific case, it is recommended that serious consideration should be given to its implementation in SMEs in other service industries.

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Stagewise Process Towards Collaborative and Value-Driven Decisions in Maintenance Networks

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Abstract Maintenance services are created increasingly in business networks, but value management is still too often supported by separate tools used by single companies. The aim of this study is to find out how the value of industrial maintenance services can be identified and modelled considering the views of each business network member (e.g. the customer, maintenance service provider and equipment provider) and how the multiple views can be used in collaborative decision making. The paper presents a three-stage process that supports the maintenance service network member companies' way towards more collaborative and value-driven decisions with the help of the tools created in a project called MaiSeMa. By increasing the collaboration level of the different parties, the value potential of the created tools and also the network increases.

1 Introduction

In this paper we discuss the management of value in industrial maintenance service networks. The tightened competition, outsourcing of support services and servitisation of industrial companies have resulted in maintenance service networks consisting of customers, maintenance service providers and equipment providers (Ahonen et al. 2010; Broedner et al. 2009; Marttonen et al. 2013; Tarakci et al. 2009). This new network setting has created value potential, but it is still somewhat hidden, as the existing management tools and methods are mainly used by single companies which do not take the collaborative context into account. Therefore, novel value management tools are needed to support the collaborative decision

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making between the network partners (e.g. Ahonen et al. 2010; MacCarthy and Jayarathe 2012; Panesar and Markeset 2008; Reinartz and Ulaga 2008).

Maintenance services are a complex research setting, where different fields of know-how interconnect and the total value comprises different accountable and non-accountable elements (e.g. availability, safety, reliability, and quality) (Ali-Marttila et al. 2015; Liyanage and Kumar 2003; Ojanen et al. 2012; Toossi et al. 2013). In addition, the value is very case-specific and depends on the maintained process, and therefore it is important to identify, model and make collaborative decisions to get a comprehensive angle of sight to the value created in a maintenance network.

The research project MaiSeMa (Industrial Maintenance Services in a Renewing Business Network: Identify, Model and Manage Value) has studied how the value of a maintenance service can be identified and modelled to each of the business network member. The project has created value management tools to support the decision making at different levels in maintenance service collaboration and promote openness and trust. Based on the overall findings, we now construct a stagewise process towards more collaborative and value-driven maintenance networks with the help of the tools created in project MaiSeMa.

Our research questions are:

- How should the developed tools be used in decision making to exploit the value potential created in service networks?
- What benefits and challenges have been identified when moving towards more collaborative and value-driven decisions?

By increasing the collaboration level of the network parties, the value potential of the created tools and the network increases. The maintenance service operations can be improved when the different parties of the maintenance service network participate and create a bigger picture together instead of just sub-optimizing from one party's perspective. Mutual trust and openness created over long-term relationships are the key elements in moving towards more collaborative and value creating networks (Kajüter and Kulmala 2005; Panesar and Markeset 2008).

The paper is structured as follows. First the research design of the project is presented. Then the created tools are introduced, followed by the stagewise process and discussion on how to utilize them in the collaborative context. Finally, conclusions sum up the main findings, with future research objectives.

2 Research Design

The research is divided into four phases, which are presented in Fig. 1. First the value of maintenance services is identified for the different parties of the network. Based on the identified needs, in the second phase the value is modelled and value management tools are created to support the decision making. In the third phase, a process is created to support the usage of the created tools. The third phase provides

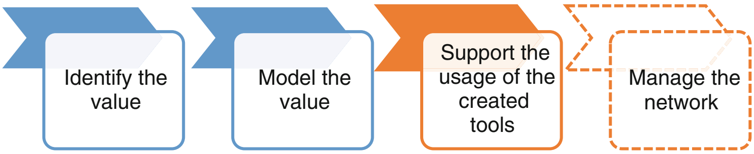

Fig. 1 Different phases of the research

an answer to the research questions in this paper by integrating the different decision making tools developed in project MaiSeMa into a stagewise process where the different parties of the maintenance network can participate. In the fourth phase, network management is in control of the companies.

The research has been conducted as a case study where two maintenance business networks form the case. The first network operates in mining industries, and the other in energy industry. Overall, seven case companies have participated in the project. The case companies include maintenance customers, maintenance service providers and equipment providers. The tools have been tested reciprocally in both networks.

As the research setting is quite complex, we have utilized both quantitative and qualitative research methods. The research data included written assignments of the representatives of the participating companies, documented focus group meetings, financial statement analysis, analytical modelling and simulation, as well as a survey and interviews. As a result of the first phase, a value profile tool and a maintenance offering framework were developed. In the second phase, additional three tools were created, a life-cycle model (LCM), a flexible asset management (FAM)-model and a performance measurement system (PMS) for network level value.

3 Realizing the Value Potential of the Maintenance Network

3.1 Identifying and Modelling the Value—Developed Tools

The value potential of service relationships and the network setting is often still hidden, as the existing value-driven processes and methods do not take the collaborative context into account (Ahonen et al. 2010; MacCarthy and Jayarathe 2012; Panesar and Markeset 2008; Reinartz and Ulaga 2008). In project MaiSeMa we have created novel value management tools that support collaborative decision making between network partners and enable also network level value creation, as it is the core of service relationships (Lindgreen and Wynstra 2005; Vargo and Lusch 2008; Walter et al. 2001). The main features of the created tools and frameworks can be seen in Table 1 where the managerial implications, openness and collaboration level required, as well as the view towards value are summarised.

Table 1 Main features of the MaiSeMa value management tools

Tool	Sample article	Managerial implication	Collaboration level required	Possible participants	Tangible value elements	Intangible value elements
Maintenance offering (NMO)	To be published	Networked maintenance with focus on core competencies	Medium/high	Customer, service provider, equipment provider	X	X
Value profile	(Ali-Marttila et al. 2015)	Identifying the value creating elements	Low/medium	Customer, service provider, equipment provider	X	X
LCM	(Sinkkonen et al. 2014)	Creating economic value by enhancing maintenance planning and decision making	Low/medium/high	Customer, service provider, equipment provider	X	
FAM	(Marttonen et al. 2013)	Addressing the impact of asset management on the return on investment	Medium/high	Customer, service provider, equipment provider	X	
PMS network	(Ukko et al. 2015)	Design of a PMS for an industrial service network	Medium/high	Customer, service provider, equipment provider	X	X

Data from the different maintenance actors suggests that a single service provider is rarely the optimum case for maintenance. Often, maintenance companies have certain key competencies but lack knowledge on other areas. With multiple actors, key knowhow on different systems could be better utilized. Also, many customers have their yearly shutdowns simultaneously, which causes momentary lack of maintenance workforce. A smarter way for organizing maintenance operations locally could enhance the timing challenges. Due to these characteristics, we propose a networked maintenance offering (NMO) framework. Within a NMO, a locally established maintenance network, actors share their key competencies, individual needs, scheduling information, etc., in order to outperform the traditional way of individual maintenance operations. Some level of data sharing, e.g., costs, across different actors is necessary within the NMO. An ideal case for a NMO would be an open books type of business.

The Value Profile tool (see Ali-Marttila et al. 2015) has been developed to support the identification of the value creating elements for each partner in maintenance service relationships. First the customer and service provider or equipment provider rank the most important value creating elements (e.g. safety at work, technical quality, reliability and knowledge) in the specific maintenance service case. Based on the responses, a value profile is drawn into a radar diagram and the partners can then discuss the elements and gain mutual understanding about the value creating (both tangible and intangible) elements in the relationship. The value potential of the relationship is realized after mutual understanding has been put into action with commonly measured target values for the elements, regular monitoring and long-term development.

LCM is an Excel-based, long-term planning and decision-making tool for industrial maintenance management (see Sinkkonen et al. 2014). Although LCM is designed particularly for managing an item (i.e. an asset or alternatively multiple assets) in networked environments, it can be utilized by a single organization as well. Depending on the data entered (e.g. maintenance costs, product-related data, production-related data etc.), LCM calculates a variety of results and figures, of which the cumulative net present value of maintenance (CNPV) and the benefit-cost ratio (B/C-ratio) where it is shown when maintenance profits exceed its costs, are the most important ones. Both CNPV and B/C-ratio are presented individually for each network partner on an annual basis. If there are significant differences in the values of CNPV, i.e. economic gains have been spread unevenly between the partners, collaborative actions should be taken in the spirit of open-book accounting to share the benefits more equitably in the network and to promote the competitiveness of the whole network.

The FAM-model is an analytical tool for studying the connection between asset management and profitability with simple mathematics (see Marttonen et al. 2013). The model shows the impact of fixed assets and working capital on the return on investment and can be used e.g. in maintenance contract negotiations or investment portfolio planning. The focus is on a tangible monetary value that is addressed through the return on investment. The value potential of the model can be realised in network-level collaboration through various agreements on the use and ownership of assets. A practical example of this is using joint spare part stocks to increase the productivity of invested capital in the network.

It can be stated that if companies aim to create value through collaboration, the collaboration needs to be managed and measured to avoid organisation-level sub-optimisation (Varamäki et al. 2008; Verdecho et al. 2009). For that reason a process model for the design of a PMS for the industrial service network has also been studied in the project (see Ukko et al. 2015). The phases of the process model are presented in Fig. 2. The comprehensive performance measurement system can be used for example for controlling and steering the operations of the service network, detecting problems and predicting future operations. In addition, the PMS can be used to develop the content and quality of the services and make the pricing of them more objective. Successfully designed and implemented PMS can also be used for rewarding and creating competitive advantages. In the right context the use of a PMS as a part of managing the service network supports the value identification for all members. By identifying and measuring the process, the most important value elements can be made visible and the operations of the network can be managed in a way that they create value for all members. Thus, the value potential of the service network can be captured by measuring right elements in the right content.

The MaiSeMa tools form a toolbox that can be utilized to promote openness and trust, either as individual tools or a process where different companies of the network participate collaboratively. Next we present the stagewise process of how the toolbox can be utilized in collaboration with different network parties.

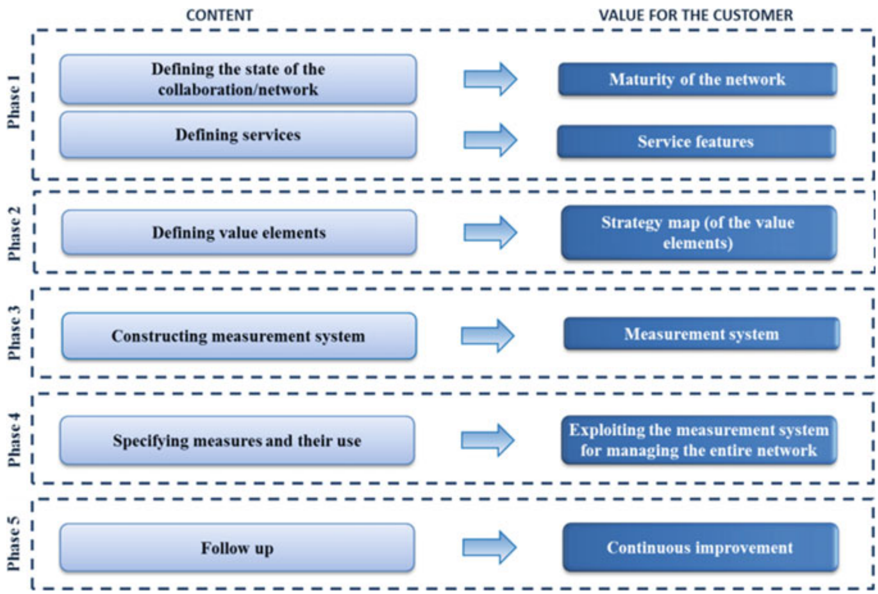

Fig. 2 A process model for the design of a performance measurement system for an industrial service network (Ukko et al. 2015)

3.2 *Three Stages Towards Collaborative and Value-Driven Decisions*

When developing the tools and methods for value-driven decisions in the maintenance network, we noticed that the existing collaboration level affects greatly the value potential that can be realized with the management tools. By increasing the openness and collaboration level of the different parties, the value potential of the created tools and the network increases. However, increasing the collaboration level and mutual trust does not happen overnight. It requires openness and long-term network relationships, like Kajüter and Kulmala (2005) and Panesar and Markeset (2008) point out. For fruitful collaboration, also initial willingness of network level partnership is required and that transition will occur step by step as mutual trust grows within the network (Ahonen et al. 2010). Therefore we suggest a stagewise process of how companies could utilize the created tools to support the transition towards more collaborative and value-driven maintenance networks and to realize the hidden value potential. Figure 3 presents an overview of the process. It should be noted that value can be co-created through every stage, but the underlying value potential grows as the collaboration level increases.

The first stage is the starting point for network-level value creation. In the first stage the participants can explore what others want from the relationship and whether they are ready to boost their collaboration. This gives the response to the question of whether the companies are ready to create value together. To find this out, the companies can use the network level maintenance offering and value profile. With the value profile the possible value creating elements can be identified,

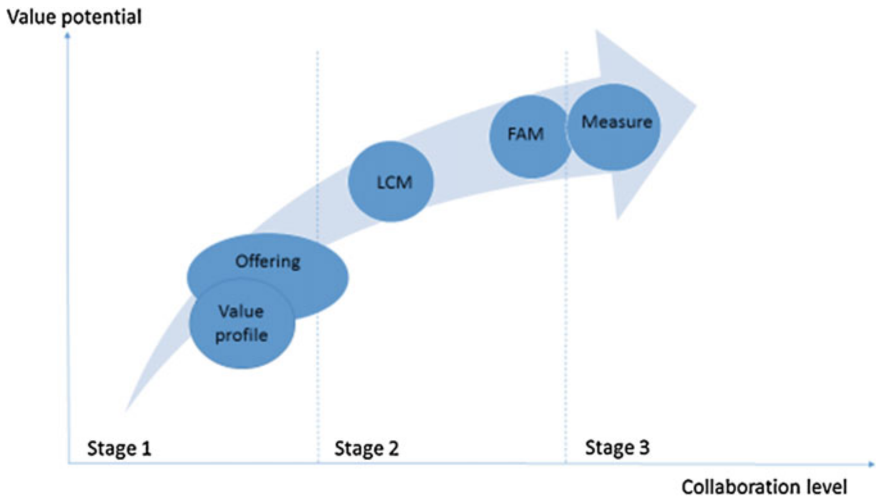

Fig. 3 Stagewise process for using value-driven tools to promote openness and trust between network partners

and based on that the foundation for collaboration scouted. It is up to the participating companies if they want to go further and fulfil the elements in collaboration or not. The collaboration level for the first stage is low, as there is no need to open data. If the participants want to get more out of the profile and realize the value potential, the needed collaboration level gets higher as the target values are jointly revised and the relationship developed over the long term. The first stage provides a context for the collaboration.

After the co-operation between the parties has been established and trust developed over medium-term collaboration, and the parties are ready for sharing some sensible data like costs and profits, they have moved to the second stage. However, at this stage the sharing of information can be still quite regulated and controlled so that the benefits and risks are clearly defined for each party. The created LCM is a common tool for planning maintenance operations together to gain benefit for each member by increasing the value of the whole network. To reach this win-win situation and exploit the full value potential, the customer, the service provider and equipment provider must work in close co-operation. This open book idea makes it possible to reach the best possible benefit for each partner. The FAM model, on the other hand, provides an opportunity to share benefits by sleeking the asset structure over the whole network. As in the previous stage, also here the value potential achieved is dependent on the level of openness between the network parties.

In the third stage of the stagewise process mutual trust is already developed over the long term, collaborative practices are established and the different parties of the network have initial willingness to build mutual goals and network level PMS. The network should be transparent, and relevant data access allowed for all network members (Ahonen et al. 2010). When exploiting the full value potential, the network makes joint decisions based on the network level PMS, and openness and trust-related issues are not just regulated with contracts but there is true interest in doing business together and increase the competitive advantage of the whole network. As Varamäki et al. (2008) states, network level PMS is needed to avoid sub-optimisation of organisations.

4 Conclusions

The new network setting of maintenance services provides an opportunity for collaborative decision-making and optimization of the whole network. Collaborative decision-making can create value for all business network members: the customer, maintenance service provider and equipment provider. However, collaboration between network members is not self-evident. Openness and trust are required. These are challenging issues for companies, as mutual trust grows step by step within the network. Therefore openness and trust between network members are formed over long-term relationships.

Previous research has concluded that network-level management tools are needed. This paper contributes to the discussion by addressing the prerequisites needed from the network partners to adopt these tools in the maintenance context. We have presented a stagewise process with multiple tools that support the maintenance service network companies' transition towards collaborative and value-driven decisions over the long term. If the collaboration level is very low between the parties, the value profile tool and maintenance offering framework can be utilized to identify the value creating elements for each party. This is the starting point for better collaboration. In the second stage, mutual trust is already gained at some level and openness of data can be considered. Here the modelling tools LCM and FAM can be utilized to plan network level benefits and asset management. The third stage is for collaboration developed over the long term, where the different parties are committed to developing the network, and collaborative practices are established. Network level PMS is here a tool that can be used to unhide the value potential of the whole network. By increasing the collaboration level and openness of the network stagewise, the overall competitive advantage of the network can be increased, as the hidden value potential is taken into use. The network is no longer only sub-optimized from one party's perspective.

The created tools can be utilized also as individual tools and at different points of collaboration as stated here, but to get the most comprehensive view, the stagewise process should be followed, as in other points the openness of data or trust might not be on a required level. Even with mature networks, the stagewise process and different tools from each stage are recommended to be regularly checked and revised to see if the collaboration and value creation are optimized for each party and at the network level.

The research has some limitations. To support the decision making as effectively as possible, information technology should support the management practices (Bititci et al. 2012; Franco-Santos et al. 2007). However, the created tools are currently separate pieces, as data management has not been in focus. Therefore, further research is needed to build a joint platform for the stagewise process tools with a common database. Another future research implication would be to implement the stagewise process into an existing network and follow the exploited value potential over the long term.

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Development of the Mathematical Model to Optimise Preventive Maintenance Activities for Service Organisations

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Abstract This paper presents an approach for optimization of preventive maintenance total cost to address both quality and reliability issues simultaneously in a single-objective environment. The concepts of operation optimization, reliability and quality loss are brought together to build the model. The proposed approach can determine optimal maintenance interval and minimize the combined preventive maintenance cost and quality loss, ensuring reliable, robust, and concurrently cost-effective product design by satisfying all the desired quality characteristics. The technique is advantageous because it allows setting and achieving the target values for the quality characteristics, obtaining the expected values by minimizing their variances, and at the same time ensuring that the design meets the reliability target.

1 Introduction

Preventive maintenance involves repair, replacement, and maintenance of equipment and products before their failures in order to avoid unexpected failures during their use. The objective of preventive maintenance is to minimise the downtime of equipment. However, excessive preventive maintenance results in unnecessary costs. Therefore, an optimal preventive maintenance schedule exists that minimises the total cost of repair and downtime of equipment.

Preventive maintenance as it affects on-line quality control system may involve two areas of applications (Taguchi et al. 1989). The first is the quality control of the

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products or equipment characteristics. The second is the reduction of the expected failures of the machine during the operation. A machine may fail if it is not able to meet the quality requirements. A machine failure may also be a sudden breakdown of the machine during operation. The failure of either type can be reduced by employing preventive maintenance schedule. However, both will add costs in terms of down time and repair/replacement. Traditionally, these two activities have been optimised independently (Pandey et al. 2012). However, researchers have shown that a relationship exists between maintenance and quality (Pandey et al. 2010), and the joint consideration of these two shop-floor policies may be more cost-effective in improving the system performance.

This paper focuses on the development of an integrated model that can be used to minimise the expected total cost of preventive maintenance (PM) action by considering both maintenance cost and quality loss. In general low maintenance frequency, low reliability indicates that the variability of the product characteristic will be high resulting in poor-quality and high quality loss. On the other hand, increase the frequency of diagnosis means that the variability of the product characteristic will be less, resulting in better quality and reducing quality loss, but increasing the preventive maintenance cost. Hence the total cost that consists of quality loss and PM cost is applied to find the most economical and efficient way of determining the maintenance intervals.

2 PM Total Cost Mathematical Model Developments

The total cost model for variable characteristics considers the following costs and losses as the yardsticks for the evaluation of quality losses cost and PM cost of the preventive maintenance system:

$$Total\ Cost\ (TC) = Diagnosis\ cost + Preventive\ maintenance\ cost + Quality\ loss\ cost \tag{1}$$

2.1 Assumptions and Notation

The following assumptions are made in the model development:

1. In the period of PM, breakdown maintenance will be performed after equipment breakdown. This activity cannot change the system failure rate.
2. The time of down time after equipment breakdown can be ignored.
3. The quality characteristic of the product is maintained very close to its target value and hence the reworked components will not have any quality loss (Table 1).

Table 1 Notation

y	The quality performance of the considered quality characteristic		
TC_M (tpm)	PM cost as function of maintenance interval		
TC	Total cost which is a function of maintenance interval '*tpm*'		
n	Checking interval (to check the amount of deviation)		
k	Cost coefficient of quality-loss function		
A	Value of the loss at which PM should be performed		
z	Number of machine	Co	PM fixed cost
tpm	maintenance interval	$CPRM_j$	PM average cost of machine j
m	Target value	cf_j	Repair cost of machine j
μ	Process mean	σ^2	Mean squared deviation
σ_m^2	Measurement error	Γ	Gamma function
L	Quality loss function	F_0	Failure probability control limit
C_{meas}	Measurements cost	PM	Preventive Maintenance
β	Shape parameter	θ	Scale parameter

2.2 *Diagnosis Cost*

The average cost associated with diagnosis, i.e. carrying out measurements from time to time:

$$= \frac{C_{meas}}{n} \tag{2}$$

2.3 *Preventive Maintenance Cost*

The model (cost-based approach) suggested by (Das et al. 2007) is considered for this cost.

$$\frac{TC_M(tpm)}{tpm} = \frac{\left(Co + \sum_{j=1}^{Z} CPRM_j\right) + \sum_{j=1}^{Z} cf_j\left(\frac{tpm}{\theta_j}\right)^{\beta_j}}{tpm} \tag{3}$$

2.4 *Quality Loss Cost*

Due to the variation of product performance, a quality evaluation is needed. One of the quality evaluation systems is based on the concept of quality loss. Quality loss is the loss to the customer incurred when the product performance deviates from the customer-desired target (Taguchi 1986).

The loss may be estimated by the quality loss function. The quality loss function is a way to quantify the quality cost of a product on a monetary scale when a product or its production process deviates from the customer-desired value for one or more key characteristics. Even though researchers have attempted to construct different types of quality loss functions, there is a general consensus that quadratic loss function may be a better approximation for the measurement of customer dissatisfaction of product quality (Taguchi and Rafanelli 1994). Assuming that m is the customer-desired target, the quadratic loss function (L) is defined as Eq. 4:

$$L(y) = k(y - m)^2 \tag{4}$$

The expected quality cost is

$$E[L] = k\left[(\mu - m)^2 + \sigma^2\right] \tag{5}$$

Equation 5 can be expressed as:

$$E[L] = k\sigma^2 \tag{6}$$

We propose to use the failure probability, $F_j(t)$, as a novel generic 'quality characteristic'. It gradually drift away from zero, the squared deviation σ^2 is given by the following integral:

$$\sigma^2 = \frac{1}{tpm}\int_0^{tpm} F_j(t)^2 dt \tag{7}$$

The probability of occurrence of machine failures is captured from past failure data is used on the Weibull distribution, it can be written as:

$$F_j(t) = 1 - \exp\left[-\left(t/\theta_j\right)\right]^{\beta_j}, \quad \left(t, \theta_j, \beta_j\right) \geq 0 \tag{8}$$

$F_j(t)$, is the cumulative failure probability of machine j at time tpm, for Weibull distribution.

This section is intended to determine the sum of the quality losses that arise under the following circumstances:

1. For the loss associated with the products before reaching the adjustment limit: Based on Eq. 7, the average mean squared deviation $\bar{\sigma}^2$ is given by the following integral

$$\sigma_1^2 := \bar{\sigma}^2 = \frac{1}{tpm}\int_0^{tpm}\left[1 - e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 dt \tag{9}$$

2. Deviations observed from the target when the quality characteristics are found to be out of control limits; and
   If the characteristic is found to be out of control during the diagnosis at interval of n months of time, then the average time the parameter is outside the control limit is $n/2$. So, the mean squared deviation in this case becomes:

$$\sigma_2^2 := \left(\frac{n}{2}\right) \frac{F_0^2}{tpm} \tag{10}$$

3. When the system under study is prone to measurement errors.
   Measurement error is an independent source of variation, causing an increase of quality loss by:

$$L_3 = k\sigma_m^2 \tag{11}$$

Adding all the costs of the quality losses together and using Eq. 6, we now present the objective function of the losses per unit time:

$$L = \frac{A}{F_0^2} \frac{1}{tpm} \left(\int_0^{tpm} \left[1 - e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}} \right]^2 dt + \left(\frac{n}{2}\right) F_0^2 + \sigma_m^2 \right) \tag{12}$$

The value of the constant k, we can take the LD50 point as the value at which 50 % of the people would do the preventive maintenance. When the failure probability goes above F_0, the preventive maintenance at an average loss of A, so the value of the loss function at $y = F_0$ is approximately A. We can therefore substitute A for the left side of Eq. 6 and F_0 for y on the right side, obtaining:

$$A = kF_0^2 \tag{13}$$

3 Total Cost Model Optimisation

Adding all the costs together, including the costs of measurements and adjustments plus the quality loss function, we now have the complete objective optimization model. The proposed model captures the merits of both quality loss and the maintenance/failure cost, and use the objective function based on this concept.

We term the proposed model the total cost model. The generic form of the total cost per unit time optimization model is given below:

$$TC = \frac{C_{meas}}{n} + \frac{\left(Co + \sum_{j=1}^{m} CPRM_j\right) + \sum_{j=1}^{m} cf_j \left(\frac{tpm}{\theta_j}\right)^{\beta_j}}{tpm} + \frac{A}{F_0^2}\frac{1}{tpm}\left(\left[1 - e^{-\left(\frac{t}{\theta_j}\right)^{\beta_j}}\right]^2 dt + \left(\frac{n}{2}\right)F_0^2 + \sigma_m^2\right) \quad (14)$$

3.1 Illustrative Example

We consider a machine consisting of three components to demonstrate the proposed model. The cost and reliability related input data are given in Table 2. The parameter θ_j is computed from the relationship:

$$\theta_j = \frac{MTBF_j}{\Gamma\left(1 + \frac{1}{\beta_j}\right)} \quad (15)$$

It is seen from Fig. 1 that as the interval is maximize, cost of quality loss, PM cost, and total cost is decreasing up to a certain value of preventive maintenance interval and increases further there on. The optimal tpm value is 6.8 months and the total preventive maintenance cost equals \$297.90, with a inspection interval n = 0.9 months (Table 3).

Table 2 Input data with three components

	Component 1	Component 2	Component 3
MTBF (months)	18	20	24
CPRM (\$)	280	350	200
cf (\$)	950	1100	1000
β	1.8	2	1.74
θ	20.25	24.57	26.97
Co (\$)	150		
C_{meas} (\$)	30		
A (\$)	500		
F_0	0.30		
Planed period, *T*	48		

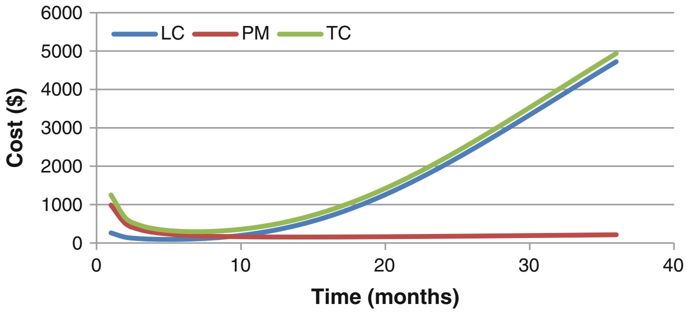

Fig. 1 Costs versus interval *tpm* for multiple components

Table 3 Various costs (Dollar) versus intervals (months) for fixed $n_{opt} = 1$

tpm (months)	*LC* ($)	*PM* ($)	*TC* ($)
1	260.47	989.29	1249.76
2	147.18	506.41	653.6
3	110.84	349.62	460.46
4	95.57	274.14	369.7
5	91.12	231.09	322.21
6	94.95	204.19	299.14
7	106.73	186.48	293.21
8	126.92	174.48	301.4

4 Sensitivity Analysis

Table 4 Results of sensitivity analysis

	Basic	+10 %	TC (%)
Cmeas	30	33	+1.0089
Co	150	165	+0.1222
CPRM	280	308	+0.1222
cf	950	1045	+0.0167
beta	1.8	1.98	−69.4342
A	500	550	+0.1014
F_0	0.30	0.33	−136.355

- TC slightly changes (≤1 %) for C_{meas}, Co, CPRM, cf, A.
- TC decrease more than 69 % if beta increases by 10 % (Table 4).
- TC decrease by 136 % if the failure probability increases by 10 %, i.e. the control limit F_0 has the highest sensitivity value.

5 Conclusions

It has been observed that there are two parallel developments for determining the optimum preventive maintenance interval, one based on the maintenance cost without considering the quality loss, and the other one based on the quality loss without considering the maintenance cost. A novel approach combining the maintenance cost and quality loss has been developed. Numerical examples have illustrated the application of the model, and the sensitivity analysis has indicated the effects of the changes in key input parameters on the optimal solution. This model is very generic in nature that can be applied to many characteristic variables. Using this model, an optimal interval which can increase the quality and reduce the cost can be achieved in the early stage of maintenance plan.

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Management System for Value Improvement of Services Toward Long Term Vision

Michihiro Amagasa and Kenichi Uchiyama

Abstract In today's competitive business situations, it is indispensable for corporations to expedite the value improvement for services and provide fine products satisfying the required function with reasonable costs. This paper provides the management system with dynamic variables for the value improvement of services based on the value engineering and the systems approach, which is regarded an ill-defined problem with fuzziness. The characteristics of this paper are to be able to perform the value improvement of services based on long term vision. Finally, in order to show how the proposed system works, a practical example on the value improvement of services is illustrated and its validity is examined.

1 Introduction

In today's competitive business situations characterized by globalization, short product life cycles, open systems architecture and diverse customer preferences, many managerial innovations such as the total quality management, the customer relationship management, the business process reengineering, the supply chain integration, etc. have been developed. The value improvement of services is also

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considered as a methodology of managerial innovation. It is indispensable for corporations to expedite the value improvement for services and provide fine products satisfying the required function with reasonable costs.

As a methodology to improve services in companies, the performance measurement system dealing with the static variables has been proposed on the basis of the value engineering (Amagasa 2014; Miles 1984). This paper provides the value improvement system of services (VISS) with dynamic variables based on the value engineering and the systems approach. The value improvement system with dynamic variables is to determine whether or not its value improvement is performed, taking account of future fluctuation of variables necessary to provide services, while the system with static variables is to perform the value improvement at that point of time. In particular, for the value improvement problems discussing in this paper, they can be defined as complicated ill-defined problems since uncertainty in the views and experiences of decision makers, so-called “fuzziness”, is present. The characteristics of this paper are to be able to perform the value improvement of services based on long term vision. Under the anticipating prediction of the future fluctuation with respect to service variables, it may be necessary to predict the fluctuation of functions and costs, including fluctuation of exchange rate, technical development and change of personnel expenses etc.

Concerning the definitions of services in marketing, a voluminous reference material has been published (Grönroos 2007; Kotler and Keller 2006; Lovelock and Wirtz 2010; Zeithamal et al. 2008). In particular, according to American Marketing Association (AMA 2015), the “customer satisfaction” will be recognized as one of the key terms of services definition. The purpose of this paper is to perform the improvement of customer satisfaction in the services based on long term vision. It is important to determine under a long term vision to improve any one of four resources including human, material, finance, information, which is needed to provide services. In other words, the determination on whether the value improvement for four resources is performed will certainly lead to directly influence to the value improvement of services. The management system has the value improvement of customer satisfaction for its object, and it is to examine whether four resources are examined to be properly used. Then, it may have a good effect on the expansion of market share and the company performance.

In VISS design process, the inherent uncertainty in decision making process can be rationally handled on the basis of fuzzy set theory. In consequence, the system we propose provides decision-makers with a mechanism to incorporate subjective understanding or insight to evaluation process, and also provides a flexible support such changes as business environment and/or organizational structure.

In order to show how the proposed system works, a practical problem is illustrated and examined as an empirical study: "Value improvement of services in the electronics company".

2 Value Improvement System with Dynamic Variables

The value of services is performed by the following formula (Amagasa 2014):

$$\text{Value of services}\,(t) = U(\text{Satisfaction of needs}\,(t), \text{Use of resources}\,(t)) \quad (1)$$

Here, U is a kind of a utility function of services depending on the time-t. The value of services (t) indicates the satisfaction of needs achieved by using the resources at time-t.

The satisfaction of needs and the use of resources are, respectively recognized as the functions and the costs of services in the value engineering. Therefore we redefine the value of services (t) as follows:

$$\text{Value of services}\,(t) = \text{Function}\,(t)/\text{Cost}\,(t)(=F\,(t)/C(t)) \quad (2)$$

where F(t) and C(t) show respectively the functions and the costs for services depending on the time (term) "t", so called "dynamic variables". The value improvement process of services is carried out depending on time-t while taking into account of factors such as the fluctuations of personnel expenses and exchange rate, the change of functions by material development etc.

We propose the system to improve the value of services defined. The value improvement system consists of five stages, that is, stages A, B, C, D, and E.

At stage A, select the measures by the nominal group techniques (Delbecq et al. 1975) and build a functional block diagram (FBD) under the "means to purpose" relationship, which is based on the system recognition process (Amagasa 2014) to clarify the essence of ill-defined problem (Fig. 1).

It's very important to express an image having in a heart of each decision maker relevant to the value improvement of services as a structural model (Nagata et al. 2009) of FBD, because the FBD derives the function evaluation value of services, that plural decision-makers' knowledge is put together and embodied to the structural model. At stage B, we compute the importance degrees of functions and assign the resources to provide them for services. The importance degrees of functions are computed by making use of the ratio method (Amagasa 2014) based on the FBD which has been already built in the stage A as shown in Fig. 2. The ratio method is described as follows. The importance degrees of functions for

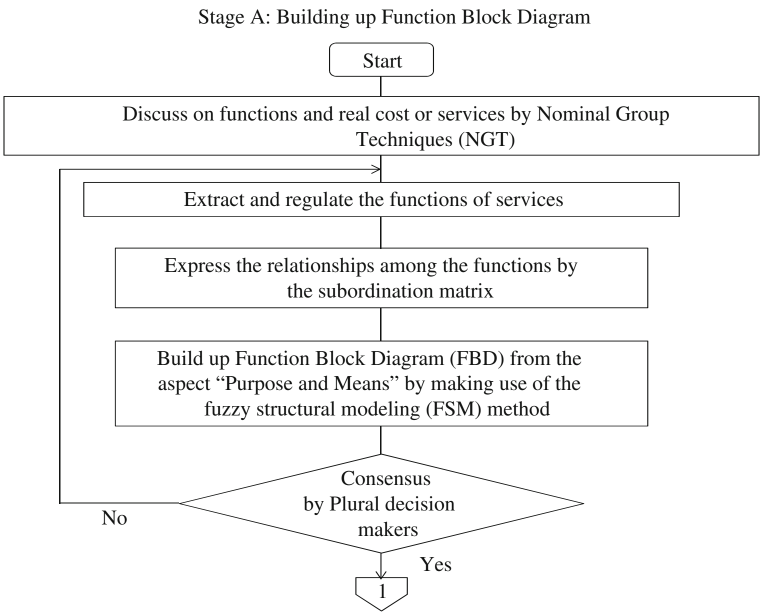


Fig. 1 VISS (stage A)

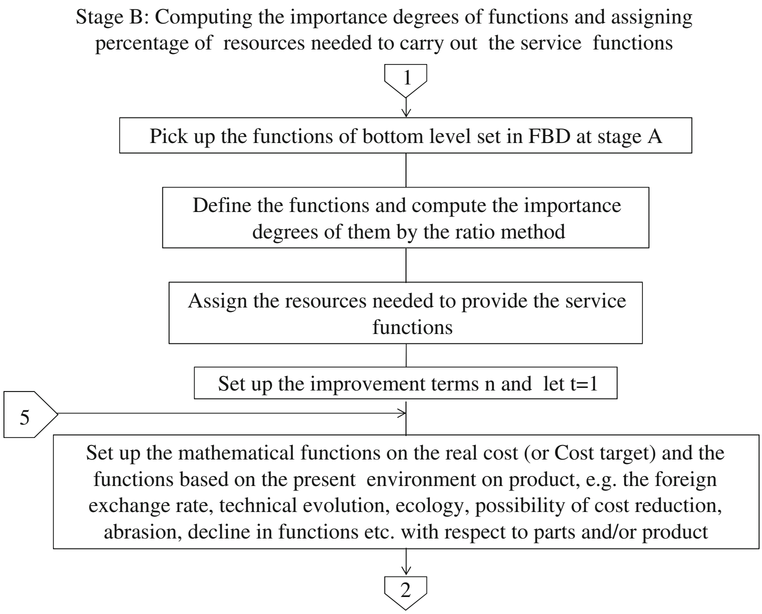


Fig. 2 VISS (stage B)

services are computed by using a matrix representing the ratio between the functions. The matrix is determined by a paired comparison among the functions based on a contextual relation "degrees of importance". In it the transitive law should be satisfied.

2.1 Resources Assignment

Since the service function to achieve the customer satisfaction is provided by the resources, we must assign the resources needed to achieve the service functions. From this, we can compute the importance degrees of functions from the aspect of resources. The assignment percentage is subjectively and empirically given based on the cost table and/or the previous learning and knowledge by the decision-makers related to value improvement of services. Here, we will explain referring to Table 1.

In Table 1, a_{ij} shows the percentage of resources, that is, "how much resources (costs or cost targets) R_i are used to provide service functions F_j, ($j = 1, 2, \ldots, n$)".

$$RF_{ij} = F_i \times a_{ij} \quad (i = 1, 2, \ldots, m; \; j = 1, 2, \ldots, n), \tag{3}$$

$$\sum_{j=1}^{n} a_{ij} = 100(\%) \quad (i = 1, 2, \ldots, m) \tag{4}$$

F_j, ($j = 1, 2, \ldots, n$) shows how much the resources are used to achieve individual sub-function constituting the service function.

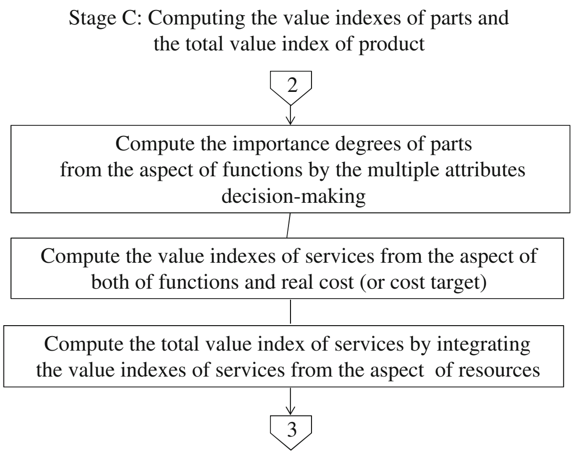
In addition, $RF_i = \sum_{j=1}^{n} RF_{ij}, (i = 1, 2, \ldots, m)$. RF_i, ($i = 1, 2, \ldots, m$) shows the total of resources used in order to achieve all of sub-functions. In other words, it means the importance degrees of functions from the aspect of resources.

At stage C, compute the value indexes of resources used to achieve the services. Then the total value index of services is computed by integrating the indexes computed (Fig. 3).

Table 1 Resources assignment

Resources	Functions	F_1	F_2	.	F_n	Total
R_1	Percentage	a_{11}	a_{12}	.	a_{1n}	RF_1
	Importance	RF_{11}	RF_{12}	.	RF_{1n}	
R_2	Percentage	a_{21}	a_{22}	.	a_{2n}	RF_2
	Importance	RF_{21}	RF_{22}	.	RF_{2n}	
.	Percentage	.		.	.	.
	Importance	.	.	.	.	
R_m	Percentage	a_{m1}	a_{m2}		a_{mn}	RF_m
	Importance	RF_{m1}	RF_{m2}		RF_{mn}	

Fig. 3 VISS (stage C)



2.2 *Computation of Value Index of Services*

The value indexes of services from the aspects of resources shown in Eq. 1 are redefined by Eq. 5 as follows:

$$V_i = RF_i / C_i, \quad (i = 1, 2, \ldots m) \tag{5}$$

where C_i is the resources that is costs and/or cost targets determined by the cost table and/or empirically based on the past data used to provide the functions of service. It will be difficult to get the cost table from the company because of the confidentiality and the disclosure of the cost table for services in companies. Here, if we set limit to management resources, that is the human resource, the material resource, the financial resource and the information resource, Eq. 5 can be represented by Eqs. 6–9.

(a) Value index of human resource (V_{h})

$$= \sum_{j=1}^{n} RF_{1j} / \text{the cost of human resource} \tag{6}$$

(b) Value index of material resource (V_{m})

$$= \sum_{j=1}^{n} RF_{2j} / \text{the cost of material resource} \tag{7}$$

(c) Value index of financial resource (V_{f})

$$= \sum_{j=1}^{n} RF_{3j} / \text{the cost of financial resource} \tag{8}$$

(d)
$$\text{Value index of information resource}\,(V_{\mathrm{i}}) = \sum_{j=1}^{n} RF_{4j}/\text{the cost of information resource} \tag{9}$$

Here, the costs (or cost targets) for each resource of human, material, finance and information is empirically and subjectively determined based on the past data relevant to the costs, and/or by the cost table in advance. By introducing the multi-attribute decision-making method described at stage C, the total value index for services is obtained from all of the aspects of the human, the material, the financial and the information based on Choquet integral $(c)\int$ (Grabisch 1995).

$$\text{Total value index} = \sum_{i=1}^{4} w_i \cdot v_i, \sum_{i=1}^{4} w_i = 1, 0 \leq w_i \leq 1, \ \text{and/or} \ (c)\int v_i \cdot w_i, \tag{10}$$

where $w_{i,}$ (i = 1, 2, 3, 4) is the fuzzy measure.

At stage D, figure out the value control graphic structure based on the value indices as shown in Figs. 4 and 5 and now discuss on the value improvement of resources and/or services based on the results of the value indexes and the value control graphic structure at term-t. This time, VISS design process at term-t finishes. As for the next, term t + 1 begins at stage B and repeats the same process as term-t if term t + 1 doesn't exceed term-n given in advance. Otherwise we proceed to stage E.

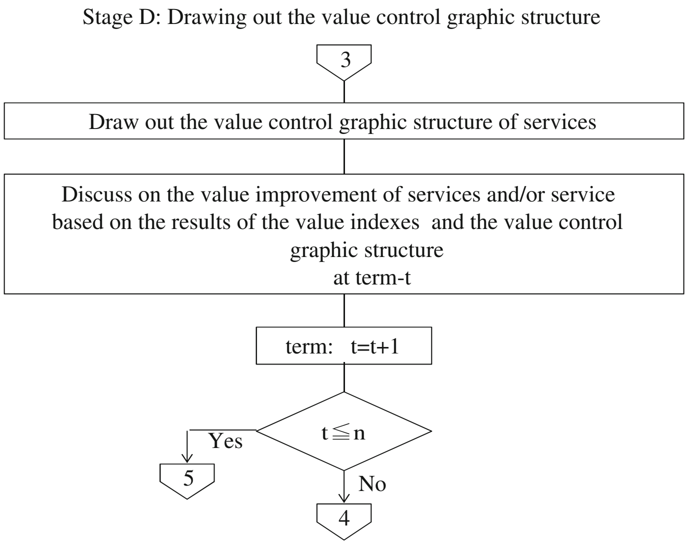


Fig. 4 VISS (stage D)

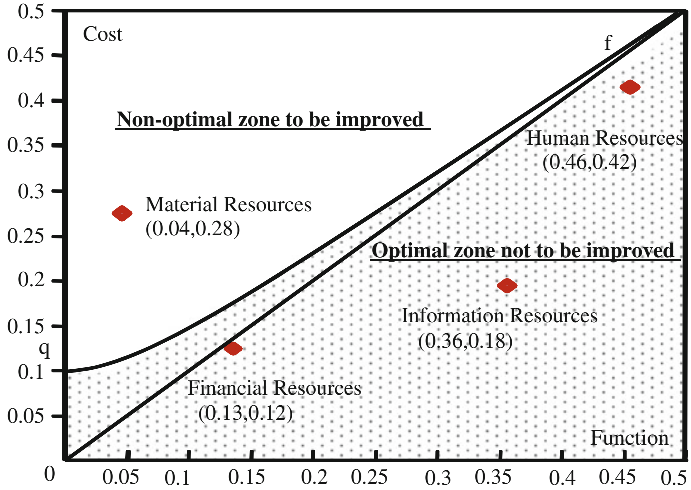


Fig. 5 An example of value control graphic structure for services

At stage E, we discuss and make an overall judgment on value improvement of resources while taking into consideration the results at n-terms. At the same time, we write the report on the value improvement of resources and/or services.

Through the design process constituting of the stages A, B, C, D and E described above, we are able to perform the improvement of the value of services from the aspects of the resources.

In x-y plane of Fig. 5, x-axis shows the degrees of functions and y-axis the costs. The curved line with the origin q on the y-axis makes distinction between the optimal zone and the non-optimal zone and is expressed as follows:

$$y = (x^2 + q^2)^{1/2}, \quad \text{where } 0 \leq q < 1. \tag{11}$$

Here the q shows the admissible level of maximum cost, and is empirically given by the decision makers. Namely, when it can be done with too low cost, the necessity to improve the factor is not required. In Fig. 5, for example, we have to improve the value of the material resource because the value of resource is in the non-optimal zone.

We examined the effectiveness of VISS mentioned above by applying the system for the value improvement of services, that is, "Value improvement of services in the electronics company" as a typical/representative example. As a result, it has been confirmed that the system is judged to be valid as a value improvement system of services. Due to the limited space, the result of it is excluded here.

3 Conclusion

In this paper, we proposed the management system with dynamic variables for the value improvement of services, and discussed about the validity of the proposed system by illustrating the practical problem: As a result, it has been confirmed that the proposed system is effective to perform value improvement for services under the dynamical changing business environments. As for the result that this paper provided, it contributes to future prediction on services, expansion of market share and improvement of customer satisfaction. Further it also contributes to the value improvement in various fields such as value improvement of inner process in companies, value improvement on planning and development etc. On the other hand, it will be necessary to use the real cost table in order to practically perform the value improvement of services. This is left as a subject to be solved in the future.

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A Data Fusion Approach of Multiple Maintenance Data Sources for Real-World Reliability Modelling

Kazi Arif-Uz-Zaman, Michael E. Cholette, Fengfeng Li, Lin Ma and Azharul Karim

Abstract A central tenet in the theory of reliability modelling is the quantification of the probability of asset failure. In general, reliability depends on asset age and the maintenance policy applied. Usually, failure and maintenance times are the primary inputs to reliability models. However, for many organisations, different aspects of these data are often recorded in different databases (e.g. work order notifications, event logs, condition monitoring data, and process control data). These recorded data cannot be interpreted individually, since they typically do not have all the information necessary to ascertain failure and preventive maintenance times. This paper presents a methodology for the extraction of failure and preventive maintenance times using commonly-available, real-world data sources. A text-mining approach is employed to extract keywords indicative of the source of the maintenance event. Using these keywords, a Naïve Bayes classifier is then applied to attribute each machine stoppage to one of two classes: failure or preventive. The accuracy of the algorithm is assessed and the classified failure time data are then presented. The applicability of the methodology is demonstrated on a maintenance data set from an Australian electricity company.

1 Introduction

Companies typically keep data about maintenance of assets in event/maintenance notifications. These data have significant potential to provide asset managers with a rich set of information about the operation of their assets, including their reliability. However, asset data are typically-collected in a "one-size-fits-all" approach

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focusing on maintenance record keeping rather than reliability modelling and analysis (Louit et al. 2009). In many organizations, data are recorded describing maintenance actions conducted on the asset. These data typically are: (1) Work Orders/Notifications (WONs), and (2) Downtime Data (DD).

A WON is a record of every action associated with maintenance (including inspection, repair, replace etc.) without specifying if the maintenance is reactive or preventive. A WON tells us if the work is a “defect” or “urgent” but it does not tell us if this constitutes a “failure”, i.e. if it stops the operation of the asset. On the other hand, DD contains asset stoppage information without stating whether the downtime is planned or unplanned. Thus, each dataset is incomplete from a reliability modelling point of view, where we need to know *both* when the asset is down and if this downtime was unplanned. Moreover, because the notification entries are made by humans and entered in lay language with little standardization, the variation in the input is extremely large.

Thus, a significant research question arises as: how typically-available asset data can be utilized for reliability models? Few efforts have been made regarding this issue. For example, Bastos et al. (2014) and Jeon and Sohn (2015) develop statistical data extraction methods to extract failure-related information from their chosen datasets. Alkali et al. (2009) used hourly readings of motor current to determine whether the mills were running or not and assumed all downtime was related to failure. Most of the methods usually used failure times which were already available to databases. However, in many cases, required information is buried in various data sets in both numerical and text formats. This complication renders traditional data mining tools unusable.

In this paper we develop a novel method to the extract information required for reliability model using the free text available in data sources. The method presented can link between data available (WON and DD) and information required (failure times) for reliability modelling. The method analyses WONs to construct a keyword dictionary using text descriptions which is in turn used to classify each DD event as a failure or preventive (preventive) maintenance event.

2 Information Extraction Methodology

The overall approach is summarized here which can be seen in Fig. 1. The basic idea is to use the WON free text to construct a classifier using words that the organization typically uses to describe urgent and unexpected maintenance. However, the WONs do not contain reliable downtime information. Thus the keyword dictionary and classifier are applied to the free text of the DD to associate each event with a failure or preventive maintenance action.

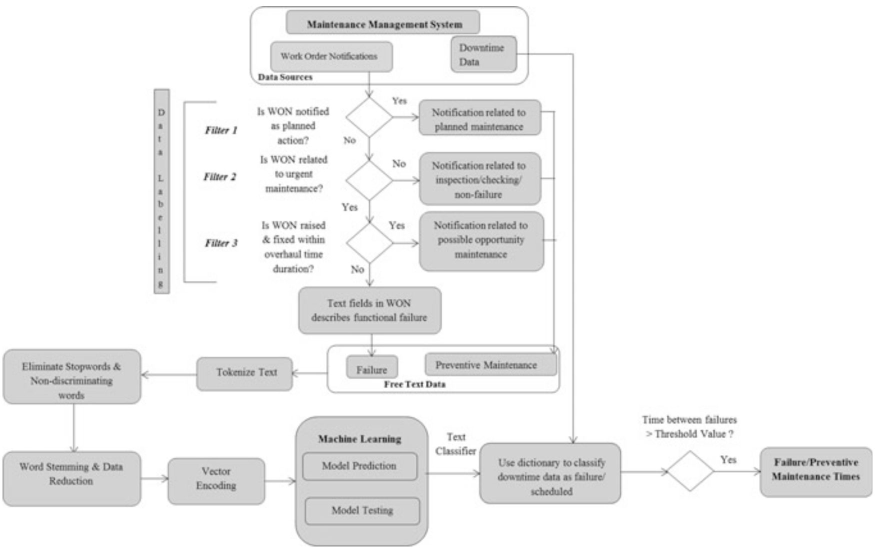

Fig. 1 Methodology to extract failure and preventive maintenance information

2.1 Data Selection and WON Labelling

WONs usually contain information regarding all types of work, planned or unplanned. In order to train a text classifier, WONs need to be labelled as failure and non-failure types. We define failure as unplanned maintenance work requires immediate downtime.

According to this definition, unplanned maintenance events in WONs are candidate failure data (Filter 1, Fig. 1). However, not all unplanned downtimes are failures. Some unplanned WONs are issued to periodically monitor anomalies or schedule and prioritize preventive maintenance actions during the next planned stoppage. Thus, we select only WONs that are urgent for further analysis (Filter 2 in Fig. 1). In addition, any WONs that are both raised and fixed while the asset has been down are classified as preventive maintenance (Filter 3 in Fig. 1). The overall filter process is shown in Fig. 1 (data labelling). Hence, WONs that have high urgency/priority likely contain language that personnel use to describe failure.

2.2 Data Cleaning and Construction of Keyword Dictionary

The free text from WON (that labelled with two of the classes: failure and preventive maintenance) will then be used to construct a keyword dictionary. After data selection and labelling the free text in the WONs are used to construct a keyword dictionary. Usually, maintenance data contain a large proportion of valuable and interesting information in text formats. For example, description of maintenance work, failure modes, types of maintenance and many more. Since, these free texts are the source of useful information; these can be used to classify the data. But before that, text cleaning is necessary to remove unwanted space, numbers, punctuation and, most importantly, non-discriminating words. At the beginning of cleaning process, all the free text are transformed into lower case followed by removing numbers, punctuation and extra spaces in between the words.

A common practice when analysing text data is to remove filler words such as "to", "and", "where", "or", "when", etc. These are known as *stop words*. Apart from that, some keywords are considered to be common but not useful in discriminating between the classes (failure and preventive maintenance here), which need to be eliminated. Text cleaning transforms the raw text into a representation known as *bag-of-words*. This ignores the orders that terms appear in rather than simply provides a variable indicating whether the term appears at all. It is then necessary to transform the terms and sentences into a form that machine learning algorithms can understand. This can be done by splitting the cleaned text documents into individual words, which is called *tokenization*. A token is the single element of text string (keyword). The classifier requires data in the form of table where each row contains a document and each column presents a keyword (here keywords are the all words within the dictionary) (Noh et al. 2015). After that, text data need to be split into training and test data sets and the keyword dictionary is formulated from training data.

2.3 Training and Testing of Machine Learning (NB) Algorithm

A Bayesian method has been used here to construct the classifier. A Naïve Bayes (NB) classifier is used to find the joint probabilities of words and classes within a set of free text. The probability of a class A for a given text field B can be calculated by using Bayes' law:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{P(A \cap B)}{P(B)}$$

Since $P(B)$ is constant for all classes, only the other variables need to be maximised. It is assumed that classes are independent of each other (Naïve assumption). The classification task is done by considering prior probability information and likelihood of the incoming information to form a posterior probability model of classification. NB model is effectively applied for (Lantz 2013):

- Text classification such as, email filtering, topic categorization etc.
- Problems in which the information from numerous attributes should be considered simultaneously in order to estimate the probability of an outcome.

The NB classifier is typically trained on data with categorical features. A sparse matrix indicates the frequency of the appearance of each keyword in the bag-of-words for each class in the training data. The training algorithm for the NB classifier can be seen in Algorithm 1. We use a Laplace Estimator (the “1” in Line 8) to nullify the zero-frequency words.

Algorithm 1 Training NB algorithm

$Train\ NB(D_f, D_p)$; D_f = Text field labelled as failure & D_p= Text field labelled as preventive

1 Extract keywords from $D_f \rightarrow V_f$

2 Extract keywords from $D_p \rightarrow V_p$

3 $\boldsymbol{for\ each}\ c \in \{f, p\}\ \boldsymbol{do}$

4 $N_c = |D_c|$ No. of documents in class c

5 $prior[c] \leftarrow N_c/N$

6 $\boldsymbol{for\ each}\ t \in V_c$

7 $\boldsymbol{do}\ T_{ct}$ Count occurrences of word t in D_c

8 $condprob[t][c] \leftarrow \frac{T_{ct}+1}{\sum_{t'} T_{ct'}+1}$

9 $\boldsymbol{return}\ prior, condprob$

With the output of Algorithm 1, we can classify new free text fields as failure or preventive maintenance in the following manner. Suppose a free text field contains the words w_1, w_2, …, w_M. We may then predict the class label, c^* using (Lantz 2013)

$$c^* = \arg \max_{c=\{f,p\}} prior[c] \prod_{i=1}^{M} cond\ prob[w_i][c]$$

We evaluate the performance of the classifier on the unseen test datasets as is standard practice in machine learning. We employ the following measures to quantify the classifier performance (Prytz 2015):

$$Recall = \frac{TP}{TP + FN}$$

$$Precision = \frac{TP}{TP + FP}$$

$$Accuracy = \frac{TP + TN}{TP + FN + FP + TN}$$

Where, TP, TN, FP, FN represent True Positive, True Negative, False Positive and False Negative classifications respectively. Finally the classifier constructed with WON data is applied to DD to classify each downtime event as “failure” or “preventive maintenance”.

3 Case Study

Maintenance data coming from coal pulverized mills of an Australian power plant over a 21 year period are used here to illustrate the application of proposed information extraction methodology. The data for 12 mills includes WONs and DD. Figure 2 shows the process of recording WON and DD during maintenance process and we can see that, the data sets are consistent with our assumptions: DD indicates that mill was actually stopped but does not specify *why*, and the WONs contain more information, but do not indicate if the issue causes a stoppage.

The incompleteness in both of the data sources independently motivates the use of the methodology developed in this paper. After applying the filters (Sect. 2.1) to

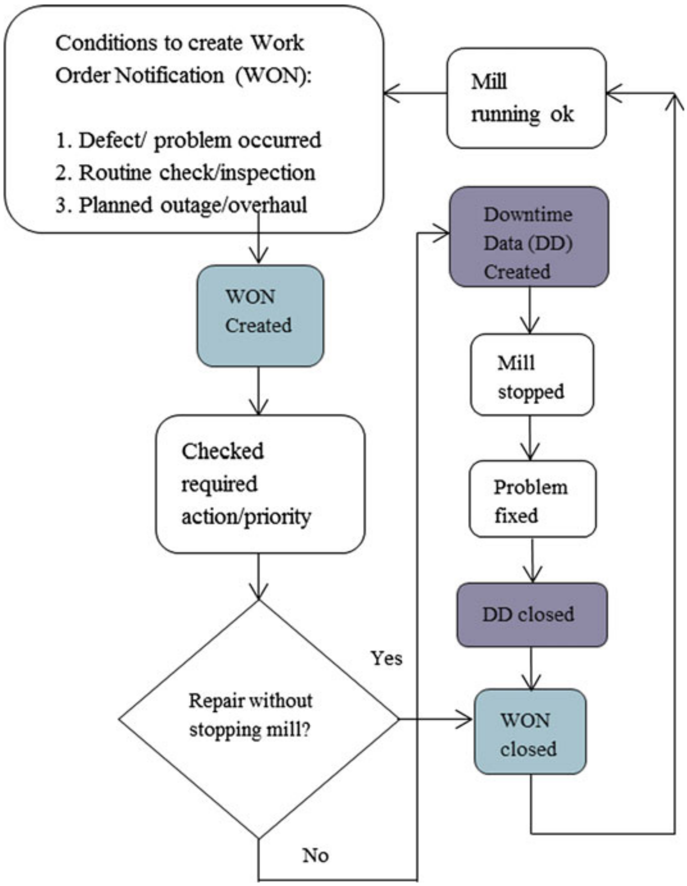

Fig. 2 Creation of two data sources during the maintenance process (coal mill)

WON (total 9401 documents), the frequencies of failure and preventive maintenance are 1068 and 8333. In this analysis, R project is used here to analyse text data as well to train and test the NB model according to the methodology in Sect. 2. After applying text cleaning process, mentioned in Sect. 2.2, a total of 1582 keywords were identified and were saved to dictionary. The NB classifier is trained on keyword dictionary and the performance of the classifier is tested by comparing predicted values of failure and scheduled maintenance work orders with actual ones not utilized in the training set. Figure 3 shows the model performance on the test data. Precision (also called positive predictive value) is the fraction of predicted failures that are truly failures, while recall (also known as sensitivity) is the fraction of predicted failures that are identified correctly.

The tested NB model is finally applied to DD and labelled them into failure and planned preventive information. Table 1 shows the outcome of the prediction per mill. It is important to mention that the predicted values cannot be validated for this case because there is no evidence of mill failure information for DD. Predicted values can be used to plot cumulative number of failures. For example, Fig. 4 shows cumulative number of failures for mill XA in two different cases. Unplanned WON means all the notifications which are urgent and unplanned while text mining means cumulative number of failures after applying text mining and filters. This information is ready for inclusion into a wide variety of reliability models (Wang and Pham 2006).

Fig. 3 Performance metrics for NB model

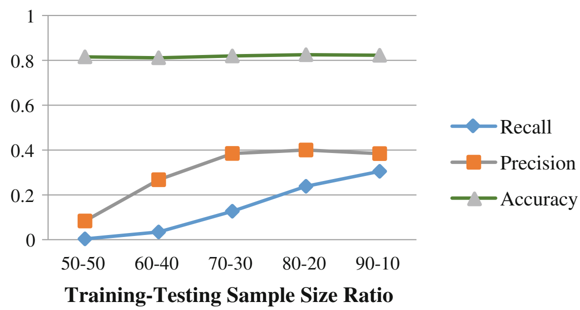

Table 1 Predicted frequencies of failure and preventive maintenance information

	Unit X						Unit Y						Row total
	Mill						Mill						
	A	B	C	D	E	F	A	B	C	D	E	F	
Failure	34	42	48	37	39	37	46	32	53	37	54	33	490
Preventive maintenance	79	99	95	73	110	69	67	77	101	107	103	82	1064
Column total	113	141	143	110	149	106	113	109	154	144	157	115	1554

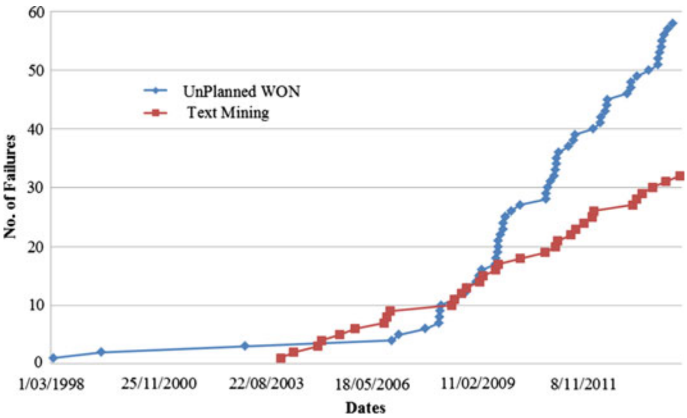

Fig. 4 Cumulative number of failures for mil XA over a 16 year period

4 Conclusion

A new data extraction methodology has been proposed here to obtain information for reliability modelling from commonly-recorded asset data. To overcome the incompleteness in maintenance one dataset with reliable free text description was used to construct keyword dictionary and extract failure and preventive maintenance data from another data source with reliable stop time data. To the best of the authors', this is the first use of text mining approaches to extract reliability information from multiple heterogeneous data sources. Such data fusion is a key challenge in exploring Big Data (Wu et al. 2014). The developed classification can be utilized to build reliability models for the optimisation of maintenance and availability of real assets.

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Asset Planning Performance Measurement

Daniel Arthur, R. Schoenmaker, Melinda Hodkiewicz and Sugandree Muruvan

Abstract Begin with the end in mind. The asset management standard ISO 55001 requires that organisations develop asset management objectives consistent with and aligned to organisational objectives. These objectives should be measurable, as should the outputs of activities executed to meet these objectives. Collectively the intention is to create a 'line of sight' between activities at the asset level and the organisation's objectives. Many organisations already have some sort of performance measurement system in place. But does this system really demonstrate a 'line of sight'? This paper addresses the question how organisations can create a visible link between the organisation's objectives, the asset management objectives and the asset management activities. The paper draws on performance measurement system literature and practice to identify key factors to be considered in the design of a system to meet the 'line of sight' requirements. These are (1) to develop a balance of perspectives (financial, customer service, internal process, talent and teamwork), (2) to have a balance between leading and lagging indicators, (3) to demonstrate relationships between indicators and objectives, and (4) to ensure the set of indicators is responsive to shifts in policy and strategy. The process of developing a performance measurement framework is described using a case study on water assets. The resulting framework comprises of three elements: the

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development of objectives, the validation of a balanced set of linked performance indicators and integration into a performance dashboard. The framework enables improved communication of the asset management priorities for informed asset investment decisions, well managed risks and increased operational effectiveness. The description includes reflections on organisational issues, like siloed information, technical approach of maintenance staff and constraints of data granularity, that need to be addressed in the development of new approaches to asset performance measurement systems and suggestions to ease the transition.

1 Background

In the absence of Regulations or Standards, companies have had autonomy in determining the level of maturity needed in their Asset Management (AM) Management System. This is likely to change with the release of the ISO 55001, the first International Standard for the management of physical assets. The ISO 55001 details the requirements for the establishment, implementation, maintenance and improvement of an AM Management System (ISO 2014b). Already some regulators in industries such as water, gas, electricity and offshore oil and gas will have adopted this Standard as part of their regulatory regime and it is expected that others will follow.

The focus of this project is on achieving one of the major requirements of the ISO 55001, which is to develop a 'line of sight' between the corporate objectives, the AM objectives and the performance indicators of an organisation. This 'line of sight' enables the organisational objectives to be translated into technical and financial decisions, plans and activities (ISO 2014a). The Institute of Asset Management refers to the line of sight as the backbone to a good management system for assets, showing the clear connectivity between the organisation plan and the on the ground daily activities (The Institute Of Asset Management 2014). Managers and employees should be able to see a link between the strategy of an organisation, the activities it employs day to day, and the indicators of success it uses. Looking down this 'line of sight' shows *how* the organisational objectives are met and looking up this 'line of sight' shows *why* activities are undertaken.

The paper is organised as follows. The literature review examines previous work on performance measurement systems and the concept of line of sight. It also introduces terminology and ideas relevant to the AM domain. This is followed by a section on the approach used and another on the results. Finally there is a discussion section reflecting on the approach and its outcomes.

2 Literature Review

One of the core requirements in the ISO 55001 Standard is the establishment of AM objectives at relevant functions and levels (ISO 2014b). These AM objectives have to meet a number of conditions such as, but not limited to, being measurable (if practicable), and being consistent and aligned with organizational objectives. The first step in developing a line of sight is therefore to establish the AM objectives in line with the organisational objectives.

The basic principles of AM and performance management (PM) are identical (NCHRP 2011). Good AM must be performance-based. AM refers to applying the PM principles to the management of (physical) assets. The line of sight is in fact a hierarchy of objectives and performance indicators, as shown in Fig. 1.

With AM as a relative new field, very little literature is available on setting up a performance management system in AM. Each organisation has a preferred approach to strategy development (Miles et al. 1978; Porter 2006). An interesting approach is shown by Hatcher et al. (2014). They show the development of the service framework for the Highways Agency based on a detailed review of corporate documents. Corporate objectives are linked to strategies (how to meet organizational plans), to services (define the service assets have to deliver) and finally to the service indicators that are relevant to the defined services.

A recent literature review on PM and performance measurement in maintenance (Parida et al. 2015) showed 27 approaches for a PM for maintenance. However, nearly all of these approaches are limited to measuring and managing maintenance. What we need is an approach that links to corporate strategy, and to AM objectives and AM activities. Earlier, Parida (2012) argued that Asset Performance Assessment frameworks need to be developed in line with the Balanced Scorecard (BSC) (Kaplan and Norton 1996) to ensure that all operational activities are aligned with corporate objectives. Other authors like Tsang (Tsang et al. 1999) have suggested the BSC as a basis for PM to integrate maintenance performance and corporate objectives.

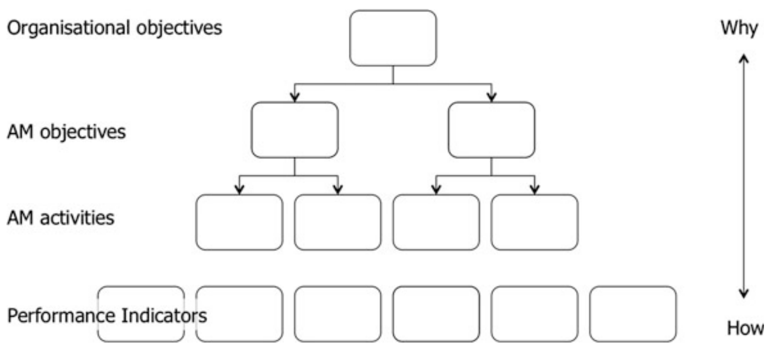

Fig. 1 Asset management as hierarchical performance management

The BSC approach was initially an approach to performance measurement (Kaplan and Norton 1992) but soon developed into an approach for strategy development and for aligning strategy, processes and indicators (Kaplan and Norton 1996). The effectiveness of the BSC approach to performance management system (PMS) development has been compared favourably with other PMS approaches (Srimai et al. 2011). Research indicates that the BSC is adopted by between 30 to 60 per cent of firms, and has the most citations of any piece of literature in the field (Neely 2005). The BSC is widely used in the business world (Perkins et al. 2014) and hence was selected as the basis for this project. We suggest that a 'line of sight' for an AM function can be developed using a performance management system (PMS) based on the BSC approach.

A core concept in the BSC is that financial performance or a company's bottom line is driven by operational indicators (Kaplan and Norton 1992). The BSC is structured around the following four perspectives:

1. Financial: Cash Flow, Profit etc.;
2. Customer Satisfaction: Time, Quality, Performance and Service etc.;
3. Internal Processes: Cycle time, Productivity, Cost etc.; and
4. Innovation and Improvement Activities: Ability to Adapt to Change etc.

Within each perspective there are a number of strategy elements. Each strategy element has an indicator associated with it. For example, within the financial perspective, the strategy might be to increase cash flow.

The four BSC perspectives can be applied to the AM context. The financial, internal process, and learning and growth perspectives are identical to organisational perspectives. The "customer" in an AM context is the user of the asset. This might be (a) groups in the same organisation e.g. equipment operators, (b) groups external to the organisation e.g. households, and/or (c) the community which the organisation serves. An example of an AM customer perspective strategy is to "improve asset availability". An internal process of "improve asset reliability" supports this, which could in turn support the financial objective of "reducing asset maintenance costs". Another way of considering these perspectives is that the internal process and talent and teamwork perspectives determine "how" the strategy will be achieved and the customer and financial perspective determine "what" will be achieved. In the context of this work we have renamed the "innovation and improvement activities" perspective as the "talent and teamwork" perspective.

In an AM context it is common to describe each strategy element as an AM objective. There are usually multiple AM objectives within each perspective. Each AM objective should have an associated set of performance indicators. In this example the performance indicator for the objective "improve asset availability" would be an indicator of asset availability. In this paper the group responsible for Asset Management is called the AM Function. The AM Function is responsible for developing and overseeing the execution of the AM Strategy (also called the Strategic Asset Management Plan) to deliver AM objectives.

There are a number of attributes of well-designed PMS (Franco-Santos et al. 2007; Nudurupati et al. 2011). The set should provide a balance of indicators and objectives; develop causal linkages between objectives and indicators; and support double loop learning (Soderburg et al. 2011). These are all attributes that lead to developing a 'line of sight' (Franco-Santos et al. 2007).

Performance measurement is the process that delivers information about the performance (of the assets and the processes used to manage them). The value of the information lies in its application. The information can be used in different ways. Research into the use of performance information provides a list of more than 40 different ways to use performance information (van Dooren 2006). Limiting this list to AM related functions leads to five different functions of PM (based on de Bruijn 2007):

1. Transparency: PM gives insight, increasing intelligence about the performance of the assets;
2. Learning and improving: the information is used to improve e.g., processes, decision making;
3. Benchmarking: the information is use to compare and to identify best practices;
4. Assessment: the information is used to appraise the performance, e.g., to set new targets for next year; and
5. Sanctioning: the appraisal is followed by positive or negative sanctions.

These functions of PM are mentioned in an increasing order of impact on the one who is being measured. PM has both positive functions and negative effects. The negative effects are enhanced by the impact the PM has (Bouckaert and Auwers 1999; de Bruijn 2007; Pidd 2005; Smith 1995). The law of decreasing effectiveness of PM (de Bruijn 2007) suggests that if a PM has high impact, the effectiveness of the PM declines because it creates strong incentives for perverse behaviour. That brings us to the most important characteristics of good indicators in a PMS. Three main conditions apply (Bouckaert 1993; van Dooren 2006):

1. Validity and reliability: the indicator has to be measurable and has to measure what it is intended to measure, time after time;
2. Legitimacy: the indicator has to be accepted, e.g., it has to be influenceable by the one who is being measured; and
3. Functionality: the indicator has to be relevant, i.e., it has to contribute to the higher-level objectives.

These main conditions lead to long lists of requirements for 'ideal' indicators, like costs to measures, timeliness, measurability and objectiveness. For here it suffices to state that indicators that fail the legitimacy condition and that are used for assessment (or worse: sanctioning) will most certainly lead to strategic behaviour, like gaming the numbers (Schoenmaker et al. 2014).

3 Approach

The aim of this work is to identify key factors to be considered in the design of a system to meet the ‘line of sight’ requirements. The first step of the project was to select a suitable case study that involves an AM Function that is seeking to develop and test an AM strategy and associated line of sight between performance indicators and AM objectives.

After selection of the case the essential phases of this project were to:

1. Develop the AM strategy and identify AM objectives;
2. Select performance indicators;
3. Test for alignment or line of sight; and
4. Reflect on the process and outcome.

3.1 Case Study

The selected case study is based on the AM Planning Group the Water Corporation, a State Government-owned and regulated water utility. They are the principal supplier of water, waste water and drainage services to hundreds of thousands of homes and businesses. They have over 3000 employees and manage a 2014 asset base of over A$15 billion. Service delivery is managed by area with a metropolitan customer service group and five regional customer service groups. The regional groups cover a vast area of 2.6 million square kilometres.

3.2 Strategy Development and AM Objectives

Strategy development is an iterative and consultative process. A key feature of success is having appropriate stakeholders in the room. In this case workshops played a key role in ensuring engagement. Five facilitated workshops were used to decide on AM objectives using a Strategy Mapping approach (Kaplan and Norton 2000, 2004). Between each workshop feedback was sought from stakeholders internal to the AM function as well a cross section of departments across the organisation. These included an internal AM community of practice, regional and metropolitan asset and operations managers.

Strategy maps were used as a means of communicating to stakeholders. Strategy maps are a visual way of providing employees a line of sight between the activities they engage in and the objectives of the organisation. (Kaplan and Norton 2004). Stakeholders had a number of options for providing feedback. These included direct feedback to the AM Leadership team, or the Project leaders. It also included the opportunity to use anonymous post-it-note on the Maps with comments validating and or questioning the outcomes. All feedback was collated and used to revise the Strategy Map and associated AM objectives.

3.3 Select Performance Indicators

Performance indicators for the AM objectives were selected with the aid of a facilitator in a separate series of workshops with a team from the AM Planning Group. As a starting point, the team reviewed existing indicators, tried to link these to the new AM objectives and discarded indicators that did not display linkages. From this they could also identify gaps where AM objectives were not adequately measured by existing approaches. A performance indicator record sheet (Neely et al. 1997, 2005) was developed for each new indicator.

If an AM objective could not be measured then it was reviewed. The balance of indicators was also reviewed to ensure the principles of the BSC approach were followed. This involved ensuring that there was a balance in the number of indicators in each perspective and there was not an excess of lead or lag indicators. Traditionally indicators have focussed on historical performance such as profit, cost and production. However there is increasing focus in organisations on leading indicators as well. Leading indicators provide early warnings, identify potential problems and highlight any need for further improvement (Hegazy and Hegazy 2012).

3.4 Test for Line of Sight

The first step in testing the line of sight is ensuring, using Performance Indicator Record sheets, the measure has a defined purpose and it relates to a specific AM objective. Performance Indicator Record sheets provide a first pass at examining the line of sight. Each indicator requires documentation of its purpose, target, formula, frequency, and source of data as well as who indicators it, who acts on it and how (Neely et al. 1997).

The second step is examining the set of indicators to see that no significant aspect of a specific AM objective has been overlooked.

The third step is the development of a Performance Dashboard. A dashboard utilises visual styles such as trend beacons, colour themes and symbols to “empower the business user to identify, manage and measure the key drivers of business success” (Bauer 2004). Displaying relevant data effectively support decision making (Wind 2005). Before the data can be populated an appropriate visual style for representing these must be chosen as “there is a limit to the ability of people to absorb the meaning of complex charts” (Pauwels et al. 2009). Spider charts are selected for this project as they facilitate the user to identify the relative strengths and weaknesses of performance.

Scores in the spider charts are normalised into a range between 0 and 5. The target and ranges are set using historical information, regulatory compliance or benchmarking information. A higher score is desirable. A colour is assigned to the score. Green represents score in the target range of between 4 and 5. Ideally all the scores should be in this region however due to budgetary and operational constraints placed upon an organisation it can be difficult to achieve this. A score of between 2 and 4 represents a satisfactory score. This light blue colour range is an acceptable level of performance for the short term however consideration should be given to how to reach the target score of 4. The red region is indicative of a score below 2 and is the limit for poor performance. If the score is within this range, the responsible group must investigate the cause and identify what corrective action can be taken.

The fourth step is to look at the trends of individual indicators and at how the historical values in sets of indicators move over time. This is particularly important in asset management, as there is frequently a time lag between activities such as preventative maintenance and performance improvements. It is particularly important that benefits of AM activity and costs of inactivity should be identifiable in the trends. That this is not always the case should trigger an investigation and discussion.

Performance indicators at the organisational level are often based on a composite of the same performance indicator at lower levels of the organisations, for example at regional level. The fifth step is to examine the impact of different regions and events on the achievement of the composite performance indicator. Are some indicators overly sensitive to the performance of certain regions or to events such as cyclones? The response to this may be to accept the values and the transparency they provide or to relook at the indicator, the way it is normalised and/or the selection of target values for specified performance ranges.

The sixth step is to examine the potential for the indicators to drive unwanted behaviour. Unwanted behaviour is mainly driven by two factors: impact and legitimacy. Can the performance indicator be influenced? The result of this may be that the function of the indicator is changed—it cannot be influenced but the organisation is in the best place to measure it. Moreover this step requires active investigation in the cause of the (dis) satisfying performance and identification what corrective action can be taken.

The purpose of the dashboard within the context of developing a ‘line of sight’ is to explore the causal relationships (functionality) between the dashboard items (Pauwels et al. 2009). If there are no apparent relationships (no functionality) between AM activities such as investment decisions, changes in maintenance strategies and resource allocations and the absolute or relative movement of performance indicators then the process needs to loop around and start again.

4 Results

4.1 Strategy Map and AM Objectives

The outcome of the initial strategy workshops produced a strategy map. The strategy perspectives aligned with the BSC with respect to finance, internal process and talent and teamwork but the customer perspective was separated into two, WA Community and Customer, creating five perspectives in total. This split was necessary in order to separate strategy that delivers short-term impacts on customers from that which has longer-term impacts on the community. The layout of the Strategy map is shown in Fig. 2.

There are 30 statements of intent across the five perspectives (WA community, customer, finance, internal processes and talent and teamwork). These determine what the AM group will do to ensure alignment of the AM function with organisations objectives. The AM objective details cannot be shared for commercial in confidence reasons. The Strategy Map was subsequently signed off by senior management and incorporated into the business planning cycle. This approval showed good buy in from the senior asset managers. This is an important requirement in asset management (ISO 2014b).

There is one AM objective for each strategy element. The number of AM objectives is shown in Table 1. There is a relatively an even spread across the thirty objectives with balance between the 'What' and 'How' perspectives.

The Water Corporation's purpose is to ensure "sustainable management of water services to make Western Australia a great place to live and invest". An example of a set of AM elements aligned to this objective is as follows. In the Talent & Teamwork element is an AM objective to "have a flexible workforce supported by

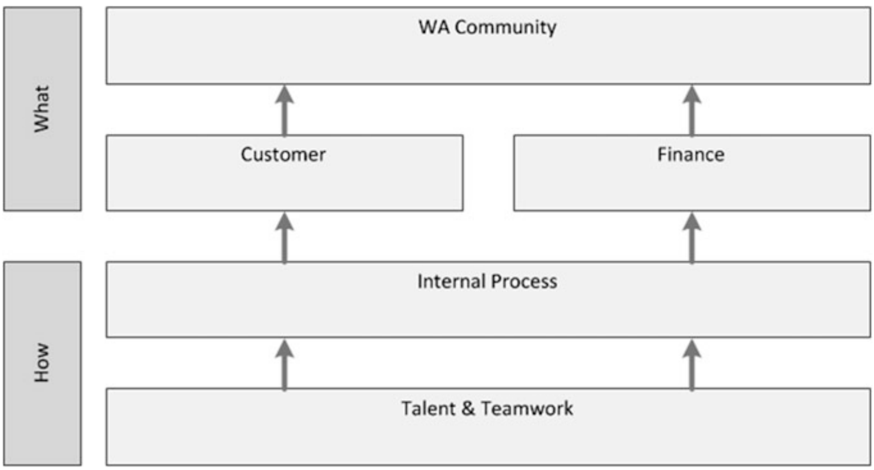

Fig. 2 Strategy map overview

Table 1 Number of AM objectives relating the AM Strategy Map

	What			How		
	WA community	Customer	Financial	Internal process	Talent and teamwork	
Lead	5	6	2	9	8	30
Total	13			17		

an AM Competency framework". Part of the AM Competency framework is focussed on ensuring AM personnel have appropriate risk and cost training which enables the Internal Process element of making "investment decisions based on clear risk criteria". This enables the Customer element of delivering "safe, reliable and consistent service that is sustainable" and the WA Community element of "recognise the impact our AM decisions have on the community".

4.2 Performance Indicators

A total of 60 indicators were selected for the 30 AM objectives. Many of these were existing indicators or modifications to existing indicators for which data was available. The spread of indicators across the perspectives and between lead and lag dimensions is shown in Table 2.

4.3 Performance Dashboard

The dashboard contained drill down functionality to target multiple users. The aim is that senior executives and asset managers throughout the organisation can use it. It is multi-tiered enabling performance at a regional or asset level to be aggregated into a composite indicator of the progress towards achieving the organisation's AM objectives.

At the highest level of the dashboard, performance is shown against each of the BSC perspectives. This is shown in Fig. 3 (please note the data is for illustrative

Table 2 Balance of indicators across the BSC perspectives

	What			How		Total
	WA community	Customer	Financial	Internal process	Talent and teamwork	
Lead	4	6	2	12	10	34
Lag	6	6	2	5	7	26
Total	10	12	4	5	7	60

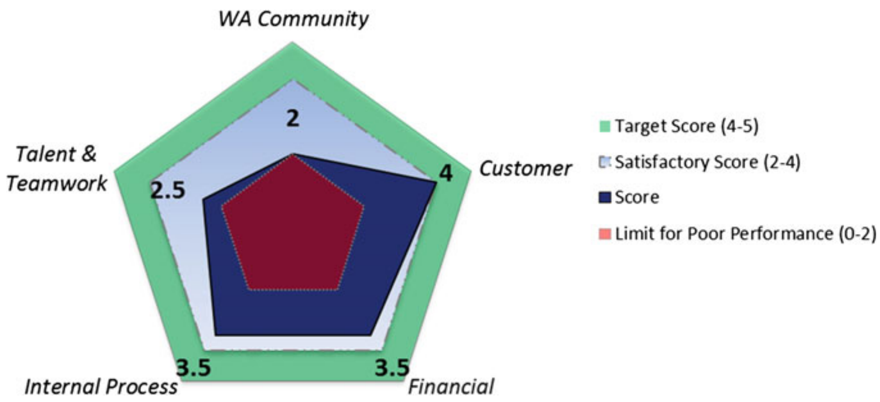

Fig. 3 Illustrative example of the highest level of the performance dashboard

purposes only and does not reflect the actual performance of the case study organisation).

Scores are normalised from the raw data into a range of between 0 and 5. A colour was assigned that reflected the performance, where a higher score being desirable.

1. The green colour represents the target range for this indicator of between 4 and 5. Ideally all the scores should be in this region however due to budgetary and operational constraints placed upon an organisation it can be difficult to achieve this.
2. A score of between 2 and 4 represents a satisfactory score. This light blue colour range is an acceptable level of performance for the short term however consideration should be given to reach the target score of 4.
3. The red region is indicative of a score below 2 and is the limit for poor performance. If the score is within this range, the user must act immediately to investigate the cause of this and identify whether corrective action is appropriate.

The perspective at each corner of the spider chart shown in Fig. 3 can also be viewed in more detail. In this example the AM objective is to “recognise the impact that our AM decisions have on the community and the environment”. There are six performance indicators against this objective as shown in Fig. 4. Once again the scores are illustrative and do not represent actual performance. This spider chart shows that here should be focus on what can be done to achieve a score of four across the performance indicators and also highlights three areas for particular attention.

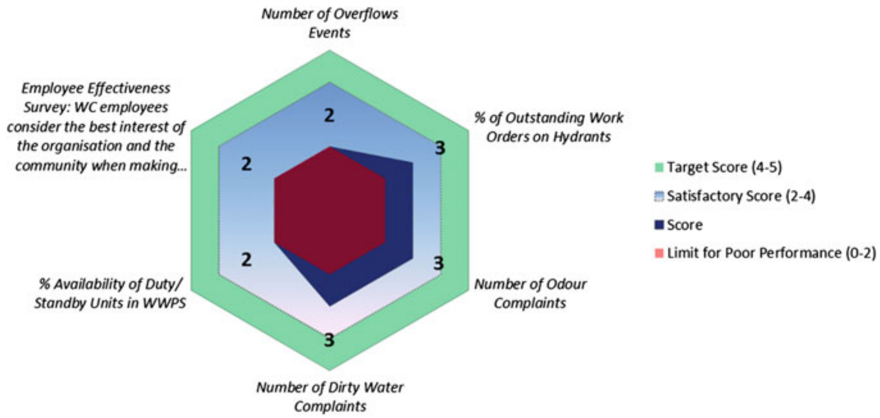

Fig. 4 Illustrative example of performance dashboard showing performance indicators for the AM objective-recognise the impact that our AM decisions have on the community and the environment

4.4 Testing Line of Sight and Balance

Testing of line of sight is an iterative process following the steps described in the approach section. In the context of this case study, this was a mature organisation and so relatively limited work was required to update the Performance Indicator Record Sheets. This mainly involved ensuring that the indicator was appropriately aligned to an existing or new AM objective. Indicators that did not contain linkage to AM objectives were discarded because they did not facilitate achieving the vision of the strategy employed at the organisation.

The driver for choosing a new indicator was to ensure the ‘line of sight’ to the derived AM objectives. If the objective could not be measured it was reviewed and if necessary discarded. This work was done in consultation with stakeholders who had necessary expertise and experience in the area of measurement being considered. This includes involving people from outside the AM function, for example in determining how to measure the “number of wastewater overflow events”.

The balance of indicators was then reviewed to ensure the principles of the BSC approach were followed. This ensured that there was not an excess of lead or lag indicators and that there was a manageable amount in each perspective.

Another step in assessing line of sight is by examining the Performance dashboard using its drill down functionality. Users of the dashboard can select elements of interest and view data historically and by region. The ability to do this may be limited by the quality and availability of historical information. Examining historical trends is necessary to establish relationships between performance indicators and the response of performance indicators to activities. For example if a large capital expenditure has been made to replace/upgrade a significant part of a region’s network then one would expect to see a reduction in unplanned maintenance and costs in subsequent years. If there is no effect visible in the performance indicator then more questions should be asked about the effectiveness of the performance indicator and the effectiveness of the capital investment.

Understanding the full extent of relationships between AM strategy, the activities undertaken to execute it and the resulting performance indicators is an on-going undertaking. The results of some activities, for example predictive maintenance programs, may not be apparent for some years.

5 Discussion

5.1 AM Objectives Within the BSC Perspectives

Table 1 shows that there are 30 AM objectives resulting from the BSC Strategy Map exercise. The customer perspective AM objectives include reliability of service supply, ensuring an acceptable risk profile, meeting regulatory requirements, considering environmental sustainability in decision making, enabling good customer service, and future proofing assets. The financial perspective is balancing life cycle cost, risk and performance and maximising the value of investments. The internal business process and talent and teamwork AM objectives support achievement of the AM objectives described above.

5.2 Affirmation and Insight

The organisation that is the subject of this case study is widely seen as a leader in the sector and it has an experienced AM leadership team. This exercise, conducted over a period of just less than a year, provided many interesting insights. Previously AM strategy development initiated by the leadership team has always had broad engagement but the problem lay in its execution. There are various process managers across a fragmented asset management framework. The process of a wide engagement strategy, conducting 5 workshops and allowing anonymous feedback resulted in a number of challenges to existing ideas as well as affirming others. There is a strong sense that the new AM objectives have a much stronger link to core values of the organisation within a more coherent framework.

There continues to be extensive discussion about the selection of specific performance indicators, how they are normalised and how targets are set. This is being assisted by the transparency provided by the dashboard and by greater focus on data availability and fitness for purpose.

A number of “sacred cow” relationships are being challenged, as they are not supported by the data being provided. This could be an issue with the data but it could be that relationships between activities and outcomes are not true. For example it has been difficult to see positive outcomes associated with higher levels of condition monitoring inspections.

Finally, there is a move away in the water industry from the traditional prescriptive regulatory regime to one in which acceptable targets are the result of a discussion between regulator and operator in which costs and risks have greater prominence. The insights created by this project will assist the case study organisation in these discussions.

5.3 Line of Sight

The project confirmed that many existing indicators were valid and aligned with AM objectives. However a number of gaps were identified where an AM objective did not contain a line of sight to an indicator. These gaps are now being addressed. Groups that are external to the AM Function were involved in the development of new indicators that impacted on them or that they impacted. Examples of those indicators are the ‘Number of Wastewater Overflow Events’ and the Water Loss Management team on the ‘Number of Leaks and Bursts’.

In one important case there was an AM objective for which no suitable indicators were proposed. This related to “We proactively engage with regulators to inform the process of setting standards and alignment”. It was suggested that this AM objective remain at least until an annual review of the Strategy and more work be done to develop suitable indicators that support this objective.

5.4 Data Quality

This work has put the spotlight on data and has shown that while much of what is collected in useful and valid there are areas for improvement and these are now being targeted with specific actions. Of particular attention is the link, or lack of, between financial and asset data management systems. Different approaches to asset hierarchies and cost accounting methods have created issues with aligning asset management activities and benefits with their costs. This is now being addressed and developments in this area will assist with achieving improved line of sight in the future.

5.5 Effectiveness of the Approach

The project has resulted in a new AM strategy and a new set of performance indicators for the Water Corporation. The work was conducted internally and benefitted from a high level of engagement by the leadership team in the AM Function. Appropriate engagement with regional and metropolitan asset managers and with other functions such as the Environmental Group was also important. The process also helped to develop a common mental model for what makes a "good" AM objective and a "good" performance indicator in the context of this organisation. The project was concluded in about 9 months at a cash cost of less than A $20k plus the in-kind contribution of Water Corporation staff. It has resulted in a set of initial performance indicators that senior management ascertain are appropriate for now and will evolve over time as more data is collected and as the effect of activities on an indicator is observed. Ultimately the effectiveness of the work will need to be evaluated over a longer period of time through retrospective analysis of the achievements of the AM function in delivering on their customer and financial AM objectives.

6 Conclusion

The intended result of implementing the approach is the identification of a line of sight for organisational objectives to performance indicators linked to AM activities. Testing this approach at the Water Corporation led to the creation of an asset planning performance measurement framework. The framework is dynamic to change and targeted at both executive and operational levels. This ensures improved communication of the AM priorities to enable informed asset investment decisions, well managed risks and increased operational effectiveness. We believe that this approach will help other asset managers, not only in the water sector, in identifying their own line of sight. The approach is relatively simple to implement and besides for the main goal—the line of sight—the approach also helps in overcoming the (financial, technical, procurement) silos in the organisation.

Implementing this approach is good start, but further work is needed on a number of aspects:

1. The approach needs to be validated in other utilities and sectors: are there organisation or sector specific factors that need to be taken into account?
2. How targets are set for each the performance indicators: the function and legitimacy of PM have to be taken into account here. An indicator used for transparency may not need a targets, and targets for indicators used for sanctioning need to be set carefully to avoid strategic behaviour. Is the user really able to influence the performance? Does the user know how to influence the performance?
3. Examine how the indicators and targets affect behaviour: the indicators may lead to positive (as intended) or negative (as not intended) learning.
4. How are the values of the indicators used for decision making; does the PMS really drive decision-making? Are the decisions for preventive and corrective maintenance driven by the higher-level objectives?
5. The line of sight is created top down (from 'why' to 'how'). The question remains as how to determine the effectiveness of the PMS to support bottom up decision making.

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Evaluation of Internet-of-Things Platforms for Asset Management

Jere Backman and Heli Helaakoski

Abstract The exploitation of Internet-of-Things technologies is continuously raising and the number of platforms increasing all the time. Companies are developing new Industrial Internet based business or service models by using IoT platforms as a backbone infrastructure. At the moment companies are already adding connectivity features to new machines, vehicles and other product models. Next step is the exploitation of collected and analysed real-time data to support profitable business and efficient operations. The first challenge companies are facing, when considering the exploitation of industrial internet solution, is choosing the suitable IoT platform to serve their business purposes. This paper presents the business and technical perspective based approaches for evaluating IoT platforms for asset management purposes. Furthermore, the paper presents an example case study of evaluating IoT platforms to support asset management research. The aim of the case study was to identify essential issues that must be noticed and to specify the requirements which the selected platform must meet to enable efficient asset management. This paper presents the results relating to the requirements and selecting the most suitable platform for asset management applications in service businesses.

1 Introduction

Enterprise asset management (EAM) is often referred as the whole life optimal management of the physical and non-physical assets of an organization to maximize value. According to the ISO 55000 standard asset management enables an organisation to realize value from assets and supports the realization of value while balancing financial, environmental and social costs, risks, quality of service and performance related to assets (ISO 55000 2014).

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The Institute of Asset Management (IAM) has developed a conceptual model for asset management in order to describe the overall scope of Asset Management and the high level groups of activity that are included within this discipline. Module Knowledge Asset Enablers forms the technical part of IAM conceptual model. This includes asset information strategy, asset knowledge standards, asset information systems and asset data and knowledge. This paper discusses the role of Industrial Internet technologies to form the backbone of Knowledge Asset Enablers by providing asset information system (IAM 2012).

Term Industrial Internet (II) is initially defined by General Electric (Evans and Annunziate 2012). The II refers to the integration of a variety of complex pieces of machinery, such as planes, locomotives, and vehicle fleets, with networked sensors and software. Eventually II will change the industrial world much more than we can imagine. It is making the complex supply and distribution networks more flexible, and more resilient. There is variety of technologies behind the term II such as Internet-of-Things (IoT), telecommunication systems, smart devices, machine learning, Big Data, and M2M communication, to collect data from machines, analyse it in real time, and use it to adjust operations. The backbone on II is IoT platforms that enable connecting individual systems and devices, collect, process, analyse and visualize data, and control the process parameters. The exploitation of IoT technologies is continuously raising and the number of platforms is increasing all the time. The first challenge companies are facing, when considering the exploitation of II solution, is choosing the suitable IoT platform to serve their business purposes. The selected IoT platform should serve the organization, its value network, business and application specific domain needs also in the future.

The significance of this paper is to propose IoT platform to support asset management in industrial environment. The evaluation criteria of IoT platforms presented in this paper help companies with the dilemma of selecting the most suitable IoT platform for their purposes. Furthermore, the paper presents a case study of evaluating IoT platform to support asset management research. The aim of the case study was to identify essential issues that must be noticed and to specify the requirements which the selected platform must meet to enable efficient asset management in different domain areas.

The research applied typical software development requirement specification process. In addition to this the research was emphasizing the suitability of IoT platform for different business models. In this way it was possible to ensure that a platform meets also other requirements than only technical ones and to assess also non-technical issues affecting to estimated success of candidates. This paper presents the results relating to the most important issues, specifying the requirements and selecting the most suitable platform for asset management applications in industry and service businesses.

This paper is organized as follows. Section 2 presents the issues to be considered when selecting the IoT platform for asset management purposes. In Sect. 3 the requirements for the IoT based asset management are presented. Section 4 presents the actual evaluation process. Finally, in the last section the wrap-up of conclusions is summarized.

2 From Asset Management to Enabling Platforms

The aim of asset management is to enable an organisation to realize value from assets and support the realization of value while balancing financial, environmental and social costs, risks, quality of service and performance related to assets (ISO 55000 2014). There are also other standards available in addition to ISO 55000. For example BSI PAS55: 2008 is a specification that itemises 28 requirements for organisations seeking to demonstrate good Asset Management practices. The body of Asset Management knowledge describes 39 subjects a whole, whereas PAS55 (28 reqs) is a requirements checklist for an organisation's management system—to direct, control and continually refine Asset Management. Figure 1 presents typical priorities and concerns of asset management by PAS55 (2008).

In addition to typical priorities and concerns also the actual activities of the asset management must be noticed. Asset management activities involve the following, among others (Komonen et al. 2005).

- Decision-making related to the ownership of production equipment
- Management of the adaptability of production equipment
- Dynamic and continuous planning of the lifetime of equipment
- Investment planning during the equipment's lifetime
- Equipment's condition monitoring and the development of its update systems
- Defining the technical and economic lifetime
- Defining the maintenance strategies
- Planning and development of the period of duty and maintenance
- All plans, expertise, systems, and measures that aim to maintain and develop the value, performance and efficiency of fixed assets and lower the costs of maintenance

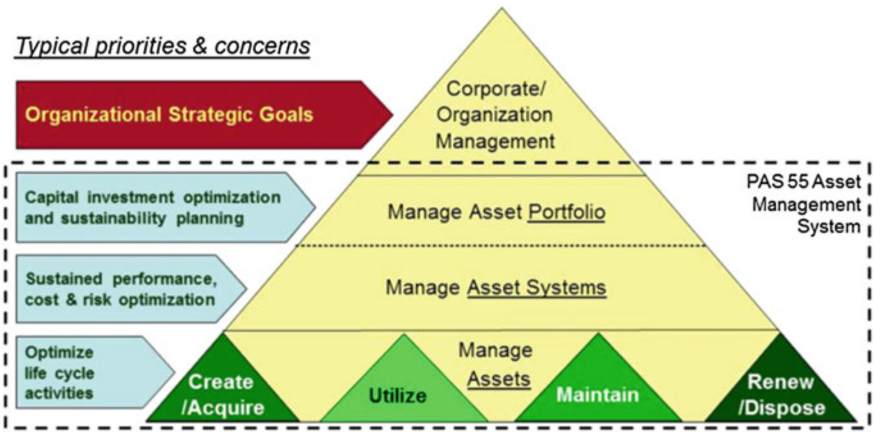

Fig. 1 Typical priorities and concerns of asset management by PAS55 (2008)

Technically the IoT platform must support or enable solution development to achieve all asset management activities in a way or another. On the other hand, the change from product provider to service provider is not only a matter of new technologies and tools but it also requires new capabilities and skills, transformation of structure and processes (Brax and Jonsson 2009). New technologies are important enablers of new services but customer point of view must be emphasised in all phases of service development, also in the development of new technologies related to IoT. It is not enough that technological tools (e.g. sensors, software, data transfer) are technically excellent but those need to respond to customer needs and support fulfilling customer's expectations and support in the provision of a good service experience. This leads to the importance of the business cases. Technology and enabled services may work well, but the operations will not likely be profitable if there are no working business cases behind. First business cases, then planned services to enable the cases and at last technology to implement the services.

When considering information technology and platforms, discussion tends to focus on technical excellence of the certain technology or solution. It is clear that technology must be good enough and enable the required support, functionalities and services. On the other hand, the technology itself is not enough. In case of the IoT platforms, the whole vital ecosystem is needed. Which platform will gather the most commonly adopted ecosystem around it, is more than challenging to foretell. It is likely that many platforms will be commonly used in the enterprises. In this case the interoperability and co-operation between different platforms have major role. If committing to some one single platform, it is important to ensure that the platform is vital for years to come. In addition to technological aspects it must be also considered the platform's users now and in the future and the platform provider's position in the field, credibility and ability to stay in the market. The worst case scenario is that the selected platform will disappear from the market for the reason or another and all developed investments, business and services will dye with it.

3 Asset Management Platform Requirements

Derived from common IoT platform requirements and needs set by asset management activities the requirements were specified from high level to the detailed low level requirements were specified in this research. In this section main high level asset management platform requirements are presented. Figure 2 presents the typical scenario for asset management needs.

IoT platforms have some basic requirements as follows:

- Platform should support data collection, transfer, analysis and reporting so that relevant information is available when needed to accelerate service
- Platform should support end-to-end information security

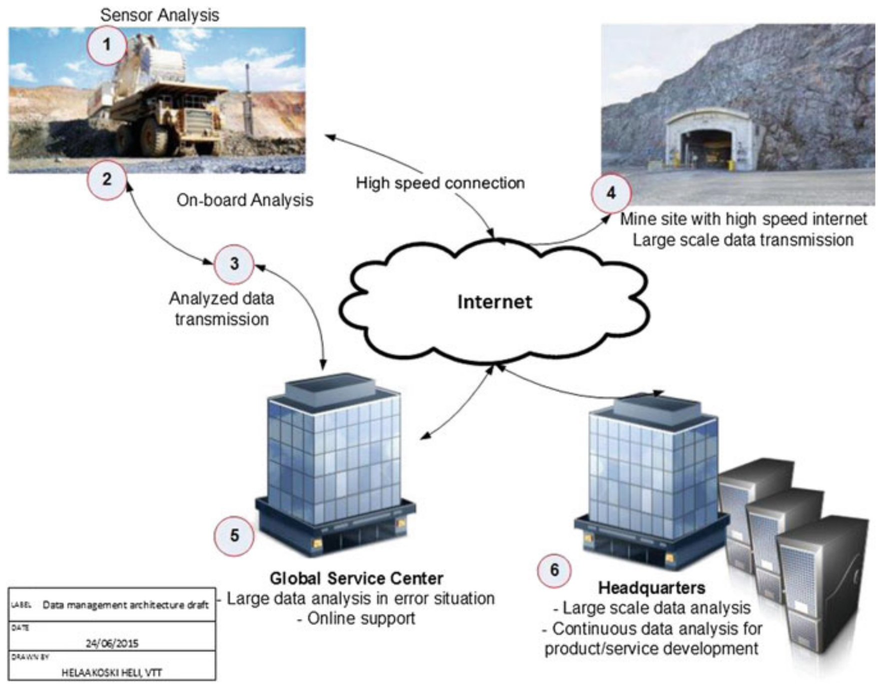

Fig. 2 Typical scenario for asset management needs

- Platform should be as flexible as possible for performance, different data types, information systems and changes in future

The collected data must have significance for the operations and services. For example dependability data should include data relating to inventory, usage, environment, and events (IEC 60300-3-2 2004). Also quality of the information must be noticed. Quality of the information has several dimensions: accessibility, appropriate amount, believability, completeness, concise representation, consistent representation, ease of manipulation, free-of-error, interpretability, objectivity, relevancy, reputation, security, timeliness, understandability and value-added (Kahn et al. 2002). Data collection and transportation sets requirements that collected data should:

- Trigger service need for customer and service provider
- Support the selection of relevant actions
- Support the execution of selected actions
- Support the development of current and new products
- Support the development of current and new services

The actual service company is developing or already providing sets requirements relating to maintenance, decision support, product and service development.

Maintenance services include planned and corrective maintenance and therefore set following requirements:

- Platform should support prediction of the maintenance need of components
- Platform should support troubleshooting after symptoms has occurred
- Platform should support the execution of maintenance tasks
- Platform should support service/product development

Decision support services include support for management and for strategic level. The services are knowledge intensive and require collection of appropriate data contents, data analysis and reporting. The platform can also support collection and analysis of relevant data for decision support related to service/product development. In general, high level requirements are same than for decision support services:

- The platform should be able to collect and save different data types from different data sources
- The platform should be able to transfer data to different kind of analysis modules
- The platform should be able to provide different pre-defined reports

The requirements presented above form the main high level requirements for asset management platform. Implementation of the requirements will support typical scenarios for asset management.

4 Platform Evaluation

The first phase of the evaluation work was to list available candidates (44 pcs) as an IoT platform. This evaluation was made in spring 2014, but at the moment there are somewhere near one hundred platforms available and more are coming. With quick familiarization with all platforms considered as candidates were listed and assessed in high level against high level requirements. The most suitable platforms were selected from the candidates for assessments in detail.

The assessment template was specified on the basis of the common requirements set for IoT platforms and high-level to low-level requirements of asset management. After this, every selected candidate platform was evaluated against assessment templates requirements/rows. The findings were written down to the specific section of the template.

The assessments were analysed in the table were all rows of the assessments findings were compared. To visualize the pros and cons, the findings were coloured. In this phase the priorities of the suitable platforms against the requirements was shaping. Figure 3 presents small example section about platform assessments analysis.

In this case three of the platforms (Azure, Axeda and Thingworx) distinguished from the others by fulfilling most of the requirements. Those were taken into closer

Company	Aeris	Arkessa	Axeda	Microsoft	deviceWISE	Etherios	SensiNode	Wapice	Oliotalo	Remion	MicroStrain	ThingWorx	Tosibox
Platform	GSP	Arkessa	Machine Cloud	Azure ISS	deviceWISE	Device Cloud	NanoService	WRM	Remote Monitoring	Regetta	SensorCloud	ThingWorx	Tosibox
Async/Sync communications	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (prob.)	Yes (prob.)	Partially	Yes	Yes
Adapt multi protocols	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Yes (part.)	Partially	Yes	Yes
Support user activate devices	Maybe	Yes	Yes	Requires dev.work	N/A	Yes	Yes	Yes (prob.)	Yes (prob.)	Yes (prob.)	Partially	Yes	
Remote control devices	Yes	Yes	Yes	Requires dev.work	Yes	Yes	Yes	Yes (prob.)	Yes (prob.)	Yes	Partially	N/A	Yes
Remote configure devices	Yes	Yes	Yes	Maybe	Yes	Yes	Yes	Yes (prob.)	Yes (prob.)	Yes	Partially	Yes	
Device grouping	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes (prob.)	Yes (prob.)	Yes	N/A	N/A	
Device abstraction	Yes	N/A	Maybe	Yes	N/A	No	Yes	Yes (prob.)	N/A	N/A	No	N/A	
Assets unlimited	Yes (restr.)	Yes	Maybe	Yes	Yes	Yes	Yes	Maybe	N/A	Maybe	Yes	Maybe	
High Availability	Yes	Yes	Yes	Yes	Yes	Yes	N/A	Maybe	Maybe	Yes (prob.)	No	N/A	
Extendible for future technologies	Maybe	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	N/A	N/A	No	Yes	
Reliable network	Yes	Yes	Yes	Yes	N/A	Yes	Yes	Maybe	N/A	N/A	No	N/A	
Reliable offline	Maybe	N/A	Maybe	Yes	Yes	Yes	N/A (may.)	Maybe	N/A	N/A	Partially	N/A	
Data processing	Yes	N/A	Yes	Yes	N/A	Yes	No	Yes (prob.)	Impl. by customer	N/A (part.)	Yes	Yes	
Semantics	No (prob.)	No (prob.)	Yes (prob.)	Yes	N/A	No	Yes	N/A	N/A	N/A	No	Yes	

Fig. 3 Example section about platform assessment analysis

consideration. The selection was finally made considering the aspects presented in Sect. 2.

5 Conclusions

When applying an IoT platform for asset management services, the platform must support or enable solution development to achieve all asset management activities in a way or another. The selection of the most suitable platform is challenging task. There are so many issues affecting to the success of the platform that systematic method is required for selection in addition human predictions and considerations relating to business, future, likelihood, etc. in the field.

In this paper the issues to consider, requirements to fill and evaluation to perform for selecting most suitable platform for asset management activities were presented. On the basis of these results the dilemma of selecting the most suitable IoT platform is much easier to approach.

The process has been performed in practice and the actual platform selection made. At the moment the selected platform is in several projects use as a base for IoT and asset management related solution development. In the future we will focus research on the actual solution development on top of the platform and utilization in data analysis, case specific service solutions etc. Time will tell how our selection will succeed in the long run, but already now we can tell that some of competing candidates have already lost the battle by losing market shares, being ran down, corporate acquisitions etc. It is clear that situation in the platform market must be followed carefully.

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Requirements and Needs—A Foundation for Reducing Maintenance-Related Waste

Marcus Bengtsson and Antti Salonen

Abstract The objective of this paper is to discuss and elaborate on requirements of maintenance and the resulting maintenance needs in order to maintain said requirements without introducing waste while doing so, taking into account both external and internal wastes. The paper will present, and elaborate on, conceptual models that can be utilized in maintenance operations in order to increase awareness of the importance of well-founded customer/stakeholder requirements in order to articulate appropriate maintenance needs in order to balance effectiveness and efficiency as well as to reduce or eliminate maintenance-related waste.

1 Introduction

In automotive manufacturing industry there is a large focus on waste elimination within production systems, especially through efforts to implement Toyota-inspired lean production systems. However, these efforts tend to focus on the more obvious wastes that directly influence the actual production and therefore requiring full support of support functions. This often leads to, for instance, maintenance performance goals striving toward maximization of equipment availability without consideration to the need, maintenance cost, or the associated waste it can create.

Industrial maintenance is a substantial financial post that cannot be neglected. The total value of maintenance budgets in Europe has been estimated to be about 1500 billion € per year (Altmannshoffer[1] 2006 in Parida 2006). The total cost for

[1]Original reference was not available for review.

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maintenance in Swedish industry, including direct and indirect cost of maintenance as well as non-realized revenue due to poor availability, was, in 2002, estimated to 6.2 % of the industry's turnover; in effect, close to 20 billion € per year (Ahlmann 2002). Though, as early as in the 1990's it was estimated that one-third of maintenance cost were unnecessary (Wireman 1990). The unnecessary cost was made up by: bad planning, overtime costs, poor usage of work order system, and limited or misuse of preventive maintenance (Wireman 1990). Additional unnecessary cost may be found in: excessive/unscheduled maintenance, unplanned or unscheduled work, excessive and/or unnecessary activities, poor spare parts management, obsolete technology, poor quality work, poor quality spare parts, and equipment unavailability (Mohanty and Deshmukh 1999). These unnecessary costs are just some of the waste that constitutes maintenance-related waste. There are others. A study by Kinnander and Almström (2008) highlights that within Swedish automotive industries, 39 % of the companies measured and documented causes of downtime, 14 % of the companies followed-up and took actions on short stops, and 14 % of the companies did not perform any preventive maintenance. The above indicates that there exists an untapped potential for automotive manufacturing companies in starting to work systematically in reducing maintenance-related waste.

Maintenance-related waste stems both externally and internally from a maintenance organization. Externally, maintenance-related waste can be found in, for example, insufficient/inappropriate, or even a total lack of, requirement setting. For instance, a common requirement that customers/stakeholders demand is to maximize equipment availability without reflecting what availability levels is good enough. Demanding an unnecessary high requirement can render waste since more resources than are needed most likely will be used in order to realize the goal. Internally, maintenance-related waste can be found in, for example, excessive or poorly executed maintenance activities. For instance, in a lean production context it is common for a maintenance organization to implement preventive maintenance, autonomous maintenance, and condition based maintenance. If alignment of the various activities is not performed, companies can end up with different actors performing the same maintenance activities in excessively tight intervals without

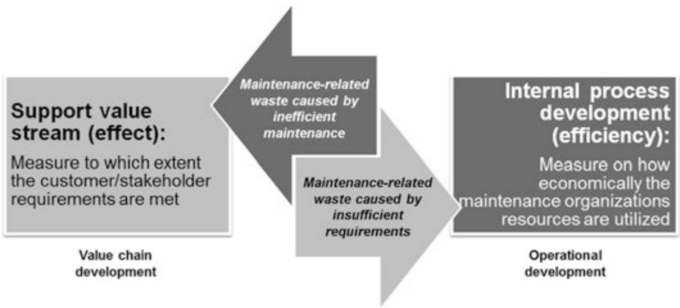

Fig. 1 Conceptual model of maintenance effectiveness (effect) and efficiency and how maintenance-related waste is created

coordination with over-maintaining as a result. That is, tying-up possible value-adding hours in machine assets for unnecessary maintenance activities, that is, both external and internal waste has been created, see Fig. 1.

2 Problem Background

Truly good maintenance cannot be achieved until both effectiveness and efficiency is taken into consideration. Neely et al. (1995) state that: "Effectiveness refers to the extent to which customer requirements are met, while efficiency is a measure of how economically the firm's resources are utilized when providing a given level of customer satisfaction" (p. 80). As so, maintenance effectiveness can be explained as how well a maintenance organization meet its requirements or goals, while maintenance efficiency can be explained as acting or producing with a minimum of waste, expense, or unnecessary effort. Effectiveness is related to indirect maintenance cost while efficiency is related to direct maintenance cost (Márquez et al. 2009). Previous research (Salonen and Bengtsson 2011) indicates that companies struggle in analyzing the indirect maintenance costs and therefore focuses on the direct maintenance costs. Thus, it is common that maintenance organizations are assessed on their effectiveness, for instance equipment availability, while only taking into consideration the direct maintenance cost. Apples and oranges are thus being compared. What should be assessed is instead maintenance effectiveness in consideration to indirect maintenance cost, and maintenance efficiency in consideration to direct maintenance cost. This confusion has, in some cases, led to cost cutting in maintenance organizations with intent to reduce internal waste but instead, in the long run, end-ups in strongly affecting external waste with increased indirect maintenance costs as a result.

Effective maintenance is thus about delivering the objective of maintenance, which is often derived as to ensure system function of the production system and to provide the parameters of cost, reliability, maintainability, and productivity (Simeu-Abazi and Sassine 2001). Coetzee (2004) shares this view on the maintenance objective, stating that: "It is the task of the maintenance function to support the production process with adequate levels of availability, reliability and operability at an acceptable cost" (p. 24). The word *adequate* is of great importance in the quote since it indirectly specifies that support of the production process being either too high or too low is wasteful. Surprisingly, efficiency is stressed as not being as important as effectiveness, as in Márquez et al. (2009) stating: "In this part of the process [strategy implementation], we deal with the efficiency of our management, which should be less important [than effectiveness]." (p. 168), or do not stress the importance of efficiency at all, as in Pun et al. (2002) stating: "Effectiveness-centred maintenance (ECM) stresses "doing the right things" instead of "doing the things right"" (p. 346). Jackson and Petersson (1999) argue that effectiveness and efficiency are closely related to the terms productivity and

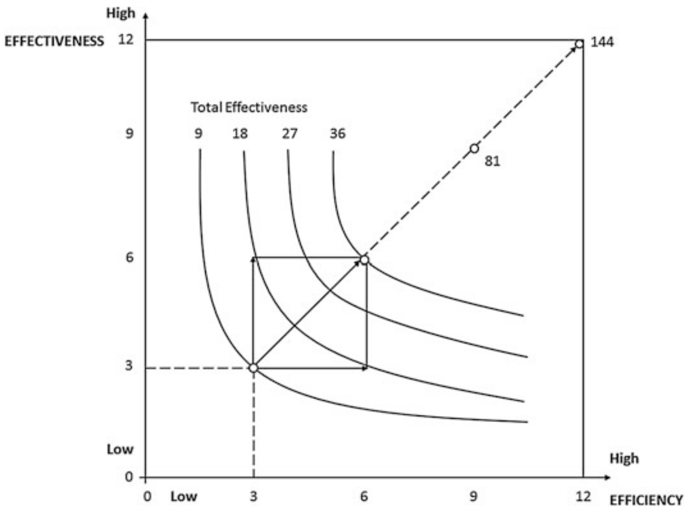

Fig. 2 As a first step, an organization can double total effectiveness by either increasing effectiveness or efficiency. However, when working to increase total effectiveness from there, working with both effectiveness and efficiency is required (adopted from Ahlmann 2002)

competitiveness. Therefore, total effective maintenance, productivity in maintenance, or even competitive maintenance, cannot be achieved until both perspectives of effectiveness and efficiency are taken into consideration, see Fig. 2.

3 Conceptual Model

In order to work towards total effectiveness in a maintenance process it is thus important to balance effectiveness (effect) with efficiency. The starting point of this task, or the foundation if you will, is to investigate the true requirements of the value stream (customer/stakeholder) and from there learn the true maintenance needs. If one does not start from the true requirements of the value stream, or work with this issue haphazardly, there is a risk in that the customer/stakeholder focuses their requirements on the wrong foundation, resulting in "*nice to have*" instead of "*need to have*" requirements or as Coetzee (2004) states *adequate levels.* That is to say, if not being perceptive and realistic, the customer/stakeholder might focus on what is nice to have without taking into account cost, direct and indirect maintenance cost included. It is nice to have, for example: 100 % machine availability, zero breakdowns, 85 % OEE, etc.—"*therefore it is wished for*". Similarly it is necessary for a maintenance organization to truly focus the maintenance goals and resources to the "*need to have*" requirements in order not to focus on maintenance possibilities. That is to say that maintenance organizations, being problem solving by nature as well as, often, having a fondness to technology and technological possibilities, might focus on what is possible to do without reflection on what is needed to do and without taking into account cost, direct and indirect maintenance cost included. We can, for example: use vibration monitoring equipment and analysis on all rotating parts, perform predetermined maintenance six times per year, purchase additional spare parts, etc.—"*therefore we do it*". This issue might be bigger when having an internal maintenance organization as opposed to an outsourced. This is due to the fact that when maintenance is being purchased externally the incentive to only require "*need to have*" maintenance is bigger as the costs are more visible.

Nevertheless, in either case of having an internal or an outsourced maintenance organization, what is needed is hard work to find and articulate true requirements on maintenance from a value stream perspective. These, most certainly, need to be differentiated and dynamic within an industrial site and over time. One flat rate requirement for a complete industrial site will not suffice. Or as, for instance, Levery (1998) states: "Why is it that organisations over-simplify maintenance requirements to fit in with organisational goals rather than base it on the *needs* of the assets?" (p. 35). Further, Levery (1998) means that requirements continuously change due to wear and tear and various changes in technology developments, product quality, and other related topics. From these, the true requirements of the value stream, maintenance can set up adequate maintenance goals and from there design a maintenance process with "need to do"-activities and from these design an organization and specify the true need of resources in order to be cost-effective, see Fig. 3.

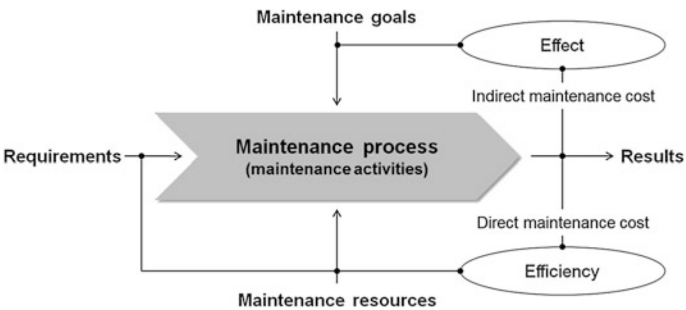

Fig. 3 Conceptual model of a maintenance process. The requirements shall be based on the true needs of the customers/stakeholders in order to be on a "need to have"-level. The maintenance goals shall be based on the requirements. The maintenance process and which activities to fill the process with shall be based on the maintenance goals while the maintenance resources shall be based on the "need to do"-activities. Efficiency is the relation between the requirements and the results compared with used resources and its resulting economical measure is direct maintenance cost. Effectiveness is determined by comparing the maintenance goals and the results and its resulting economical measure is indirect maintenance cost. The model is adapted from O'Donnell and Duffy (2002) and Eriksson (2009)

3.1 *Trade-offs in Maintenance*

One aspect of efficiency and in having a cost-effective organization is to be aware of various trade-offs that exist in maintenance activities. For instance, *good maintenance* has been defined as when: "…seeing very few corrective maintenance events; while performing as little preventive maintenance as possible." (Cooke and Paulsen 1997, p. 136). With this view one can clearly see that there exist trade-offs in maintenance operations. There is always an optimum level to strive for. As in the example quote above, too much preventive maintenance would possibly imply too high direct maintenance cost as well as losses in machines due to too much planned maintenance. Too much corrective maintenance on the other hand would possibly imply too high indirect maintenance cost as unplanned maintenance increases production losses (not even mentioning safety and environmental losses). There is though, clearly, large variations from industrial context to context regarding this view on corrective and preventive maintenance, particularly concerning safety and environment. There is, of course, a big difference in comparing, for example, the nuclear industry with automotive manufacturing industry. And this is the gist of it, requirements and trade-offs need to be industrial contextualized as well as differentiated and dynamic within that specific context. General statements such as 80/20 % preventive maintenance/corrective maintenance can be totally misleading in both examples above. In a nuclear industry context 20 % corrective maintenance can be detrimental to safety and environment while 80 % preventive maintenance, in some automotive manufacturing contexts, can be totally out of proportion and cost (direct maintenance cost, efficiency) much more than it generates (indirect maintenance cost, effect).

Below, some additional examples of trade-offs in maintenance that need to be taken into consideration with the perspective of effect and efficiency are given:

- predetermined maintenance versus condition based maintenance,
- operations based preventive maintenance versus calendar based (scheduled) preventive maintenance,
- cost of spare part storage versus cost of waiting time for shipping of spare parts versus cost for increased buffer sizes versus cost of redundancy of machines,
- focus on decreasing repair time (quick fixes of breakdowns) versus focus on root-cause analysis (could imply increasing repair times while increasing time between failure),
- autonomous maintenance versus professional maintenance,
- internal competence versus purchasing external service specialists,
- internal training and competence development versus external training and competence development, etc.

This list is by all means neither final nor written in stone and some bullets might not even be in question in some industrial contexts. However, it can serve as examples of various trade-offs that need to be taken into consideration in order to find the most beneficial solutions and activities in an organization without unnecessarily doubling, or even tripling, up on efforts.

4 Discussion

In recent years, reliability and maintenance have been recognized as being of critical importance to the success and long-term future of an organization (Fraser et al. 2015). However, maintenance, in most industries, is highly costly. Certainly, much of the cost is spent to achieve competitive production; however, still, much of the maintenance activities and its related cost are pure waste. One viewpoint that can be used in working to reduce or eliminate maintenance-related waste consists of viewing maintenance with the perspectives of effectiveness and efficiency. This paper advocates the necessity to work with both perspectives in order to realize total effectiveness in maintenance and that the start of such work is in setting up well-founded customer/stakeholder requirements that are differentiated, dynamic, and based on the true need of the assets, in both a short- and long-term perspective, and from there work on realizing these as resource-efficient as possible.

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The Use of Mobile Technologies and Their Economic Benefits in Maintenance

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Abstract The use of mobile devices enables maintenance staff to gain access to information and services relevant to the task in hand in near real time and wherever some form of network access is provided. Essentially, mobile device users become mobile actors who dynamically interact with the physical environment, i.e. workplace, and supporting information systems, leading to faster response to events and an increased performance. This paper provides insight into the acceptance prospects and best practices of the mobile technologies in the area of maintenance. Furthermore, the potential financial impact is discussed as a key driver for the adoption of mobile technologies in the maintenance practice.

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1 Introduction

Mobile technologies usage in maintenance can have many benefits, with increased organisational performance being a key expectation. However, mobile devices have not been exploited to their full potential in industrial daily practice by maintenance departments. It is, therefore, important to be aware of the factors that might impede the integration of the mobile technologies into the field. Thus, technology acceptance theories are becoming important contributing to better understanding. Hence, it is, crucial to understand those factors, since mobile technology has the potential to help maintenance managers automate data collection and analyses, support processes and reduce maintenance costs (Lee et al. 2004; Baglee and Knowles 2013). Reviews in the field highlighted both the significant potential and rapid advances in the field of Information and Communication Technologies (ICTs) in Condition Monitoring and Maintenance (Campos and Prakash 2006; Campos 2009). Furthermore, the importance of a cost-effectiveness analysis is key because it is the way to indicate if any profit or competitive advantage can be achieved by using more automatic maintenance tasks by means of ICTs, especially in predictive maintenance (Conde et al. 2009; Alrabghi and Tiwari 2013). The current paper goes through the technology acceptance theories and best practices in Sect. 2. Section 3 deals with the economic benefits of using the mobile technologies in maintenance. Further on, in Sect. 4, the main statistics and lessons learned from a survey carried out on the use of mobile devices are considered. In Sect. 5 the discussion and conclusions are presented.

2 Technology Acceptance and Best Practices

The acceptance of Information Systems (IS) by users has been researched for several years and has involved cross-disciplinary domains with a specific focus on explaining the intentional variance of Information and Communication Technologies (ICTs) acceptance by users and understanding technology acceptance. These theoretical developments regarding the possible motives and barriers on the way of accepting and adopting the technologies are manifold and have resulted in several acceptance models. For instance, the Unified Theory of Acceptance and Use of Technology (UTAUT) assume four concepts affecting the behavioural intent and usage behaviour of ICTs, namely: the performance expectancy, the effort expectancy; the social influence and the facilitating conditions. However, the concern about the UTAUT model is that it does not include attitude and self-efficacy as direct determinants of behavioural intention in the UTAUT model, which have proved to be important factors with the help of the technology acceptance research (Venkatesh et al. 2003). ICTs enablers can support enterprises in meeting expected benefits such as an increased organisational performance and productivity, insofar as they are accepted and used by employees in an organization

(Venkatesh et al. 2003). Consequently, the IT adoption technologies with their different factors are important to understand in order to be able to facilitate the acceptance of any kind of ICTs as well as the mobile technologies in the maintenance department. Apart from studies linked to technology acceptance theories, other efforts have focused more on the specific domain of maintenance and asset management. In Europe, the European Federation of National Maintenance Societies (EFNMS), through its European Asset Management Committee (EAMC) performed a survey of EU industry regarding the state of play in Asset Management best practices (EFNMS/EAMC 2012). How organisations manage data related to their assets is of particular interest. It is worth noting that although maintenance—related events were typically recorded in systems such as Computerised Maintenance Management Systems (CMMS), the loop between acquiring information and reaching decisions is not actually closed, leaving much room for improvement regarding the usage of ICTs enablers. According to the EFNMS report, part of the problem is specifically related to the fact that quality or actionable data may not, in most cases, be available at the right time and in the right place and to the persons authorised to have access to it. This highlights the need for greater penetration and adoption of ICTs, especially mobile ICT solutions. A key area of improvement that mobile ICTs can contribute to is enabling true mobile collaboration (Emmanouilidis et al. 2009). Specifically, removing time and space constraints, mobile maintenance staff can take advantage of portability, accessibility, reachability, identification and localisation features when interacting with a maintenance—oriented information system and relevant physical environment in the workplace. Taking into account that among the main factors impeding successful CMMS implementation in industry are selection errors, insufficient commitment, poor training, limited addressing of key organisational issues, underestimation of difficulties and consequent limited allocation of resources and lack of a demonstrable use of system output, an expert opinion study has produced some interesting results regarding expectations and adoption prospects for mobile ICTs in maintenance and asset management. Upon consulting experts in the field, the study considered technological, organisational and human capital issues, relevant to mobile ICTs adoption and prospects in this domain (Syafar and Gao 2013). Specifically, the study suggested that in order to improve the adoption effort, it should be accompanied by relevant business process alignment in the three broad organisational layers (strategic, tactical and operational) in company's activities and should prioritise implementation, targeting the most critical processes or assets to demonstrate impact. Leaving the broader picture to focus on individual projects and specific implementation and technology adoption aspects, the results may follow not only the general pattern but can also provide additional and more focused insight that can be obtained regarding specific technological solutions. For example, the adoption of e-training solutions in maintenance and asset management depends on aspects of introduced technological elements, functional features as well as content type and quality (Papathanassiou et al. 2013). Relevant technological innovation brings greater flexibility, efficiency, mobility and ease of use due to specific functional design features, i.e. navigation patterns, short path to relevant knowledge, interface design patters, as well as content-related features that facilitate adoption by users. Additionally, regarding e-maintenance solutions adoption, one should appreciate efforts made in industry to reduce information and services fragmentation via appropriate integration mediation mechanisms, which remain technically transparent and not-noticeable by users, while, nonetheless, increasing the seamless experience of services usage and information delivery to maintenance personnel (Pistofidis et al. 2012).

3 The Economic Benefits of Using the Mobile Technologies in Maintenance

When addressing mobile technologies for maintenance, both business process analysis and the assessment of impacts must be conducted. Financial benefits that e-Maintenance technologies can offer must be addressed carefully, relying on the principles of the Cost Benefit Analysis (CBA). CBA is a well established methodology, see (Prest and Turvey 1965), and it is based on the evaluation of the possible costs and benefits of a project. Indeed, the CBA has been carried out by paying a specific attention to the fact that costs and benefits result from the introduction of new technologies. A methodology, previously developed for the assessment of new technologies in logistics, is one of the main and possible areas to exploit. Examples are provided by Miragliotta et al. (2009). The methodology consists of 3 steps. The first step is the Analysis of the AS-IS process, according to ABC (Activity Based Costing) method, in order to identify the cost drivers of each activity. The second step is the Development of a technical solution for the process under concern. Finally, the Assessment of the impacts of the solution and the evaluation of costs and benefits is carried out through a comparison between AS-IS and TO-BE scenarios. In addition, Gilabert et al. (2015) presented how simulation tools can help identify a new predicting maintenance approach by means of ICTs in the cost-benefit of the product life cycle or plant productivity. The reliability information on which the maintenance strategies simulator relies is the probability density distribution of failure for the system or component. Such function determines the possibility of a failure occurring at a given time. The Weibull distribution is frequently employed because it is applicable to different phases in the life of a component or system. Given this function it is possible to apply the Monte Carlo method for performing a random sampling and as a consequence for obtaining possible times at which failure occurs. With this methodology it is possible to obtain a time of occurrence of a failure and, therefore, to anticipate the type and number of maintenance actions performed following a particular maintenance strategy and their result in terms of cost.

This process is repeated according to the Monte Carlo method of analysis to offer a faithful description, and time and costs are accumulated. The cost per unit time is used in order to compare the results obtained with different maintenance strategies. Further on, while making the assessment of impacts, a classification of typical costs and benefits can be kept in mind. In particular, costs and benefits can be divided in Tangible and Intangible benefits (Fumagalli et al. 2010; Jantunen et al. 2010). A formal and clear understanding of the relation between the activities and the mobile technologies is a key aspect to be considered during the assessment. Fumagalli et al. (2010) demonstrated, with the help of a case study analysis, that significant benefits can be obtained with a small scale investment, whose payback time was (in 2010) reasonably well under three years in all the cases. Interestingly, 2010 can be considered still the time when mobile devices were not so diffused. Just to give an example, Apple iPad was presented in January 2010 and can be somehow considered the precursor of the tablets. Moreover, starting from 2010, the mass diffusion of this kind of portable devices increased. Of course, this type of mobile devices is not comparable with industrial mobile devices, but the diffusion of tablet as mass product has contributed to the cost reduction, allowing one to foresee that payback time could be within around only one year and maximum two years. Evidently, it depends on the type of company business and the way the company is organized. Fumagalli et al. (2010) showed that large companies offering a wide range of maintenance services to many different types of customers, performing their activities in a formal and procedure-driven way, can benefit from the newly introduced mobile technologies by gaining process efficiency. On the other hand, Original Equipment Manufacturers (OEM) with less developed maintenance division can benefit from efficiency, but this hardly compensates the costs of the introduction of mobile solution into the field service. To this end, it is always beneficial to consider developing the proper business model of maintenance service first, trying to avoid pushing it in terms of technology advantages.

4 Industrial Use of the Mobile Technologies

In order to provide empirical evidence regarding the diffusion of using mobile solutions for maintenance, this section reports the research results obtained by the Observatory on Technologies and Services for Maintenance (TESEM, http://www.tesem.net/english-site), a permanent unit was created in December 2010 as part of the Observatories of the School of Management of Politecnico di Milano. TeSeM is a collaborative platform where a network of several Italian universities operates to monitor the state of the art on maintenance choices in the field of industrial plants. TeSeM observes small, medium and large companies in Italy. Indeed, TeSeM has collected information about the use of Personal Digital Assistant (PDA) and thus mobile solution for many multi-national European and worldwide companies, which are located in Italy. Information comes from 277 companies interviewed from 2011 to 2015. Statistics show that 10 % of the companies adopt such solutions. Moreover, considering the classification of small-medium enterprises (SMEs) and big enterprises, the following statistics have been calculated according to the results of an interview conducted in the aforementioned companies. Specifically, in SMEs 6 % of companies adopt mobile solutions and in big enterprises 13 % of the companies adopt mobile solutions. In more recent years, i.e. from 2013 to 2015, a more detailed analysis was performed for specific sectors. Results analysis reveals, for instance, that in the Food and Beverages sector, 21 % of companies adopt mobile solutions and the metalworking sector 5 % of companies adopts mobile solutions. Finally, the end expectations regarding the use of mobile devices have been investigated. The results of the analysis are based on the number of companies that use mobile solutions, namely 10 % of all the companies and show that in some cases companies use mobile solutions for more than one purpose. For instance, 18 % of the companies that adopt mobile solutions use them for managing work orders, 2 % exploit them for managing safety procedures of maintenance activities, 20 % apply such technologies for supporting inspections, 18 % for condition monitoring, 29 % for supporting spare parts warehouse management and 13 % to consult technical documents and drawings.

5 Discussion and Conclusions

It is important to understand the best practices of Information Systems (IS) adoption as well as their different contributing factors in order to be able to facilitate the acceptance of ICTs and in particular mobile technologies in the maintenance departments. The importance is highlighted by the fact that e-Maintenance has created a radical change in maintenance practices. Consequently, having the correct information when is needed at hand can provide operational and financial benefits to most organisations. The advances in wireless technologies and low cost and easy to use mobile devices allow this to become a reality through portable, available and affordable systems. In addition, from an economical point of view, ICT-enabled innovation provides enormous opportunities. The most important functional benefit is the availability of relevant and reliable information and services where needed. On the other hand, efficient maintenance strategies such as CBM rely on information since they enable maintenance actions planning based on evidence of need and not merely on pre-determine schedules. Moreover, it is easy to understand how much support a maintenance engineer needs from an information system to carry out practical maintenance tasks. In all available economic studies the introduction of e-Maintenance has proved to be justified. Naturally, the more complicated the industrial environment is, the higher the economic benefits and the shorter the payback time for investments are expected to be.

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Successful Creation of Radical Manufacturing Technology Innovations

Pooja Chaoji and Miia Martinsuo

Abstract Manufacturing technologies are often developed incrementally, and less attention has been directed at radical innovations. Radical manufacturing technology innovations pursue significant performance improvements in the production process and are expected to enhance the competitiveness of the firm. This paper explores the successful creation of radical manufacturing technology innovations by analyzing previous empirical research and characterizing the emergence and management of the innovations. Companies engage in radical manufacturing technology innovations by bringing in advanced manufacturing technologies, carrying out technology-related R&D in processes, and innovation in their supply chain processes. Innovation by adopting new technologies developed elsewhere appears as more dominant than innovation by creation. Forthcoming research is proposed on different management practices for different types and contexts of manufacturing technology innovations, and on how digitalization-related innovations can be made into a source of competitive advantage.

Keywords Manufacturing technology · Radical innovation · Success

1 Introduction

Radical innovations in products and technologies have a high impact in terms of offering completely new benefits, significant improvement in known benefits, or significant reduction in costs (O'Connor et al. 2006; Maine et al. 2014). As such,

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radical innovations have a significant potential to increase the competitiveness of a firm in its industry. During the past three decades competitive pressures on manufacturing firms in advanced industrial economies have increased because of various reasons such as globalization, economic crises and the rise of manufacturing strongholds in emerging economies (MacBryde et al. 2013). The importance of creating successful radical innovations in manufacturing firms has therefore increased.

However, there is another side to the development of radical innovations, namely the high risk and uncertainty associated with them. Previous research has suggested that some radical innovations can only be developed through spin-offs or entrepreneurial ventures, outside of the incumbent firms (e.g. Christensen 1997). Also, research suggests that mature technology firms have great difficulties in repeated innovations (Dougherty and Hardy 1996). In order to survive under competitive pressures, companies are required to rejuvenate their manufacturing systems, which will require both incremental and radical innovations in manufacturing technologies. Whilst continuous, incremental innovations are built into the routines of manufacturing firms (Klingenberg et al. 2013), much less attention has been directed at radical manufacturing technology innovations. Therefore, the success of radical manufacturing technology innovations presents a relevant and important research gap.

The purpose of this paper is to explore the successful creation of radical manufacturing technology innovations. The goal is increased understanding on the sources, characteristics and success factors in creating radical innovations in manufacturing, and the identification of research gaps to guide further research. The focus is on two research questions:

1. How do radical innovations in manufacturing technologies emerge?
2. How are successful radical innovations in manufacturing technologies managed?

This paper will synthesize evidence from existing empirical studies on radical innovations in manufacturing technologies. Previous empirical research on radical manufacturing technology innovations were sought from the key journals of operations and innovation management. This involved a preliminary keywords based search in ISI (Web of Knowledge) database using *radical innovation in manufacturing technology* which resulted in 71 articles. These were used as a starting point for locating relevant articles, journals and authors, and guided further efforts in locating empirical research-based journal publications discussing emergence and/or management of radical innovations in manufacturing technology. The articles were reviewed taking a content analytical approach, to identify common themes and differences. The analysis results in a summary of what has been studied and is known already and identification of gaps in knowledge to guide further empirical work in the field.

2 Success of Radical Innovations in Manufacturing Technologies

An innovation is an entrepreneurial endeavour to introduce a change in the commercial and industry environment (Drucker 1985; Schumpeter 1934). Schumpeter defined an innovation from an economic perspective as the introduction of a new good—or of a new quality of a good, the introduction of a new method of production, the opening of a new market, the conquest of a new source of raw/semi-processed material, or carrying out the new organization of any industry (Schumpeter 1934, p. 66). In this research, we consider primarily the innovations concerning the introduction of a new production process.

Based on the degree of novelty in the technology and configuration involved in innovations, they may be categorized as radical or incremental. Radical innovations involve distinct new knowledge or (re-)combination of existing knowledge, whereas incremental innovations take minor steps and involve little novelty (Raymond and St. Pierre 2010). Innovation radicalness is easier to sense than to define or measure (Dewar and Dutton 1986) and can be represented on a continuum between radical and incremental as the endpoints (Buschgens et al. 2013). Discrepancies over what constitutes ‘radicalness’ also arise from whether the level of newness can be defined at the level of the firm (e.g. Damanpour et al. 2006), at the level of the industry (e.g. Sinha and Noble 2008) or at the level of technology that is new-to-the-world (e.g. Chang et al. 2012). In this paper, we review studies on radical manufacturing technology innovations without giving regard to the discrepancies in how radicalness is defined. We refer to the core production technology involved within the overall new production process as radical manufacturing technology innovation (RMTI).

Existing research on RMTI can be broadly divided into three primary themes: (1) adoption and integration of AMT (advanced manufacturing technology) within firms, (2) technology-driven process R&D (research and development), and (3) supply chain process innovations.

1. The advent of computerization that started around 1970s in the traditional mechanized and manual production equipment has been one of the major changes in the history of manufacturing, and has contributed to large number of RMTIs commonly referred to as Advanced Manufacturing Technologies (Khazanchi et al. 2007). Pennings (1987) defined AMT as “an automated production system of people, machines and tools for the planning and control of production processes, including the procurement of raw materials, parts and components and the shipment and service of finished products”. Typical examples of AMT include computer numerical controlled machines, computer aided design, robotics and flexible manufacturing systems, and these

technologies share a typical characteristic that they are easy to integrate electronically (Gomez and Vargas 2012). Some research studies include manufacturing planning systems, such as Just-in-time, Manufacturing Resource Planning and Enterprise Resource Planning under the umbrella term AMT (Swink and Nair 2007).

2. Research on technology-driven process R&D focuses on the science-based and technical development of new methods of production. These are often difficult to distinguish from within overall R&D activities, where radical product and process innovations are intertwined (Raymond and St. Pierre 2010). New-to-the-world innovations involve multiple technical breakthroughs and RMTI lie at the link between a successful invention and its commercialization. An example of ongoing process R&D could be reducing the production cost of fuel cells, which is currently a major issue withholding their commercialization (Kawase 2015).
3. Research on supply chain process innovations is often focused at the firm level. It encompasses both developments in the manufacturing methods by use of new equipment and improvements in the organization and coordination of various production and distribution activities. Supply chain process innovations may or may not involve the use of new technology, and accordingly can be divided into technological and organizational types (Reichstein and Salter 2006). Research on radical technological process innovations in firms shows that adoption of RMTI is a major source of radical supply chain process innovations in manufacturing firms (e.g. Reichstein and Salter 2006; Hervas-Oliver et al. 2014).

The success of a RMTI lies in the realization of the radical performance improvement in the output produced by utilizing the new production process. For example, Gomez and Vargas (2012) and Cardoso et al. (2012) perceive that the success in adoption of new technology in production lies in the effective functioning of the overall new production process and the resulting 'utilization' of the new technology to improve the overall performance of the production output. Various measures of success have been used in earlier research. Swink and Nair (2007) measure success using five dimensions of manufacturing performance: cost efficiency, quality, delivery, process flexibility, and new product flexibility. Hervas-Oliver et al. (2014) measure success in manufacturing innovation based on improvement in three production process indicators of cost reduction, flexibility and capacity improvement. Khazanchi et al. (2007) measure success of manufacturing innovation based on plant-level performance areas of product quality, scrap minimization, on-time delivery, equipment utilization and manufacturing lead time by using subjective scales of measurement. The reviewed literature also involved use of objective firm-level measures of success in RMTI such as sales growth (Dewar and Dutton 1986) and firm survival (Sinha and Noble 2008). Therefore, measurement of success in RMTI relies on the overall performance improvement in the output made by the new production process.

3 Emergence of Radical Innovations in Manufacturing Technologies

At a given point in time, a production technology in use must submit to commercial appropriateness (Schumpeter 1934), or as Schumpeter put it, the half-artistic joy of technically perfecting the productive apparatus is disregarded in business. Research and development for the creation of radically new production methods is as important as its successful adoption and utilization within the existing production process or its implementation within a completely new production process.

Existing research on RMTI suggests that the development and utilization of RMTI occur in different organizations. Damanpour and Wischnevsky (2006) distinguish between innovation generation and innovation adoption, and according to their research, the processes of generating and adopting innovations are distinct phenomena that are facilitated in different organizational conditions. Organizations that innovate-by-generation and those that innovate-by-adoption differ with respect to their innovation capabilities, processes and culture. They emphasize that the emergence of RMTI within firms that innovate-by-generation and innovate-by-adoption follows different paths. The phases of innovation generation include: recognition of opportunity, research, design, commercial development and marketing; whereas the innovation-by-adoption includes two main phases: initiation and implementation (Damanpour and Wischnevsky 2006).

Table 1 summarizes existing studies on the emergence of RMTI in firms. Many of the research results highlight the role of the organizational context. The observed set of studies focus dominantly on RMTI-by-adoption, and few studies consider RMTI-by-generation (Raymond and St. Pierre 2010; Reichstein and Salter 2006; Un and Asakawa 2015).

Acquisition and utilization of new machinery and equipment is one of the major modes of RMTI in firms (Reichstein and Salter 2006; Hervas-Oliver et al. 2014; Khazanchi et al. 2007; Ettlie et al. 1984). Review of previous empirical research on innovation-by-adoption (see Damanpour and Wischnevsky 2006) reveals that the initiation phase consists of recognizing a need, becoming aware of a possible innovation, and evaluating its appropriateness, leading to the decision to adopt the innovation. The implementation phase consists of all events and actions that pertain to modifying the innovation and the adopting organization, using the innovation initially, and continuing to use the innovation until it becomes a routine feature of the organization. Therefore, organizations form the context for the adoption and utilization of RMTI.

According to existing research on the emergence of RMTI within firms, the strategy and structure of organizations determine the propensity for a firm to engage in the creation or adoption of RMTI (Ettlie et al. 1984). Ettlie et al. suggest that an aggressive technology policy and unique structural arrangements, such as concentration of technical specialists, centralization and informal structures, result in favourable pre-innovation conditions supporting radical process adoption. While evidence in empirical research supporting unique structures such as centralization

Table 1 Empirical studies on the emergence on radical manufacturing technology innovations

Source	Context	Methodology	Key finding for this study
Ettlie et al. (1984)	Adoption/creation of new packaging RMTI for cooked and sterilized food in meat, canning and fish industries in USA	Statistical analyses; data collection by survey (n = 147) and interviews (n = 56)	Aggressive technology policy and concentration of technical specialists promote RMTI
Dewar and Dutton (1986)	Adoption of RMT in footwear manufacturing firms in USA	Statistical analyses of survey data (n = 40)	Size and depth of knowledge resources are significant predictors of adoption of RMTI
Gomez and Vargas (2012)	Adoption of AMT (numerically controlled machines, robotics, computer aided design, flexible manufacturing) in Spanish manufacturing firms	Statistical analyses of secondary data from annual surveys in 1994, 1998, 2002, 2006	Complementary assets, such as technological resources (R&D), are important determinants of RMTI
Raymond and St. Pierre (2010)	Product R&D, process R&D and their associated innovation outcomes in 205 Canadian manufacturing SMEs	Statistical analyses of secondary data from survey	Link between product R&D intensity, process R&D intensity and innovation outcomes in firms is governed by contingencies
Reichstein and Salter (2006)	Process innovations in 2881 manufacturing firms in UK in 2001	Statistical analyses of secondary data from survey	Major determinants of RMTI in firms include presence of radical product innovations, firm strategies focusing on cost-leadership or product development and active collaboration with equipment suppliers
Un and Asakawa (2015)	Process R&D collaboration partners of 781 manufacturing firms in Spain between 1998–2002	Statistical analyses of secondary data from survey	Suppliers and universities form potential process R&D collaborators, against customers or competitors

of authority as predictors of RMTI in firms remains weak (e.g. Dewar and Dutton 1986), generally consistent results have been observed regarding technological resources at firms in determining the likelihood of RMTI (e.g. Dewar and Dutton 1986; Gomez and Vargas 2012; Raymond et al. 2010; Reichstein and Salter 2006).

Earlier studies have attempted to establish causal links between some firm level characteristics and the likelihood of emergence of RMTI in firms. For example, Gomez and Vargas (2012) observed that firm size, propensity to export and being part of business group act as predictors of the likelihood of RMTI. Reichstein and Salter (2006) observe that firm size and close relation with suppliers are predictors of process innovations in firms. Un and Asakawa (2015) suggest close collaborations with suppliers and universities to be sources of RMTI for manufacturers. In the case of the adoption of AMTs, previous experience in the use of AMTs at a firm acts as significant predictor of RMTI involving AMTs in future. Since AMTs can be integrated electronically, existence of AMTs within a plant encourages adoption of other technologies that can be integrated with the existing AMTs to obtain systemic benefits of AMT (Da Rosa Cardoso et al. 2012; Sinha and Noble 2008).

4 Managing Radical Innovations in Manufacturing Technologies

Managing RMTI appears as somewhat different, depending on the approaches and sources of the innovation. According to Damanpour and Wischnevsky (2006), in the case of innovation-by-creation, the critical innovation issue is to manage the innovation project in a timely and efficient fashion, whereas in the case of innovation-by-adoption, it is to assimilate the technology extensively into the organization in order to produce the desired organizational change. They perceive that the key managerial challenge in the generation of innovation is matching of the organization's technical capabilities with market opportunities; whereas the key managerial challenge in innovation-adopting organization is matching the organization's strategic requirement with capabilities and potentials of the innovations existing in the market. Despite the expected potential of RMTIs to result in radically improved production performance measures, for example in the case of AMT, only 25–50 % of the implementations are observed to be successful in achieving the projected improvements (Khazanchi et al. 2007).

Table 2 summarizes previous research on key issues in managing RMTIs successfully. Five main topics emerge from previous research as key factors: (1) a supportive organizational culture and control; (2) external integration; (3) internal integration; (4) efficient use of complementary assets; and (5) timing of the RMTI.

Organizational culture and control. Research on the successful management of RMTI addresses the challenge of managing the team members involved in radical innovation projects because such work is difficult to measure and control in terms of both behaviour and output (Buschgens et al. 2013). Buschgens et al.'s research suggests that the best way to control progress of radical innovation projects is through organizational culture and alignment of individual's objectives with the firm. Management of innovation requires paradoxical enablers in an organization's culture. On one hand, it requires a culture of flexibility and empowerment, to enable creativity, empowerment and change that drive exploration necessary for radical innovations, and on the other hand control and efficiency in order to drive delivery of results with discipline and focus on outcomes (Khazanchi et al. 2007). In the case of implementation of AMT in manufacturing plants, Khazanchi et al.'s research suggests that the combination of flexibility and control values in organizational

Table 2 Empirical studies on the successful management of radical manufacturing technology innovations

Source	Context	Methodology	Key finding for this study
Buschgens et al. (2013)	Previous studies on relation between organizational culture and innovation	Meta-analytic review	Positive correlation between successful innovations and presence of a developmental culture, based on values of flexibility and external orientation; negative correlation with presence of a hierarchical culture
Da Rosa Cardoso et al. (2012)	Implementation of new production technologies in firms in Brazil	Mixed-method analysis of qualitative data (literature review, secondary data, expert/practitioner interviews)	Organizational design, mainly structure, needs to be reviewed as part of decision to adopt particular AMT
Swink and Nair (2007)	AMT adoption in manufacturing plants in North America	Statistical analysis of survey data	Design-manufacturing integration acts as complementary asset, supporting in realizing maximum benefits of AMTs
Khazanchi et al. (2007)	Adoption of similar AMT (computerized die/mold machinery) in a large sample of firms in North America	Statistical analyses of survey data	Flexibility values in a firm's culture are critical for success in AMT implementation
Stock and Tatikonda (2008)	Adoption of wide category of technologies (operational and non-operations uses) in a large-sample (91 firms) of firms in USA	Statistical analyses of survey data	Highlight the importance of inter-organizational factors (between firm and technology supplier) in success in new technology implementation
Sinha and Noble (2008)	New manufacturing technology adoption in UK's metal working and engineering industry in 1981 and 1986	Statistical analyses of survey data	Proper timing of adoption decisions in firms related to new production technology are critical in determining firm survival

culture, congruence in perception of values between managers and operators have a positive influence on the plant performance outcome when adopting RMTI.

External integration. Some studies focus on the interaction between the technology supplier and the innovation adopter firm as a key ingredient in managing the RMTI successfully. In particular, Stock and Tatikonda's (2008) research recommends increased user involvement in RMTI development for greater implementation success. They observed a positive relation between higher project criticality, i.e. more attention and resources and successful management of innovations involving external technology adoption. Advanced processes and supplier integration are needed for manufacturing firms to manage external technology adoption in their production successfully (Stock and Tatikonda 2008).

Internal integration. The success of a new manufacturing technology adopted in a firm's production process comes from its successful integration into other organizational elements (Hervas-Oliver et al. 2014; Khazanchi et al. 2007). Technology is only an enabler, whereas the architecture in which it is placed has a far greater impact in the firm's success (Gomez and Vargas 2012). Previous research has revealed various enablers for integrating new technologies into a firm's own processes. For example, a preceding analysis of the impact of manufacturing technology adoption and implementation on the organizational characteristics is recommended as a part of the manufacturing technology selection process (Da Rosa Cardoso et al. 2012; Stock and Tatikonda 2008). Also, the firm must plan reviewing its existing organizational characteristics in order to prepare for the change process and set realistic expectations (Stock and Tatikonda 2008; Da Rosa Cardoso et al. 2012). They should also establish a coordination group to manage the process of the manufacturing technology selection, adoption and implementation (Da Rosa Cardoso et al. 2012). Finally, communication of intended improvements through technological change could mobilize resources and personnel better (Da Rosa Cardoso et al. 2012).

Efficient use of complementary assets. Complementary assets are resources or capabilities that allow organizations to capture the profits associated with a strategy, technology or innovation (Teece 1986; see Swink and Nair 2007). These assets may be tangible, such as existing equipment (Sinha and Noble 2008) or intangible, such as R&D investments (Gomez and Vargas 2012). Swink and Nair (2007) suggest design-manufacturing integration as an important complementary asset for RMTI involving the adoption of manufacturing technology. An effective process of combining product and process specialists can contribute to generating appropriability from the RMTI. This can also contribute toward better planning of the RMTI adoption by considering links to the firm's overall manufacturing strategy, since there are possible trade-offs between various technology-performance relationships. Some of the other examined contingencies for the success of RMTIs are infrastructural and demographic variables such as worker empowerment, quality programs and process type (Swink and Nair 2007).

Timing of RMTI. Given the time-sensitive nature of returns on investment in certain manufacturing technologies, success of RMTI also depends on capability of firms to make timely decisions about their adoption (Sinha and Noble 2008; Agkun et al. 2014). This capability is related to presence of typical characteristics in organizational culture, notably the willingness to cannibalize, values for future orientation and tolerance are also important for enabling success with radical innovations (Buschgens et al. 2013).

Besides the management of successful RMTIs, enablers of success in RMTI have been analysed from various perspectives. In their review, Damanpour and Wischnevsky (2006) observe the following as enablers of success in innovation-by-creation: business-project fit, R&D-manufacturing-marketing-interaction, the uniqueness of the innovation, the user-benefit or economic advantage of the innovation, the role of an innovation champion, patent protection and competition in market, among others. On the other hand, they review that the factors that predict successful innovation-by-adoption include organizational complexity, centralization of decision making, organizational members' internal and external communication, perceived risk of the innovation, the capacity of the organization to absorb information, and the complexity of the innovation.

5 Discussion and Conclusions

We have investigated the emergence of radical innovations in manufacturing technologies through reviewing earlier empirical research in technology-related operations and innovations. Earlier research has had a strong emphasis in the adoption of advanced manufacturing technologies (e.g. Khazanchi et al. 2007; Gomez and Vargas 2012) and it has covered also technology-based process R&D (Raymond and St. Pierre 2010) and supply chain process innovations (Reichstein and Salter 2006). The dominant view emphasizes manufacturing firms as adopters of RMTI developed elsewhere, instead of creators of RMTI. As technology suppliers can provide RMTI to multiple firms, the real innovation is not in its adoption, but in how well firms master their utilization as a source of competitive edge. Many studies reviewed in this paper focused on how to manage the successful adoption of technologies, and not so much on how to manage their creation and utilization.

A particular interest was to understand how successful radical manufacturing technology innovations are managed. Success is covered in previous research in terms of the performance improvement of the production process, and it has been assessed through quite ordinary measures of costs, quality, flexibility, delivery efficiency and capacity (e.g. Swink and Nair 2007; Hervas-Oliver et al. 2014). Our review showed that the successful management of RMTI requires a supportive organizational culture and control; integration of external suppliers; internal integration; efficient use of complementary assets; and the right timing of the RMTI.

The results show tentative indications that different kinds of enablers and management practices are needed for different types of manufacturing technology innovations, and in the different phases of creating, adopting and utilizing them. As radical manufacturing technology innovations have been studied merely from some parts of these viewpoints and with certain types of technologies, more research is needed on the contingent nature of managing RMTIs.

Currently digitalization (e.g. sensors and remote monitoring, internet of things, 3D printing) is changing the nature of production in existing industries. As there is hardly any focused research on these RMTIs, comparable with AMT, digitalization-related manufacturing innovations are proposed as an important avenue for future research. Even if digitalization can be considered a generic innovation that can potentially affect any manufacturing firms, its radical potentials for specific firms and networks and for the industry more generally call for further research. Particularly the institutional implications of digitalization to the manufacturing industries deserve further research attention.

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Simulating the Impact of Deferred Equipment Maintenance

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Abstract Deferring the maintenance activity can often be detrimental to the asset's operation. This is usually the case where minimal repair actions are performed for severe failures. Here, deferring the maintenance activity ends up accelerating equipment deterioration, thereby resulting in more severe failures. In this paper, a discrete event simulation model for quantifying the effect of deferred maintenance on system performance such as production loss and observed failure rates is proposed. The simulation study incorporates four maintenance activities proposed in the ISO 14224 that include inspection, modify, extensive repair and corrective replacement. Each maintenance activity is evaluated based on its impact on the remaining useful life of the component. A real life case of a thermal power plant is discussed.

1 Introduction

Maintenance activities are performed with the objective restoring the equipment after failure, enhancing the equipment reliability or improving availability. In literature, well-known maintenance strategies include failure based maintenance (FBM), time/use based maintenance (UBM) and predictive maintenance (PdM) (Pintelon and Van Puyvelde 2013). Depending on the strategy deployed, maintenance actions often vary and may include corrective, preventive, or pro-active actions. Moreover, depending on aspects such as technician proficiency, adequacy of repair capacity, production demand or sufficiency of the diagnostic

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capacity, maintenance practitioners may opt to postpone or defer the maintenance activities. However, deferring the maintenance activity may accelerate component degradation, more so for severe failures. On the other hand, implementing a more robust maintenance regime for failures of marginal severity often results in unnecessary stoppages and high demand for spare parts. Examples include activities such as corrective replacement where the component is restored to the as-good-as-new (AGAN) condition. For these reasons, a balance is often necessary between implementing minimal and extensive maintenance actions. More importantly, the optimal balance needs to take into account aspects such as failure severity of the component at time of repair and impact of the maintenance actions on the equipment's remaining useful life (RUL).

In this paper, a simulation modelling study is proposed that evaluates the impact of deferring maintenance activities on equipment performance. The deferred maintenance strategy is compared with more robust maintenance actions/activities, here, extensive equipment repair and corrective replacement. The proposed maintenance activities are derived from the ISO 14224 standard. Moreover, the model proposes several failure severity classes derived from the MIL-STD-882 standard. Depending on the selected maintenance activity, component degradation or renewal is influenced and quantified based on the remaining useful life after the maintenance action. The simulation study is validated using the case study of turbocharger component failure in a thermal power plant.

2 Related Literature

In literature, several authors propose a mix of analytical and simulation models for optimising maintenance decisions, e.g. see Van Horenbeek et al. (2010). Many of these models largely propose optimal intervals for performing preventive maintenance (Pintelon and Van Puyvelde 2013). However, the models seldom take into account individual maintenance actions or their influence on the component's RUL. Moreover, the models often assume perfect component renewal after maintenance action, i.e. restoration to the AGAN state. In practise, this is not usually the case. Often depending on the nature of repair activities and the failure severity, the equipment may be restored to the as-bad-as-old (ABAO) or a worse state. Existing maintenance modelling approaches fail to sufficiently take these aspects into account. In related research, several authors consider the maintenance strategy selection as a multi-criteria decision making problem (MCDM) and as such propose selection frameworks based on techniques, e.g. analytic hierarchy process (AHP), e.g. see (Fouladgar et al. 2012; Zaim et al. 2012). However, viewing the selection process as MCDM problem, but, ignoring the impact of the maintenance actions on the RUL is rather simplistic. The simulation model proposed in this paper addresses these flaws.

3 Simulation Model for Optimal Maintenance Actions

3.1 Conceptual Model

Figure 1 outlines the 5 steps of the proposed simulation model. In step 1 the operation of the unreliable turbocharger is mimicked where failure is triggered from its characteristic lifetime distribution. The failure distribution is derived through fitting distribution functions on datasets for the turbocharger's time to failure

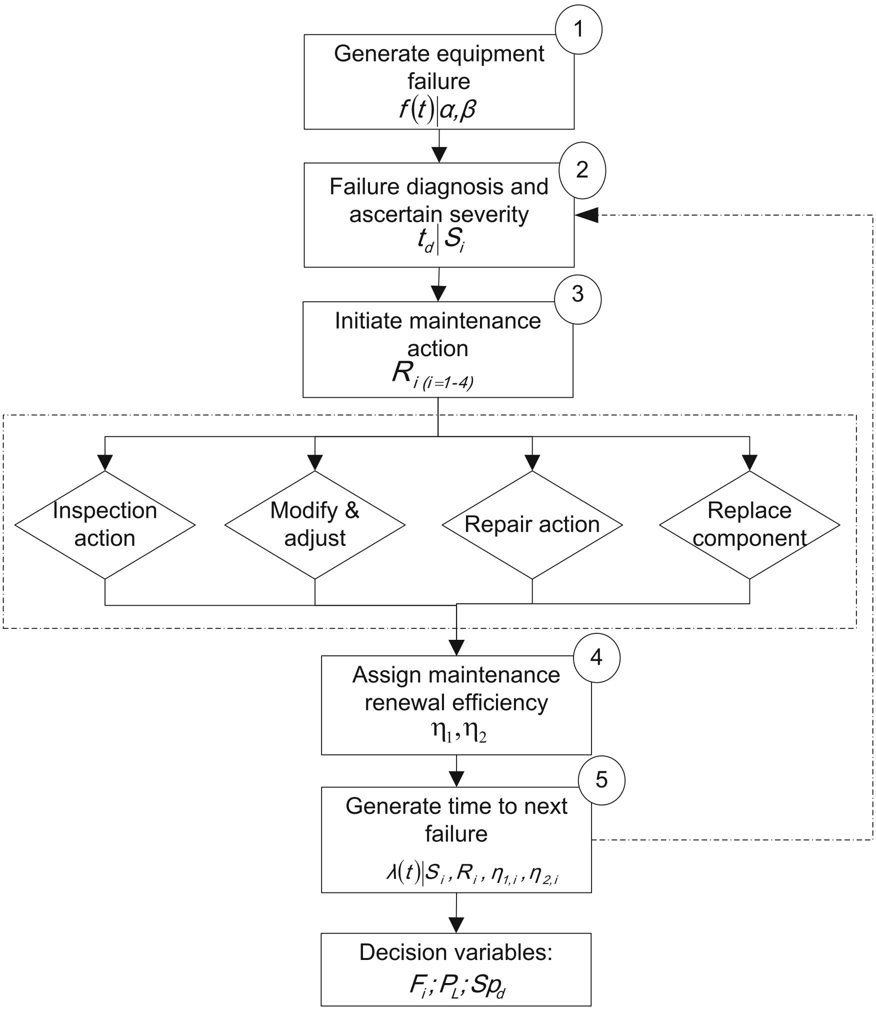

Fig. 1 Flow process for selecting the maintenance action and evaluating its impact on system performance measures

(Chemweno et al. 2015). When failure is observed, the diagnostic process is initiated in step 2 where the failure severity, S_i is evaluated. The diagnostic time, t_d is conditioned on the failure severity and sampled from a triangular distribution. As mentioned, four severity levels are defined and based on the MIL-STD-882 standard where level 4 equates to catastrophic component failure. In step 3, the process of selecting the appropriate maintenance/repair actions R_i is modelled. The alternative actions include; (i) inspection, (ii) modification and/or minor adjustments, (iii) repair, and (iv) corrective replacement. The selected action influences the RUL of the turbocharger after repair. In this context, inspection equates to minimal repair, and depending on the failure severity, accelerates component degradation. On the other hand, corrective replacement equates to perfect renewal or AGAN and depending on the failure severity, may enhance the RUL. In step 4, the maintenance efficiency is generated with the assigned value influenced by the nature of failure severity and the selected maintenance action. For instance, a severe component failure, e.g. S_4 combined with inspection equates to minimal repair action and as such, low maintenance efficiency is assigned. As a result of the low efficiency, the RUL after repair is degraded with shortened time to next failure expected. Step 5 is linked to step 4 where the expected time to next failure is conditioned on the failure severity, type of repair action, and the assigned maintenance efficiency value. The impact of aspects specified in steps 1 to 5 are evaluated through several performance measures, i.e. failure rate $\lambda(t)$, power production loss P_L, and the expected number of component replacements Sp_d, the latter quantified by the expected demand for spare parts over the simulation period.

3.2 Application Case Description

The simulation study is validated in the use case of turbocharger operation in a thermal power plant engine. Maintenance records from the plant were recorded over a 3 year period from which useful input parameters were derived and depicted in Table 1. Several model assumptions are also considered and include:

Table 1 Overview of simulation model input parameters

Parameter	Input distribution
Turbocharger uptime (h)	WEIB [0.8, 2073]
Diagnostic time (h)	TRIA [1, 2, 5]
Repair time (h)	TRIA [1, 3, 5]
Spare part replenishment lead-time (days)	EXP [2]
Simulation replication length (days)	Constant [1083]
Number of replications	100

1. Repair capacity constraints are ignored and assumed always available;
2. A severe failure combined with minimal maintenance action accelerates component deterioration.
3. A minor or marginal failure combined with extensive repair or corrective replacement renews the component to the AGAN state;

4 Results and Discussion

4.1 Effects of Implementing Minimal Maintenance Actions

This scenario explores the influence of minimal maintenance actions and assumes a situation where maintenance practitioners opt for inspection or modification/minor adjustments irrespective of the failure severity. In practice, the choice of these actions equates to deferring maintenance activities, more so, for severe failures. Figure 2 depicts results derived by varying the inspection parameter, R_{insp} from 10 to 100 %. At 10 % variation, we assume that irrespective of the failure severity, inspection is performed in 10 % of the cases, while the remaining proportion, i.e. 90 % is distributed to the remaining three actions, i.e. modify, repair and corrective replacement. The same reasoning applies to inspection threshold of e.g. 90 %. The results are compared to the reference case where balanced selection of maintenance actions is implemented, i.e. equal chance (25 %) of selecting each of the four

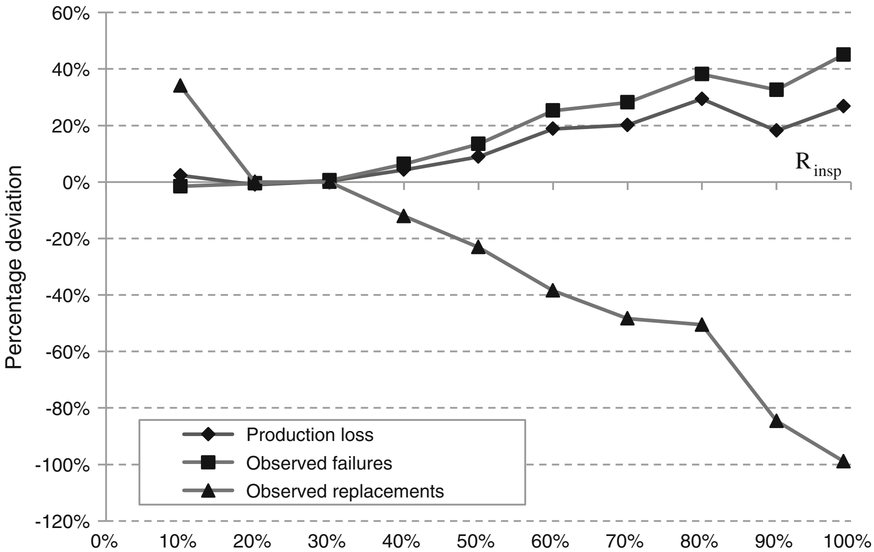

Fig. 2 Impact of varying inspection maintenance action on equipment reliability indicators

maintenance action. From Fig. 2, implementing a maintenance regime relying predominantly on inspection is observed as detrimental to generated power and the observed failure rate. Here, power generation losses of as much as 27 % and failure rate increases of as much as 45 % are observed. On the other hand, the demand for component replacement diminishes as a result of the predominant inspection regime. This observation is attributed to the fact that component replacement is assumed to occur only during catastrophic failure where corrective replacement is implemented.

4.2 Effects of Implementing Repair and Corrective Replacement

Figure 3 depicts the results of implementing a more robust maintenance regime. Thus rather that deferring maintenance for severe failure, e.g. through inspection or minor modification, extensive repair is undertaken. The results show a reduction in power generation losses and expected failure rates by as much as 29 and 19 % respectively as compared to the reference case. This is largely attributed to enhancement in the RUL of the turbocharger. Moreover, the extensive repair actions are associated with reduced demand for spare parts where reductions of as much as 59 % is observed. Figure 4 depicts the results of implementing higher proportion of corrective replacements for observed failure. From the results, one can observe a reduction in failure rate by as much as 25 % as compared to the

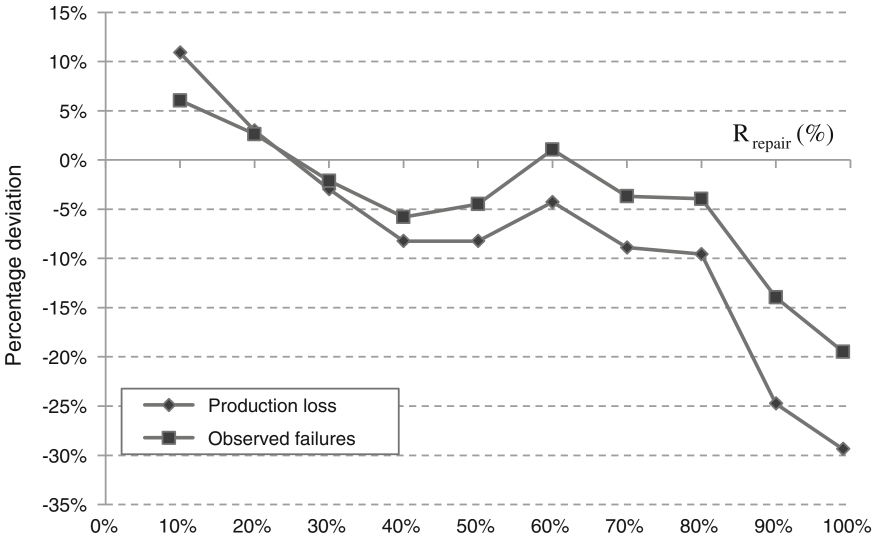

Fig. 3 Impact of varying repair action on power production loss and observed failure rates

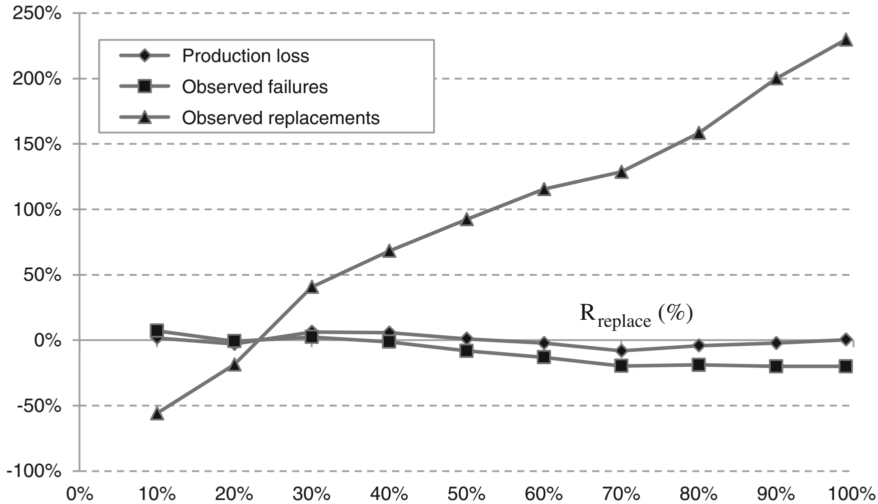

Fig. 4 Impact of implementing corrective replacement actions on power production loss and observed failure rates

reference case. However, the reduction is achieved at the expense of higher spare part demand. Here, the demand reaches a proportion of as much as 230 % compared to the reference case. This emphasises the negative impact of implementing corrective replacement for failures of marginal severity. In practice this may correlate to instances where the organisation lacks sufficient capacity or skills for undertaking extensive repair actions.

Moreover, higher proportions of corrective replacement negatively influence power generation. For instance, a production loss of 8 % is observed at corrective replacement of 70 %. This can be attributed to productivity losses due to un-necessary downtimes during the corrective replacement actions or long spare parts replenishment lead-times. In the model, the procurement lead-time from the original equipment manufacturer (OEM) is assumed exponentially distributed with EXP [2] days. During this period, the equipment is assumed off-production.

5 Conclusion

In this paper, the influence of implementing high proportions of minimal maintenance actions is evaluated using a simulation model. These minimal actions correlate to deferring maintenance where tasks such as inspection or minor modification are performed for severe failures. As expected, deferring maintenance accelerates the component degradation thereby reducing the expected remaining useful life. On the other hand, implementing extensive repair actions enhances the component's remaining useful life and further reduces the need for new parts.

Although corrective replacement enhances the components remaining useful life, at higher proportions, corrective replacement negatively influences power production, more so, for failures of minimal severity. Future work will explore the influence of combined maintenance actions, e.g. inspection and repair, or repair and replacement. The influence of the combined actions will also be evaluated in the context of spare parts usage.

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Improving Online Risk Assessment with Equipment Prognostics and Health Monitoring

Jamie Coble, Xiaotong Liu, Chris Briere and Pradeep Ramuhalli

Abstract The current approach to evaluating the risk of nuclear power plant (NPP) operation relies on static probabilities of component failure, which are based on industry experience with the existing fleet of nominally similar light water reactors (LWRs). As the nuclear industry looks to advanced reactor designs that feature non-light water coolants (e.g., liquid metal, high temperature gas, molten salt), this operating history is not available. Many advanced reactor designs use advanced components, such as electromagnetic pumps, that have not been used in the US commercial nuclear fleet. Given the lack of rich operating experience, we cannot accurately estimate the evolving probability of failure for basic components to populate the fault trees and event trees that typically comprise probabilistic risk assessment (PRA) models. Online equipment prognostics and health management (PHM) technologies can bridge this gap to estimate the failure probabilities for components under operation. The enhanced risk monitor (ERM) incorporates equipment condition assessment into the existing PRA and risk monitor framework to provide accurate and timely estimates of operational risk.

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1 Introduction

Advanced reactors can provide the United States with a safe, sustainable, and carbon-neutral energy source. However, these reactors face significant technical hurdles to commercialization due to the unique features and characteristics inherent to their revolutionary designs, such as non-light water coolants, integral primary systems, and advanced component designs. The controllable day-to-day costs of advanced reactors are expected to be dominated by operation and maintenance (O&M) costs. Equipment condition assessment coupled with online risk monitors can potentially enhance affordability of advanced reactors while maintaining high levels of safety through optimized operations planning and maintenance scheduling. The enhanced risk monitor (ERM) combines online risk assessment with condition assessment of key active components to support safe and economic operation of advanced reactors (Coble et al. 2013). The ERM is expected to improve the safety, economics, and availability of advanced reactors by providing a tool for optimizing O&M activities.

In order to demonstrate the efficacy of the ERM for advanced reactors, a Simulink-based model of a prototypical advanced reactor (PAR) is under development at the University of Tennessee. The PAR design features two liquid metal primary systems each connected to a dedicated steam generator, which are then connected to a common balance of plant. This paper presents the development of this simulation model, including the system models used and the integration of degradation of key plant components. Section 2 briefly presents the ERM framework. Section 3 describes the PAR simulation model. Simulation results for normal and degraded operation are given in Sect. 4. Finally, the research is summarized and areas of ongoing work are given in Sect. 5.

2 Enhanced Risk Monitor

Risk monitors provide a point-in-time estimate of the system risk given the current plant configuration (equipment availability, operational regime, environmental conditions, etc.). However, current risk monitors do not account for unit-specific normal, abnormal, and deteriorating states of plant equipment. Current risk monitors are built on probabilistic risk assessment (PRA). PRA systematically combines the event probability and probability of failure (POF) for key components to determine the hazard probability for subsystems and the overall system (Wu and Apostolakis 1992). Standard NPP PRA uses a static estimate of event probability and failure probability. A more accurate risk assessment can be made using estimates of the actual component POF based on equipment condition assessment. The ERM has the potential to enable real-time decisions about stress relief for susceptible equipment while supporting effective operations, outage, and maintenance planning. A general framework for the ERM has been proposed (Coble et al.

2013; Ramuhalli et al. 2014), which supports traditional safety-related PRA as well as assessment of other types of risk, such as availability, productivity, or other economic risks. Accurate assessment of these risks can be used to inform operations and maintenance planning and plant supervisory control algorithms.

The ERM differs from current online risk monitors in several key ways. ERM uses the results of online, real-time equipment condition assessment to determine the POF of key active components over a given time horizon. The underlying fault and event trees in the ERM must account for changing success criteria based on the operational loads and ambient conditions. For instance, a plant operating at full capacity may require 100 % coolant flow, while the same plant operating at reduced capacity may be able to operate safely and reliably with reduced coolant flow.

The proposed ERM methodology has been evaluated using the PAR design and time-varying POF for key components (Ramuhalli et al. 2014). For this simple demonstration, where component failure probability depends solely on time, the estimated risk varies over three orders of magnitude throughout the nominal reactor life. Periodic equipment condition assessment is simulated for a single component, which leads to component-specific POF. The incorporation of the updated POF value into the ERM changes the risk profile, both in risk value and the uncertainty in the risk. ECA is assumed to give a more certain estimate of the component POF, resulting in less overall uncertainty in the future risk estimate. These results suggest that the inclusion of ECA and component-specific POF will provide a more accurate and more precise estimate of system risk.

3 Prototypical Advanced Reactor Design

In order to demonstrate the ERM methodology, the PAR design was devised (Fig. 1). This reactor power block does not represent any specific commercial advanced reactor design, but combines proposed operational features common to many designs in order to evaluate the efficacy of the ERM across the breadth of proposed advanced reactors. The power block features two reactor cores, each connected to a dedicated intermediate heat exchanger (IHX) and steam generator. The output of these two steam generators is then connected to a common balance of plant (BOP). The BOP includes steam drums, turbine, condenser, feedwater pumps, and feedwater heaters. The key systems identified in this power block that require physical models include: reactor core and IHX, steam generator, and BOP. Additionally, the effects of degradation of selected active components are modelled numerically. The following sections describe the system and component models implemented in MATLAB-Simulink.

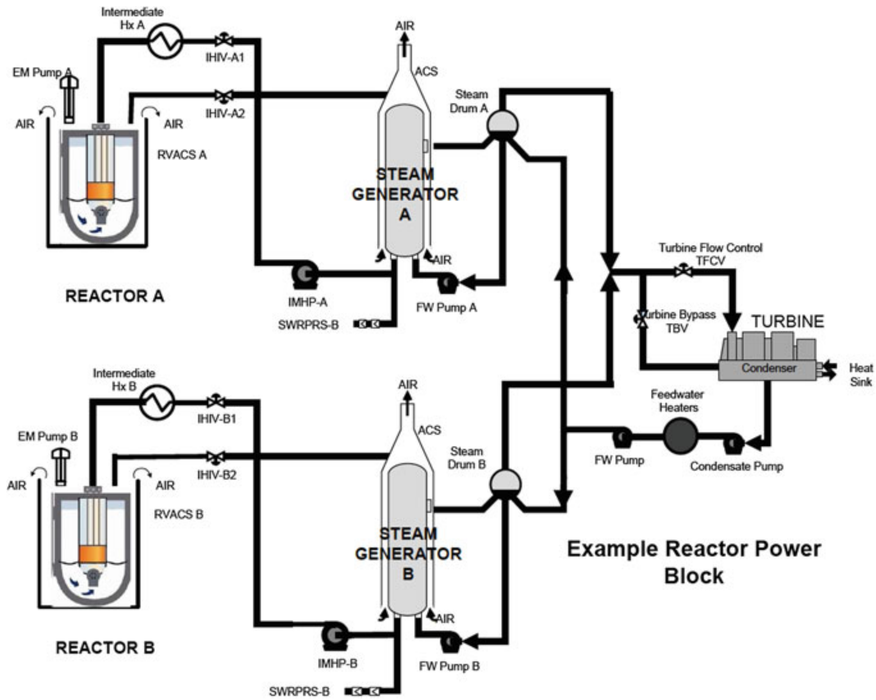

Fig. 1 PAR power block

3.1 Primary System

The reactor core and IHX model is based on the Experimental Breeder Reactor (EBR)-II. EBR-II was a pool-type sodium-cooled fast reactor (SFR), which output 62.5 MWt and 20 MWe. PAR features two EBR-II primary systems feeding a common BOP, giving a total of 40 MWe output for the power block. The PAR primary system model is based on existing perturbation models of the EBR-II core and IHX (Berkan and Upadhyaya 1988).

A nodal formulation of the reactor core and IHX are used with point reactor kinetics and heat transfer models. The core model includes the active core, inner and outer blankets, lower and upper reflectors, and piping in a 25-node model (Berkan and Upadhyaya 1988). Core bowing and control rod expansion reactivity effects are neglected in the EBR-II models. The core bowing reactivity effect may become significant at high temperatures as the structural material inside the vessel expands radially. The thermal bowing cannot be handled without increasing the order of the model by introducing radial lumps. The contribution of thermal bowing to reactivity is small compared to other feedback effects. At steady state conditions, the control rod expansion reactivity effects are assumed to be negligible. The IHX is described by a 12-node model based on Mann's heat transfer model (Berkan and

Upadhyaya 1988). The core and IHX models are coupled with the primary sodium pool into one module to simulate the two PAR primary systems.

3.2 Steam Generator

Each primary system is connected to a dedicated steam generator, also based on EBR-II (Berkan and Upadhyaya 1988). The steam generator is a natural circulation, recirculation steam drum/evaporator system, extracting heat from the sodium to produce superheated steam at 820 F at full power. The entire system is divided into thirteen lumps each representing average physical quantities. On the evaporator side, the primary tube wall and the secondary lumps are divided with a moving boundary determined by the subcooled region height. The primary phenomena included in the model are the homogeneous flow in the boiling region; the mass and energy dynamics; the distribution of mass between downcomer, subcooled, boiling, and drum regions on the secondary side; and momentum equations for the flow from downcomer to subcooled regions and flow leaving the boiling region.

3.3 Balance of Plant

Finally, the two steam generators are connected to a common BOP system, which includes:

- Turbine-generator system;
- Condenser;
- Condensate pump, secondary feedwater pumps, and main feedwater pump; and
- Multiple feedwater heaters.

An existing BOP model, designed for a 180 MWe small modular reactor, was leveraged and sized appropriately for the smaller output of the PAR design. The BOP is based primarily on the models in Shankar (1977) and Naghedolfeizi (1990).

3.4 Component Degradation

The described system modules will connect together to provide simulation data of normal plant operations. Key active components that affect PAR performance and output include pumps, valves, reactor vessel auxiliary cooling system (RVACS), and steam generator auxiliary cooling system (ACS) (Ramuhalli et al. 2013).

Degradation of these components is modelled through numeric simulation of the effects on component and system performance. No physics of failure models are employed. Instead, the effects of evolving degradation and failure of key components on the overall system performance are numerically simulated. For instance, a faulty valve may have slower response to control actions or may have a limited range of operation; a degraded pump may give reduced flow; and a fouled IHX may have reduced heat transfer coefficients. Work to date has focused on the degradation of primary and intermediate sodium pumps.

Cavitation of centrifugal pumps can limit performance and compromise safe operation of the plant. The cavitation of pumps in the primary and secondary loops is modelled numerically through the effect of pump degradation on sodium flow rate, based on degraded pump curves (Grist 1998). This model of pump failure reduces volumetric performance due to inadequate coolant flow.

4 Simulation Results

The system and component degradation models are combined to provide normal and degraded operational data for the PAR design. The results of model validation for normal operation and the effect of pump cavitation on system performance are given in the following subsections.

4.1 Model Validation

The perturbation response of select variables to a −5 cents reactivity insertion is given in (Berkan and Upadhyaya 1988). The response of the nonlinear PAR Simulink model to the same perturbation is compared to these results in order to validate the implementation of the primary system model. Figure 2 shows the fractional reactor power response to the perturbation for both the PAR Simulink model and the EBR-II model. Figure 3 shows the response of the sodium tank temperature to the same perturbation. In both signals, the response shape and magnitude of change agree very well. Because the original model was validated against EBR-II operational data, we expect the nonlinear PAR primary system model to represent operational conditions for non-degraded operation in the proposed system. Steam generator and BOP models are currently under development and being validated for the proposed PAR power block model.

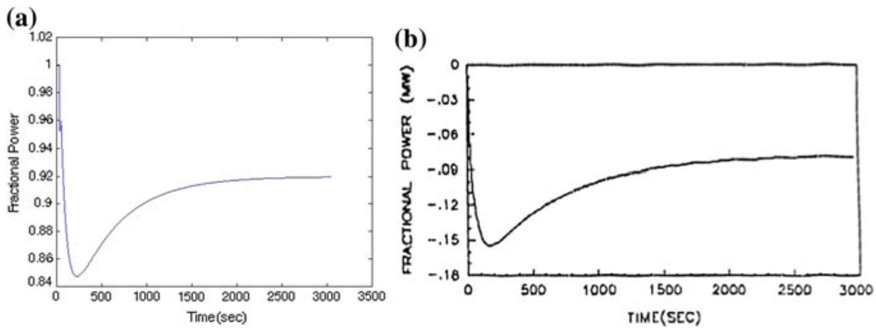

Fig. 2 Fractional reactor power response to a −5 cents reactivity insertion for the **a** PAR Simulink model and **b** EBR-II model (Berkan and Upadhyaya 1988)

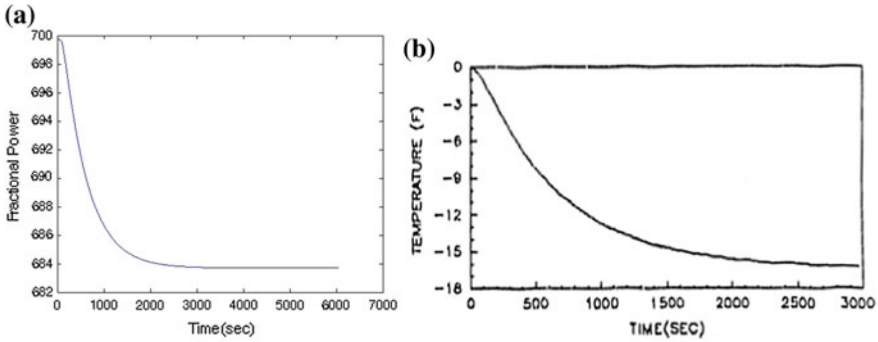

Fig. 3 Sodium tank temperature response to a −5 cents reactivity insertion for the **a** PAR Simulink model and **b** EBR-II model (Berkan and Upadhyaya 1988)

4.2 Pump Cavitation

Degraded pump performance is simulated through a transformation of the pump curve to accommodate the lost flow capacity. Flow in either the intermediate or primary loop is reduced to simulate the cavitation of pumps. Currently, degradation of only one component is investigated; degradation of multiple components simultaneously is an area of ongoing work.

To evaluate the effect of pump cavitation on system performance, the system is run at full power conditions (i.e., zero reactivity insertion) and the primary or intermediate sodium flow rate is reduced. The simulation is allowed to reach steady-state to determine the effect on fractional reactor power. Table 1 gives the steady state fractional power for reduced flow conditions in the primary or intermediate sodium loops. The results indicate that the core power decreases as pump cavitation leads to reduced flow in either primary or intermediate loops. The

Table 1 Steady state fractional core power due to degraded primary and intermediate sodium pumps

Primary sodium flow rate (gpm)	Intermediate sodium flow rate (gpm)	Fractional core power
9000	5890	1.0
7000	5890	0.87
5000	5890	0.74
9000	3000	0.74
9000	2000	0.53

Full flow is 9000 gpm in the primary loop and 5890 gpm in the intermediate loop

component condition and performance has a direct impact on overall plant performance. The extent of this effect at other power levels is an area of ongoing study.

5 Summary and Future Work

Enhanced risk assessment of critical active components can improve asset protection and management, allowing for safe, reliable generation during extending operating cycles and longer reactor lifetimes. Incorporation of dynamic health assessment of key active components in risk monitors supports the economics and minimizes the long-term costs of advanced reactors by: (1) informing O&M decisions to target maintenance activities during outages, (2) optimizing plant performance, and (3) supporting extended operating cycles by ensuring reliable component operation. This heightened risk awareness is particularly important for advanced reactors due to the typical location of key components internal to the vessel, harsher operating environments, and extended periods between maintenance opportunities.

A simulation model of a prototypical advanced reactor is under development to further develop and evaluate the ERM methodology. The PAR model includes physical models for the primary system, steam generators, and balance of plant, as well as numeric simulation of equipment degradation. As the model development progresses, additional component degradation models will be incorporated. The system performance with multiple degraded components will be simulated, and these results will be used to evaluate the efficacy of the ERM framework to estimate real-time operational risk.

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Agile Asset Management

Alastair C. Crombie

Abstract This paper describes a theory developed through efforts to improve the effectiveness of Asset Management for Small and Medium Enterprise's (SMEs) as well as a desire to improve the Asset Management of the authors own organization. The idea, however, comes from a need to expand the service portfolio offered by said organization. Services within some aspects of Asset Management were a natural extension of the existing service lines of the organization within Safety, Process Safety and Risk Management. As part of the Asset Management business plan, one of the focus areas was identified as SMEs, being a market with potential.

1 Introduction

This paper describes a theory developed through efforts to improve the effectiveness of Asset Management for Small and Medium Enterprise's (SMEs) as well as a desire to improve the Asset Management of the authors own organization. The idea, however, comes from a need to expand the service portfolio offered by said organization. Services within some aspects of Asset Management were a natural extension of the existing service lines of the organization within Safety, Process Safety and Risk Management. As part of the Asset Management business plan, one of the focus areas was identified as SMEs, being a market with potential.

The information that is referred to throughout this article has been collected in the most part as a secondary result of various discussions with SMEs on Asset Management. The picture described here has been pieced together from the amalgamation of the various discussions and as such cannot be described as a systematic survey of the organizations involved. Such a survey may be a further step in this work if the opportunity presents itself. It should be noted however that a considerable number of organizations have been contacted about some or all of the issues discussed in this article and it therefore represents a not insignificant statistical sample.

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Initial discussions with SMEs about improving Asset Management are usually met with scepticism. The answer to most questions was a variation of, ‘that would be nice but we do not have the time and/or money’. The industry that the organization operated in seemed to have little influence on the answer. SMEs within Oil & Gas, Petrochemical, Process and Utilities all had differing levels of awareness of Asset Management but the majority had similar initial responses. The concepts are sound and they would get around to it at some point, just not now.

The same level of enthusiasm held true within the authors own organization. When first discussed, some of the ISO 55000 (ISO 2014) concepts were not greeted warmly. In order to get past this scepticism it would first be necessary to define the reasons for it.

2 The Barriers

Discussions were conducted internally and externally with other SMEs in order to try to understand the reasons behind the lukewarm reception and to try to understand the main challenges organizations of this size faced with regards to Asset Management. The Asset Management challenges faced by each organization were quite individual but there were some similarities identified and this is discussed further in Sect. 3.

It would seem the reasons behind a lack of enthusiasm were to do with an inability to see a way past the barriers that were perceived as stopping organizations from adopting holistic Asset Management practices. The efforts required to implement structured Asset Management processes were seen as greater than the perceived rewards. It was in short an intuitive cost benefit analysis. However, the intuitive decision was usually not based upon factual analysis.

These barriers appear to be common across organizations and are easily identified.

2.1 Language

The hardest barrier to identify is actually the easiest to remove and that is language. In discussions with SMEs, it was not immediately obvious but became apparent over time that the wording and terminology of the ISO 55000 series combined with the jargon used by Asset Management professionals was in itself a barrier to implementation.

The identification of language as a barrier proved difficult because few people are willing to admit to being slightly confused by the meaning and purpose behind the language being used. This meant that direct questioning about the understanding of concepts proved less fruitful than direct questioning on other subjects and it was necessary to revisit the topic from different angles in order to get a clear understanding.

Once identified as a possible barrier a simple test as to the validity of this theory was tried by varying the amount of jargon used in discussions with SMEs. There was a direct correlation between the simplicity of the language and the enthusiasm for implementing change.

2.2 Time

The three remaining main barriers were easily identified and often mentioned by the SMEs within the first minutes of discussions. The first of these is time.

'We just don't have time' was a common reply and one that proved difficult to counter. Even for those organizations that had some ideas or plans in place for improving Asset Management and who had accepted that change was necessary it was still a challenge to commit to the necessary time.

It is clear that there is an association by some organizations between ISO 55001 and some of the other common ISO standards such as 9001 (ISO 2008) and that this association is not entirely positive. Reference was sometimes made to the time that was used for implementing ISO 9000 and that it was not currently possible to undergo a similar process. Occasionally there was also reference to poor ISO 9000 implementation and that the same mistakes would not be made again.

2.3 Cost

The cost barrier is similar to that of time. Investments in internal improvement processes are a difficult decision to make for SME's. As a rule, Asset Management improvement projects were not being adequately defined. This meant that often the time, cost and output were only vaguely identified and it was difficult to assess the benefits of individual projects.

It is difficult to immediately identify and prioritize potential asset management improvements without first having access to an organizations information and data. It can therefore be difficult to be specific about potential improvements during initial discussions unless the organization has already identified its priorities, if this is not the case initial discussions with potential clients can become vague and unfocused. This can give the impression that improvements may not be cost effective.

2.4 Value

The perception of value was the final major barrier identified in this study. Value is related to time and cost and has to be greater than the effort required. Therefore it is necessary to have a very clear and concise picture of the value that Asset Management improvements can bring.

It is commonly accepted that Asset Management improvements are, in general terms. a good idea. However, there was not a lot of analysis being done to quantify this. As a result, there was no clear picture of the value potential improvements would bring and therefore impossible to assess cost vs benefit. This in turn led to decisions on implementation being vague and often postponed.

Obtaining asset data from the organization in question should always be attempted. Data analysis will always identify areas of improvement and allow quantification of what those improvements will bring. To this end, a colleague developed a simple yet powerful software tool. The tool provides excellent Gap analysis and decision support capabilities and allows the identification of priorities from existing information. It also provides immediate added value to any organization in its own right.

3 The Theory

Now that the barriers were identified, it was possible to assess ways of removing them. In simple terms, in order to achieve the execution of Asset Management improvement projects within these SMEs, the projects would have to be well defined, limited in scope, cost and be able to provide clear and documentable value within a short timeframe.

3.1 Agile

As an organization with specialist software as one of its business areas, program development methods are a regular topic of discussion. Some years ago, it was decided to adopt Agile Scrum programming as the preferred development method in-house. Agile is the name given to a series of software development methods that were first explained in the 'Manifesto for Agile Software Development' (Beck et al. 2001). This manifesto describes development based upon small self-managing cross functional teams as opposed to large cumbersome development programs that had been the norm. There are a number of iterations of Agile methods but they have in common that they promote teamwork, frequent deliveries, stakeholder focus and response to change. Agile provides the following benefits (Cohn 2010).

- Higher productivity and lower costs
- Improved employee engagement and job satisfaction
- Faster time to market
- Higher quality
- Improved stakeholder satisfaction

There are immediate similarities to the principles of holistic asset management. Agile aims to provide similar benefits and aims to do so through similar methods.

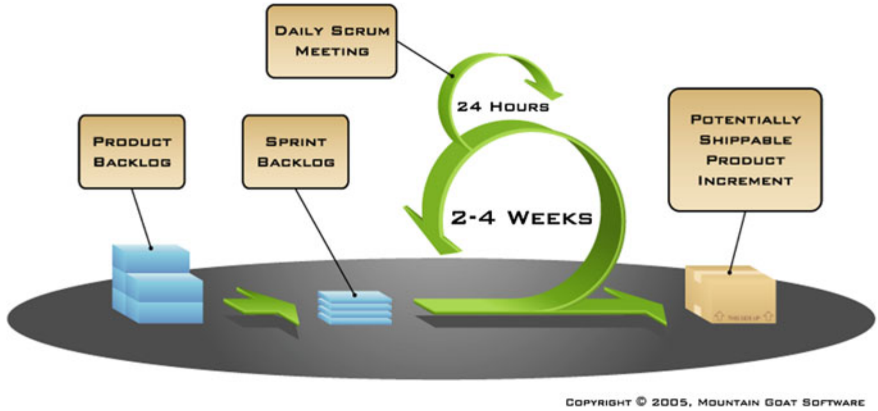

Fig. 1 A graphical representation of Agile Scrum (Mountain Goat Software 2005)

A considerable volume of literature is available on Agile and its methods for those wishing to learn more.

A particular Agile method known as Scrum (Schwaber and Sutherland 2013) will be briefly explained further. Scrum consists of a number of short development cycles known as Sprints. Each Sprint has as a goal to produce one or more potentially commercial deliverable. The deliverables are chosen at the start of the Sprint cycle from the Product Backlog, this is the complete list of items that describes the functionality and features to be added to the product. The deliverables to be developed for a particular sprint are known as the Sprint Backlog. Figure 1 shows a graphical representation of the process.

Three distinct roles are involved in the Scrum process

- The Product Owner—Responsible for defining and prioritizing the Product Backlog.
- The Scrum Master—Responsible for the Scrum process. The Scrum Master is a guide and coach.
- The Developers—These are the Scrum team members. A self-organizing group who is responsible for executing the Sprint backlog.

3.2 Adapted Application

The Agile methodology is spreading to be used as a project management technique for other types of projects. The theory expounded upon here is that this is an excellent technique for asset management improvement projects for SME's.

Firstly an organization identifies a Product Owner, an Asset Manager would be a good choice if the role exists, if not, a person who has been advocating changes in Asset Management from within the organization. What is important is that the role is given the sole responsibility and authority to make decisions on Asset Management priorities throughout the organization. This can be on behalf of a committee or senior management but all requests about Asset Management improvement priorities must go through this role.

The other role that must be identified at the start is the Scrum Master, or in this case, the Asset Champion. This is the role of facilitator, a person who is comfortable with holistic Asset Management techniques, ISO 55001 if that is being considered as the framework and this development method. This is someone who can help and assist both the Sprint teams and the Asset Manager, who can help control external influences so they are channeled in a positive manor and who can provide guidance and illumination both inside the team and externally to the wider organization.

The first task is to create the Product Backlog, or in this case the Asset Management Backlog; the prioritized list over Asset Management improvements. This is done by the Asset Manager with assistance and guidance from the Asset Champion. This can be developed through a GAP analysis. If an organization has chosen to use ISO 55001 as the Asset Management framework then an analysis is a straightforward exercise. If however ISO 55001 is not the framework to be adopted then it will be necessary to define what level of Asset Management maturity is being aimed for. Industry benchmarking, best practices, authoritative bodies and various national and international standard are all useful here. The decision support software tool is proving invaluable here.

The result of the Gap analysis will result in a list of systems, processes, items and procedures that together make-up the requirements necessary to achieve the defined level of Asset Management maturity. The next step is prioritization. Priorities will vary from organization to organization and will depend on any number of variables but things to consider include:

- Policy and Strategy—These will often need to be the first items developed as they may not exist at all in many SME's and will dictate a lot of the following work.
- Easy wins—Projects that quickly highlight measurable improvements help to convince all stakeholders that the process is worthwhile.
- Systems—If Gaps include the need for new or modified IT based systems it is useful to decide if they will be developed first or last. It can be advocated to implement a system first and then build processes and procedures around it or vice versa. Either way a firm decision at the beginning will help avoid trouble in the middle.
- Continuous improvement—A robust process for continuous improvement developed early on will help all processes from that point.

The next step is selecting the priorities to be included in the first sprint and beginning the planning. It is best to choose only a small number of tasks for each Sprint in order to have a realistic chance of completion, completing one task is always better than half completing two. The composition of the Sprint team will be dependent on the deliverables for any particular Sprint and will change from Sprint to Sprint. It will be made up of a small number of members whose knowledge and skills are relevant to that particular Sprint backlog.

3.3 Flexibility and Interconnectivity

One of the cornerstones of holistic Asset Management is the consideration of the interconnectivity of each of the subjects and how the whole is greater than the sum of its parts (IAM 2014). On first glance, the above methodology may appear to be contrary to this philosophy. This is not the case. The method breaks up what can be a daunting task for an SME into manageable pieces, each of which offer individual benefits but each piece builds upon the previous one, gaining those benefits, learning from them and adding to them.

The prioritized list, the Product Backlog, will change overtime. New stakeholder requirements and the outcomes from previous Sprints will alter priorities or add new ones. The Scrum methodology automatically assimilates these new priorities without affecting progress. Previous deliverables may at any time be revisited in a new Sprint if new or changing priorities require it. In this way, it ensures its own continuous improvement process.

4 The Practice

4.1 Improvement Project Priorities

In general terms, priorities are as individual as the organizations that make them and of course are entirely dependent upon the Asset Management goals of that particular organization. There would however seem to be some categories that most priorities would fit into.

- Profitability—Those tasks related to improving financial performance either through reducing costs or improving efficiencies.
- Scalability—Those tasks related to reducing growing pains or improving standardization.
- Controllability—Those tasks that are designed to increase the knowledge of how assets are operated and the information therefrom.

There are other categories, but these would seem to be some of the most common. One interesting note is that for those SMEs that this paper is based on, certification was not a priority.

4.2 GAP Analysis

A GAP analysis for the authors own organisation was performed using ISO 55001 as the benchmark. It is not the intention of the organisation to achieve certification at this time but it was decided to use the international standard as a reference and then evaluate the findings to see if they were considered relevant. The list below shows the top five priorities as concluded from the GAP analysis:

1. Management of Change
2. Asset Management Leadership
3. Organisational Culture
4. Asset Operations
5. Asset Information Systems

4.3 The First Improvement Project

With the Gap analysis prioritized, it is possible to plan the first Sprint. In this case, it was actually decided to start with priority two rather than one, as it was felt that a focus on leadership was necessary to lay the foundation for all other works and would ensure a better chance of success.

Each of the priorities above contains any number of individual tasks not all of which can be completed in a single Sprint. It was necessary to identify a manageable Sprint Backlog taken from the single priority Asset Management Leadership. There is a need for a balancing act between tasks that will have as great an impact as possible but staying within a time and cost limited framework. After consultations between the Asset Manager/Champion and senior management, the following Sprint Backlog was agreed for the first Sprint of four weeks.

- Asset Management Newsletter—Develop and publish an internal newsletter promoting Asset Management and the coming improvement projects
- Scenario Analysis—An analysis would be conducted to evaluate various 10-year scenarios. This would provide decision support, assist in future strategy work and could be used in communication with stakeholders
- Management workshop—A workshop would be held with all managers to communicate the importance of Asset Management, to re-enforce the importance of leading by example and to explain the coming improvement program.

Some of the major markets that the author's organization operates in have undergone significant downturns, resulting in challenges that have, of necessity, to be addressed first. The start of the Sprint has therefore been delayed.

5 Conclusions

Although the method has not been tested as fully as is necessary to declare it a success, there are still some things that can be concluded and others that can be inferred.

The method does allow SMEs to approach Asset Management in a fashion that is within acceptable limits of time, cost and effort. It can be used by one or two individuals all the way up to much larger teams. As with all Asset Management, it is a continuous process so care should be taken not to see each Sprint as a disparate project but rather as a part of the whole.

As the method can be conducted by a few individuals care should be taken to ensure that the entire organisation is included. The Asset Champion has an important role communicating the progress and improvements being made as well as ensuring that the deliverables from the Sprints are absorbed by the organisation and used constantly. This may well be one of the weaknesses of this theory so it is critical that the whole organization is engaged.

In smaller organizations, it is often the case that a single person fills more than one role. It is not prudent to do that here. The author tried to be both Asset Manager and Asset Champion and this was not ideal. The two roles require different viewpoints and relate to stakeholders in different ways. It is difficult for stakeholders and the person in question to distinguish between the two and can lead to more noise than is necessary. It is also a considerable amount of work and the persons taking on these roles will have normal duties in addition.

While this method has not been completely tested as yet, it should be noted that the work done so far has generated considerable enthusiasm for Asset Management within the organization. The ability to see that improvements can be achieved within an acceptable budget has had a direct influence on perception and small improvements can be seen.

The ability to quickly identify areas requiring attention based on an organizations own information has proved to be an invaluable tool. The software tool developed, and under continuous development, has provided significant value in its own right and can provide the starting point for further analysis. Being able to perform an effective Gap analysis without the need for interruptions provides one less barrier for organizations to proceed.

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Big Data in Asset Management: Knowledge Discovery in Asset Data by the Means of Data Mining

Diego Galar, Mirka Kans and Bernard Schmidt

Abstract Assets are complex mixes of complex systems, built from components which, over time, may fail. The ability to quickly and efficiently determine the cause of failures and propose optimum maintenance decisions, while minimizing the need for human intervention is necessary. Thus, for complex assets, much information needs to be captured and mined to assess the overall condition of the whole system. Therefore the integration of asset information is required to get an accurate health assessment of the whole system, and determine the probability of a shutdown or slowdown. Moreover, the data collected are not only huge but often dispersed across independent systems that are difficult to access, fuse and mine due to disparate nature and granularity. If the data from these independent systems are combined into a common correlated data source, this new set of information could add value to the individual data sources by the means of data mining. This paper proposes a knowledge discovery process based on CRISP-DM for failure diagnosis using big data sets. The process is exemplified by applying it on railway infrastructure assets. The proposed framework implies a progress beyond the state of the art in the development of Big Data technologies in the fields of Knowledge Discovery algorithms from heterogeneous data sources, scalable data structures, real-time communications and visualizations techniques.

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1 Introduction

Assets are complex mixes of complex systems. Each system is built from components which, over time, may fail. Previously the diagnosis of problems occurring in systems has been performed by experienced personnel with in-depth training and experience (Chiang et al. 2001). Computer-based systems are now being used to automatically diagnose problems to overcome some of the disadvantages associated with relying on experienced personnel (Price and Price 1999). Asset Management (AM) enables the realization of value from assets throughout its full life cycle. It involves the coordinated and optimized planning, asset selection, acquisition/development, utilization, care (maintenance) and ultimate disposal or renewal of the appropriate assets and asset systems (TWPL 2015). The layered structure of AM is presented in Fig. 1.

ISO 55000 is an international standard for Asset Management launched in 2014. It is based on PAS 55 (Publicly Available Specification) published by British Standard Institution in 2004 which gave guidance for good practices in physical asset management. ISO 55000 extends the definition of assets as it covers any asset that creates value for organization, not just physical production asset. The standard provides a framework for developing an asset management system, and enables organizations to achieve business objectives through the effective and efficient management of its assets (ISO 2014).

Data relevant to asset management are gathered, produced and processed on different levels by different IT systems (Galar et al. 2012; Kans 2013; Zhang and Karim 2014) e.g. ERP (Enterprise Resource Planning) for business functions; SCADA (Supervisory Control and Data Acquisition) for monitoring process and controlling the asset; CMMS (Computerized Maintenance management System) and CM (Condition Monitoring) for maintenance functions, and SIS (Safety Instrumented Systems) for safety related functions. Nowadays the challenge is to

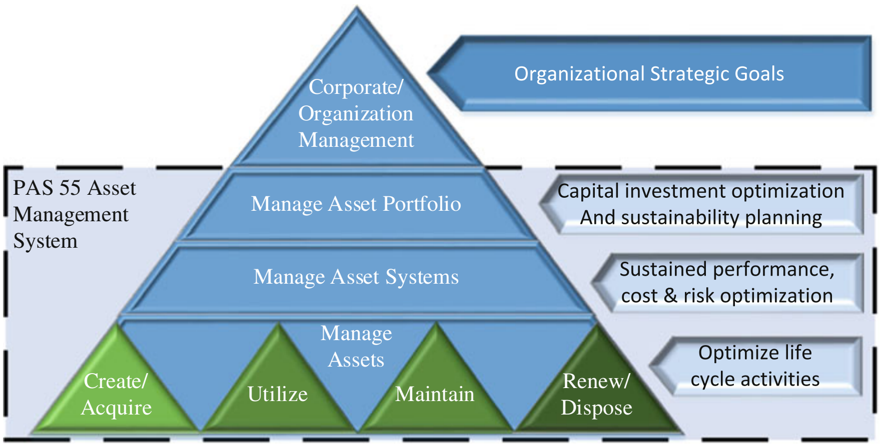

Fig. 1 Layered structure of Asset Management, based on PAS55 (TWPL 2015)

provide intelligent tools to monitor and manage assets (machines, plants, products, etc.) proactively through ICT, focusing on health degradation monitoring and prognosis instead of fault detection and diagnostics. Maintenance effectiveness depends on the quality, timeliness, accuracy and completeness of information related to machine degradation state. This translates into following key requirements: preventing data overload, ability to differentiate and prioritize data (during collection as well as reporting) and to prevent as far as possible the occurrence of information islands.

While the use of a good version of either technology can help to achieve the maintenance goals, combining the different data sources into one seamless system can exponentially increase the positive effects to operations and maintenance group's performance. Only a few years ago the idea of linking CMMS, SCADA and CM technologies was mostly only a vision or at best too expensive. With the technology available today it is relatively easy and inexpensive to combine the information supplied by these systems as long as there are taxonomies and ontologies properly defined in order to describe the actors and their relation. For this purpose, this paper discusses the application of big data for knowledge discovery in asset management and proposes the use of the reference model CRISP-DM for the knowledge discovery process.

2 ICT Applications Within Maintenance

The general opinion among the asset managers is that the application of information technology brings dramatic results in machine reliability and O&M (operations and maintenance) process efficiency, however only few operations and maintenance managers can show or calculate the benefits of such applications (Kans 2012; Kans 2014). Technology providers are trying to develop more and more advanced tools while the maintenance departments seem to struggle with the daily problems of implementing, integrating and operating such systems. The users combine their experience and heuristics in defining maintenance policies and in the usage of condition monitoring systems. The resulting maintenance systems seem to be a heterogeneous combination of methods and systems in which the integrating factor between the information and business processes is the personnel. The information of the assets goes through these human minds forming an organizational information system and creating a high reliance on the expertise of the asset management staff.

Indeed, the contribution of operation and maintenance data to the different asset management stages has been triggered by the emergence of intelligent sensors for measuring and monitoring the health state of a component, the gradual implementation of Information and Communication Technologies (ICT), and the conceptualization and implementation of e-maintenance. Today there are two main systems deployed in maintenance departments, Computerized Maintenance Management Systems (CMMS) are the core of traditional maintenance record-keeping practices and Condition Monitoring Systems (CM) which are capable of directly monitoring asset components parameters. However the attempts to link observed CMMS events to CM sensor measurements have been fairly limited in their approach and scalability. Moreover information from SCADA which is mainly used in operation for supervisory purposes is seldom fused with the mentioned above.

During the last decade, the global competition and advancement of ICT have forced Production and Process Industries through a continuous transformation and improvement process. The business scenario is focusing more on e-business intelligence to perform transactions with a focus on customers' needs for enhanced value and improvement in asset management. Such business requirements compel the organizations to minimize the production and service downtime by reducing the machine performance degradation. The above organizational requirements stated in ISO 55000 necessitate the development of proactive maintenance strategies to provide optimized and continuous process performance with minimized system breakdowns and maintenance. With these changing systems of the business world in the 21st century, a new era of data e-services coming from asset data has emerged.

A top-shelf CMMS can perform a wide variety of functions to improve maintenance performance. CMMS is primarily designed to facilitate a shift in emphasis from reactive to preventive maintenance (PM) by allowing the maintenance professionals to set up an automatic PM work order generation. CMMS can also provide historical information which is then used to adjust the PM system setup over time to minimize repairs that are unnecessary, while still avoiding run-to-failure repairs. PM for a given piece of equipment can be set up on a calendar schedule or a usage schedule that utilizes meter readings. A fully-featured CMMS also includes inventory tracking, workforce management and purchasing in a single package that stresses database integrity to safeguard vital information. The final result is optimized equipment up-time, lower maintenance costs and better overall plant efficiency. In summary CMMS contains the asset hierarchy and it is an excellent starting point as taxonomy but no ontology.

On the other hand the CM and SCADA systems should accurately monitor the real-time equipment performance and condition in order to alert the operators and maintenance professional of any changes in performance or behavior trends. There is a variety of measurements that a CM and SCADA package might be able to track and the very best CMs are expert systems that can analyze measurements like vibration and diagnose machine faults. Such expert system analysis will put maintenance procedures on hold until absolutely necessary, thus extracting maximum equipment up-time. In addition, the best expert systems offer diagnostic fault trending where individual machine fault severity can be observed over time. SCADA systems provide information related to the performance of the asset and provide screenshots of a number of performance indicators at a time (commonly called nowcasting). This information together with a number of alarms and incidences linked to sensor thresholds have been historically used for process monitoring but never fused with other information in order to get benefits out of the immediate supervision.

SCADA, CMMS and CM systems have strong benefits that make them indispensable to maintenance and operation improvements. CMMS is a great organizational tool but cannot directly monitor equipment conditions whereas a CM system excels in monitoring those conditions but is not suited to organizing your overall maintenance operations. Finally SCADA collects huge amount of data for supervision of the process but is not integrated in a holistic view for asset management. The logical conclusion is to combine these technologies into a seamless system which helps to avoid catastrophic breakdowns and eliminates needless repairs to equipment that is running satisfactorily and same time optimizing the operation.

So far integration has been addressed largely from the view point of representing the collected information to the end-user (operator or manager) in an effective manner, i.e. bridging the gap between information from plants and equipment and the enterprise resource planning (ERP) platforms.

3 Big Data and Knowledge Discovery

During the last 10 years and especially during the last 5 years, a set of technologies to capture, process and visualize large volume of data has been developed. In business sectors not very fragmented, where most of the information is already structured and comes from the same source, the use of big Data Analytics is nowadays a standard (e.g. bank sector or pharmaceutical sector). For these sectors, there are also a great number of software tools and IT services that cover most of the end user needs. Some successful implementations of Big Data have been summarized in Chen et al. (2014). During the flu pandemic in 2009, Google obtained timely information from big data analysis that was more valuable than those from disease prevention centers. Base on those models have been built to forecast spreading of influenza and to predict places where influenza will spread from. In 2008 Microsoft purchased a company that had system to predict trends of airlines ticket prices. After incorporating it to big data search engine, the system was able to save nearly 50 USD per ticket per passenger, with forecasting accuracy around 75 %. However, these examples are only the exception, since most businesses, susceptible to incorporate the Big Data concept, have not done it yet, either for the lack of specific tools (real time communication, scalable data structures, complex predictive algorithms or visualizations tools) or the excessive cost to involve all the required stakeholders.

In Chen et al. (2014) authors define big data as a the datasets that could not be perceived, acquired, managed, and processed by traditional Information Technology and software/hardware tools within a tolerable time. IBM researchers in (Zikopoulos and Eaton 2011) modelled big data in terms of 3V properties: Volume—amount of data, Variety—unstructured data coming from multiple sources and Velocity—high rate of data generation. In Lomotey and Deters (2014) this model has been extended into 5V, by adding: Value—understanding the cost and value of the data and Veracity—need to check accuracy of the data and data cleaning. Data Mining is one of the processes for Knowledge Discovery that aims in creation of new knowledge.

In Lomotey and Deters (2014) an Analytics-as-a-Service tool has been presented toward Knowledge Discovery in Big Data. It has been indicated that existing data mining techniques have been designed for structured and schema oriented data storages. Proposed approach aim to perform topic and terms mining from unstructured data silos. In McKinsey & Company report (Manyika et al. 2011) the value that creative and effective utilization of big data could create has been summarized: in U.S. medical industry it may surpass 300 billion USD; retailers may improve their profit by more than 60 %; EU could save over 100 billion EUR by utilizing big data to improve the efficiency of government operations.

Data produced in asset management can be described in terms of the 5Vs described by Zikopoulos and Eaton (2011) and Lomotey and Deters (2014). Data from sensors like accelerometers or acoustic sensors can be acquired with velocity of tens of thousands of samples per second per each measuring point. Having hundreds or thousands of those points, big **volume** of data is being produced. Some maintenance related data are structured while some are not, such as free text comments for performed maintenance actions or failure reports. Moreover, data from different systems are in different formats. This is the source of **variety** of data in asset management. Those data has potential value when properly employed in asset management, but in order to achieve this, there is need to asses and manage the **veracity** of the data, i.e. the data uncertainty. Finally, understanding the **value** of data, i.e. how data can enable efficiency and effectiveness in maintenance management, for instance for improved decision making, and to choose the most cost-effective means to process the data is important.

Data mining in big asset data can discover knowledge in terms of new patterns and relations not visible at a glance. The big data approach enables incorporation of contextual information in Maintenance Decision Support Systems (Galar et al. 2015). One example of useful knowledge that could be discovered is root causes of failure. This can provide an input for design improvement, as well as for more accurate maintenance planning.

4 CRISP DM

The knowledge discovery process, like any other structured process, has to be supported by harmonized and standardized methodologies. These methodologies enable the definition of taxonomies and ontologies necessary for the efficient use of big data, and for reaching the objectives of the organization. Several data mining methodologies are available, such as the KDD process, SEMMA and CRISP-DM (Nadali et al. 2011). CRISP-DM (CRoss Industry Standard Process for Data Mining) was conceived in late 1996 by the automotive company Dailmler-Chrystler, the statistical software provider SPSS, and the data warehouse provider NCR (Chapman et al. 2000). CRISP-DM is the most popular cross-industry standard process for data mining today, based on an iterative process model (Bosnjak et al. 2009; Nadali et al. 2011). Surprisingly, searches for articles regarding the application of CRISP-DM in maintenance or asset management result in no hits. This clearly shows that the standard not yet has found its way into the data mining intensive area of asset health monitoring.

The reference model covering the life cycle of data mining projects consists of six phases: business understanding, data understanding, data preparation, modelling, evaluation and deployment, see Fig. 2. The developers of the model point out that the model in not rigidly sequential but iterative, and moving back and forward in the phases is necessary (Chapman et al. 2000). The *business understanding* phase focuses on understanding the business related objectives and requirements of the problem or project. These are thereafter translated into a data mining problem definition. In the *data understanding* phase you become familiar with the data and its quality, and form a first hypothesis regarding hidden information. The *data preparation* phase aims at constructing a final data set to be fed into the model and in the *modelling phase* modelling techniques are selected and applied. Before final deployment of the data model or models selected, the model(s) has to be evaluated. This is made in the *evaluation phase*. Especially the fit to business objectives is important to evaluate. In the *deployment phase* the model is implemented into the organization, and fit into the overall decision making context.

4.1 A CRISP-DM Approach for Failure Diagnosis of Railway Infrastructure Assets

In this section, the applicability of the CRISP-DM model for asset management is shown. This is made by exemplifying the process of data mining for railway infrastructure assets in Swedish railway transportation.

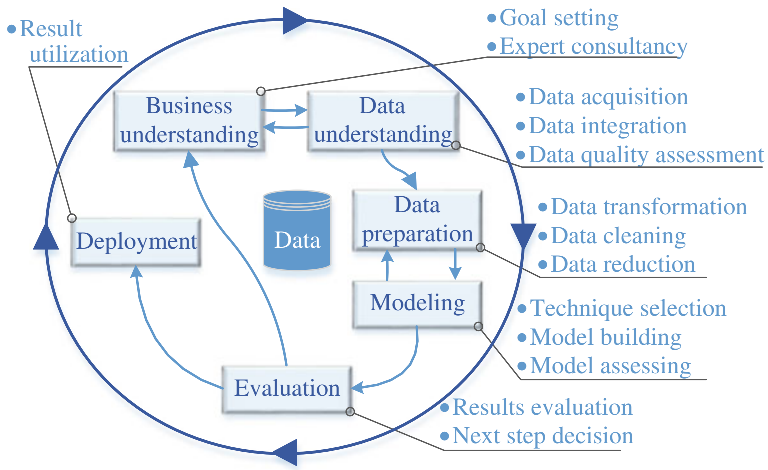

Fig. 2 The CRISP-DM reference model

Phase 1: Business understanding. The objectives of the Swedish railway transportation are expressed in terms of delivery quality. The delivery quality is measured using six key indicators: punctuality, capacity, robustness, safety, usability, and environment and health, and for each of the key indicators annual and long term goals are set. The overall transport policy objective is "to ensure an economically effective and long-term sustainable supply of transportation for citizens and industry across the country", The Swedish Transport Administration (2014, p. 14). The objectives of operations and maintenance are directly related to these objectives: "Operation and maintenance are performed for the traffic to come forward with the promised delivery of quality now and in the future." In order to reach this, choosing the right action is seen as one of four focus areas, i.e. to require control of the condition on the infrastructure, to understand the deterioration and that the condition is maintained through a cost-effective mix of preventive and corrective maintenance actions. Today, the current systems does not allow for detailed understanding of the true condition, neither on the true causes and modes of failure. Mining the big data set for creating a better knowledge base for failure diagnostics and prognostics is needed. In this example, the failure diagnosis will be in target.

Phase 2: Data understanding. Continuous controls and inspections of the infrastructure are done by operations and maintenance (O&M) contractors, and failure data are reported into the troubleshooting system "Ofelia". Based on failure symptoms, the contractors report data on faults, causes and what action is performed into the failure report. In addition, failures leading to acute maintenance actions are also reported. The data set is a mix of pre-set options (for faults, failure cause and action) and free text descriptions. Failure causes are reported into one of four main categories (external conditions, work, material or operator) and on subcategory, while action and fault are categorized on one level only. The faults, causes and actions can be further described in free text, but this is not mandatory. Symptoms can either be a predetermined category or a free text description. Also, data such as time, place, asset/component, contractor etc. is registered. In addition, there is some condition monitoring data of e.g. track condition available. To sum up; the data set is large, heterogeneous with respect to data types, mainly based on inspections, and partly incomplete. Volume, variety and veracity are relatively high while velocity and value is semi-high.

Phases 3 and 4: Data preparation and modelling. A large number of available models for data mining exist, such as artificial neural networks (ANN), cluster analysis, decision trees, genetic algorithms, Bayesian networks, or rule based models (Bosnjak et al. 2009). Several of these are applicable for failure diagnosis as well. Galar et al. (2015) summaries the available methods in four categories: reliability-based maintenance, model based methods, signal based methods, and statistical methods. Due to low level of real-time data available, the signal based methods are not applicable. Instead, model based or statistical methods are the best options. Large amount of longitudinal data are available that could be used for learning, but the complexity of the system might result in models too complex for efficient use of ANN. Statistical methods, such as Bayesian networks or Markov models, could be applicable, as well as for multivariate analysis methods. Before deciding on the method, a thorough examination of the data set and its properties has to be done, e.g. check for statistical errors and normal distributions. In practice, a couple of methods should be selected and preliminary tested before the final selection and application takes place.

Phases 5 and 6: Evaluation and deployment. Obtained models need to be evaluated. In this case we especially need to ensure Veracity and Value—the two of Big Data V's that address the business side. Iterating the inner loop, at some point, the results provide enough business value to move into deployment and operationalize a model (Pilcher 2013). When the model is properly evaluated, it has to be fit into the overall context and implemented into the new or existing ICT environment. The failure diagnosis method will be utilized by the analysts in first hand for the purpose of gaining better understanding of the failure patterns for railway infrastructure, and for understanding root causes of failures. Therefore, the model has to be integrated into the other analysis tools available. Moreover, this knowledge will be utilised for improved O&M planning and as input for more accurate price models, which will affect the processes and systems used for these purposes.

5 Conclusions: A New Way to Handle the Assets

The old view of data as record keeping is transformed to the data centric view to reveal an asset capable of driving business improvement. There is hidden value in the data it just need an investment in the process of discovery (Pilcher 2013). One of the triggers for big data approach for asset management is Internet of Things. It is a paradigm where everyday objects are connected to the Internet. It allows devices communication with each other with minimum human intervention (Perera et al. 2014). In this approach physical asset equipped with multiple sensors can produce large volume of data. Those data could be used through the knowledge discovery to build for example asset degradation prediction model that can be employed for optimization in form of a Maintenance Decision Support System. A data driven approach is not as accurate as physics based approaches, however do not require excessive knowledge about underlying physical processes.

The proposed framework described in this article implies a progress beyond the state of the art in the development of Big Data technologies in the fields of Knowledge Discovery algorithms from heterogeneous data sources, scalable data structures, real-time communications and visualizations techniques. Specifically, the further directions of the Big Data fundamental research can be summarized as follows:

- Real time KD algorithms from heterogeneous asset data sources that will cope with privacy preserved processing, feature and instance selection, discretization, data compression, ensemble classifiers and regression models, and spatial and temporal alignment of data.

- Scalable data structures based on cross-domain data sources acquisition by means of a virtualization layer between data acquisition process and data analytics. This should also include new solutions that combine new databases capabilities to integrate heterogeneous data sources on high-performance accessing systems based on Clouds.
- Enabling Big Data Communications by means of open interface gateways with monitoring systems providing timestamp and position synchronization, heterogeneous communication support, including mobility and aggregation, and priority protocols for real time transmission of information.

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Use of Generational Models for Asset Management Strategies in an Australian Metro Rail Organisation

Ralph Godau and Mary McGeoch

Abstract The purpose of the following paper introduces and outlines Metro Trains Melbourne's approach to developing and utilising a 'Generational Model' to describe the evolutionary states of the organisation's asset class and group strategy documentation. It further summaries the results of the various asset developmental states as they are described in the model, as well as the criteria and scoring for evaluating and ascertaining the generational level for asset class and group criticality and developing subsequent strategies. This enables the targeting of specific improvement actions as to what generation each asset class and group strategy should be developed is used to ascertain the minimum generational level based on the criticality of the asset class and group. The rate of progress through to higher generational levels is also based on criticality (high criticality asset classes and groups are given higher priority than medium/low criticality asset classes and groups) and other factors that arise and any additional condition information needs to be compared against the baseline forecast (determined at the previous generational level) to determine the confidence in the forecast and assumptions made in that forecast. The scoring system is based on whether the asset classes and groups comply, partial comply or do not comply with the criteria, the outcomes are that of generational improvement. The paper presents the resulting MTM's asset class and group strategies that are currently either in the first, second or third generation, strategies of which have been developed for all of the asset class strategies. A variation of this Generational Model is also being utilised in the development of the MTM group strategies. The key benefit of introducing the Generational Model is the ability to manage stakeholder expectations. It is argued that this case study, and accompanying research, is a contribution for the area of strategic asset management and within the International Journal of Strategic Engineering Asset Management.

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1 Introduction

As part of Metro Train Melbourne's (MTM) journey to obtain PAS55 Certification (achieved in 2013), the development of its Asset Class Strategies (ACS) required an innovative approach. Consideration needed also to be given to the expectations of MTM's key stakeholders, as well as establishing and maintaining a continuous improvement framework.

2 The Generational Model

The purpose of the Generational Model concept is to provide a clarification process in relation to the review procedure that MTM initially introduced as a series of 'peer reviews'. The Generational Model is a set of criteria that enables a more rigid and structured means of gauging the evolution of the ACS. For MTM, this same concept has now been utilised for the development of the Asset Management Group Strategies (AMGS) as well as other key asset management documentation. This has resulted in the establishment of a new and consistent language that facilitates a more informed dialogue between stakeholders. Another important aspect associated with the development of ACS' by using the Generational Model is that it encourages the visualisation of what the final document and outputs would 'look like'. This was particularly useful for ACS Specialists who had never transcribed these documents before.

The concept of the Generational Model being used to consider the evolutionary nature of process, people or documents is not new, in particular through the use of capability maturity model techniques. For example, it has been used in the education sector (Nelson et al. 2015) to consider teaching practices and how they impact on student experiences. It has also been used in the management area (Bititic et al. 2015) in improvement performance measurement. The key implication drawn from both of these studies from a practical implication perspective is that the continual use of such models should result in growth in the maturity level of ACS that would lead to improved management and renewal/maintenance forecasting of the railway infrastructure.

Simply, the Generational model is based on four principles or stages:

1. Awareness
2. Learning
3. Understanding
4. Proficiency

3 Evolution of Generational Model for Asset Management Plans

The concept of the Generational Model for asset management documentation was first conceptualised in local government at Brimbank City Council approximately 10 years ago. It was introduced in order to resolve the issues of misunderstandings about the differences between the various versions of Asset Management Plans (AMPs; equivalent to the ACS at MTM) by the CEO and Councillors. At the time, the CEO was concerned about the differences in such things as "renewal gap/backlog", levels of service, assumptions, condition assessments, lifecycle modelling, and asset information, and so on, between the different versions. The CEO wanted to understand why and how to communicate this to Councillors, community and other key stakeholders.

As a result, the CEO sought information on the ways in which the Asset Management team could provide context to the versions of AMPs presented. Therefore, the initial concept for a Generation Model to assess the development of AMPs was designed to provide a communication tool for the CEO but was found also to support the continuous improvement of these plans. As such, it was used to underpin improvements in Council's Asset Management Maturity (as part of Municipal Association of Victoria's STEP Asset Management Program).

It was this basic model (set of requirements spanning the four generational stages) that was used as the starting point at MTM (Version One). The difference at MTM was that this concept was used at the onset of the development of the ACS' and reporting of the status was embedded into the document (both within the summary page, as well as within the body).

The evolution of the ACS Generational Model (ACSGM) is also attributed to the team of eight Specialists at MTM who were also responsible for the development of the ACS. No such documents existed prior, and over an 18-month period this team developed and gained sign-off of 59 ACS's, which were critical in aiding MTM to attain PAS55 Certification in November 2013. At the time, MTM was the only railway organisation in the Southern Hemisphere to achieve such a result; and this was further used to address the resultant non-conformances to maintain certification by November 2016 (Staples and Godau 2014).

The adoption of a matrix style of the Generational Model was proposed by one of the Senior Consultants, Brenton Marshall (GHD) working for MTM on the development of an ACS at the time. Marshall identified key themes and suggested that this could be used to refine the criteria. This then created a process of further advancement, with the suggestion to develop a scoring system (attributed to Robin Barlass, then Head of Network Strategy & Development for MTM), to provide a quality measure for each ACS.

This elaboration provided more clarity to the Specialists writing the ACS, clearer understanding of the gaps, improved identification of improvement actions, and a greater common understanding on what stages of development the ACS had progressed to, and where management required them to be.

3.1 The Concept of Four Generational Stages/Levels

Why four generational stages for the development of AMPs?

The chief driver for quality AMPs is the measure of correlation between predictive lifecycle modelling and the actual behaviour of assets in the operational environment. This requires (firstly) the collection of asset information, intervention levels and options, performance data and future objectives or levels of service, and (secondly) that the lifecycle and forecast modelling is developed to reflect the real world, so that it provides management with a high level of confidence in the assets meeting the objectives or providing a level of service that is desired by the business now and into the future.

The activities required to do this take considerable time, often years, before they would influence the next version of an AMP. So to help explain to decision makers what type of document they are dealing with a Generational Model is needed.

For example, the collection of asset condition data (especially for long-life assets) is one key variable that underpins lifecycle modelling. Condition data is used to develop degradation curves for long life assets. The confidence in the degradation curves depends on the number of condition assessments undertaken (typically every three years) over a reasonable time (e.g. 100-year lifecycle assets may equate to 10 years) and the associated validation process to determine whether the modelling reflects what is actually happening. The condition assessments then became milestones under the ACS Generational Model under the criteria of "Accuracy of Condition Assessments & Fault/Defect History" (refer to Appendix 1).

4 Application of Asset Class Strategy Generational Model

As stated, the development of the ACSGM was designed to help Asset Class Strategists develop an ACS and identify improvement actions to fill the gaps. The ACS purpose is to:

(i) Ascertain what information is available and how it can be used to describe the asset class in sufficient detail, including its function and interfaces
(ii) Assign targets that support the overall objectives, meet the group or line requirements, and derive levels of service for the asset class, subclass, type and component based on asset and/or network criticality
(iii) Develop asset profiles and historical analysis covering asset condition, health, utilisation, failure history, performance history and maintenance/renewal expenditure
(iv) Understand asset deterioration and associated consequences
(v) Understand risk and current mitigation strategies and how this impacts meeting the objectives
(vi) Use all of the above to develop planning and costing scenarios, e.g. optimised or constrained lifecycle scenarios based on budgets, levels of service and resources

The ACS Guidelines was developed to support the above process, and stipulates that each ACS must state the Generational Level, including information justifying the level selection by addressing any area of inadequacy in the strategy which could be improved on for the next iteration of the document. The purpose is to identify improvement actions that inform a two to three year improvement program. As the program is implemented, the completion of the improvement actions guides the next iteration of the ACS allowing it to progress through the Generational Levels.

In Table 1, the first iteration of the 59 ACSs and assigned Generational Levels are presented. Of the 59, zero were at Fourth Generation, seven were at Third Generation (12 %), 11 were at Second Generation (19 %) and 41 were at First Generational Level (69 %).

The first 22 listed ACSs (all high and selected medium/low criticality) were assessed against version one of the Generational Level criteria, which had no scoring system and was positioned to a level based on the judgement of the author, and then verified by the Asset Management System & Compliance Manager. The final 37 ACSs were assessed against version two of the Generational Level criteria and were assigned a score against each criterion. Figure 1 provides a summary by asset class and criticality. The original aim was to achieve a minimum of second Generational Level for high criticality asset classes. This was achieved for Electrical, Rolling Stock and Signals & OCS but not for Track and Structures. The available information needed to support a second Generational Level ACS for Track & Bridges is targeted for the second iteration of these strategies.

MTM is currently reviewing 14 high and medium criticality using version three of the Generational Level criteria (see Appendix 1) as a priority to improve the quality of these ACSs. The priority is driven by stakeholders requiring higher confidence levels in the outputs of the ACS (e.g. the renewal program) and MTM's preparation for seeking a franchise extension with Public Transport Victoria (PTV).

Changes to the Generational Model were based on feedback from the Asset Class Strategists and is an evolutionary activity wherein which the strategist are working through the process of learning what is useful and what drives better decision making and continuous improvement planning. Below italicised are the changes between version two and version three of the Generational Model. Items that were excluded where either already covered or were deemed not to add value to the assessment. Items included in version three were focused on gaps in capability or knowledge required to write quality ACS'.

Criteria used in version two of the ACSGM included:

Asset Management Objectives (AMO) Linkage, Roles & Responsibilities Definition, Asset Hierarchy, Information Systems & Data Quality, Accuracy of Condition Assessments & Fault/Defect History, Level of Service Definition, Depth of Risk Assessment, Route Analysis, Decision Making, Planning Period, *Confidence, Improvement Planning, Targeted ACS Generational Level.*

Table 1 First iteration of the 59 ACSs and assigned generational levels

Criticality	Asset class group	Asset class strategy	Generational level
High	Signals and OCS	Point mechanisms	2
		Interlockings	2
		Track circuits	2
		Trainstops	2
	Rolling stock	Comeng	3
		Xtrapolis fleet	3
		Nexas fleet	3
	Electrical	Inspan wiring	2
	Track and structures	Track system	1
		Bridges	1
Medium	Signals and OCS	Control and indication	2
		Power supply system	1
		Telemetry communication	2
		Protection	1
		Signals	2
		Train control communication systems	3
		POTS	3
		Passenger information system	3
		Pneumatic power supply and distribution	2
		Enclosures	1
	Electrical	1500V switches	1
		22KV switches	1
		Control and indication equipment (scada)	1
		AC circuit breakers	1
		DC circuit breakers	1
		Buildings and environment	1
		Substation services	2
		Pole replacement	1
		AC protection relays	1
		22KV AC transmission	1
	Track and structures	Track drainage	1
		Level crossings	1
		Overhead/Signal structures	1
		Lightpoles/Retaining walls/Other	1
	Stations and facilities	Lift and escalators	1
		Fire equipment	1
		Buildings	1
		Platforms	1
		Subway	1
	Rolling stock	Depos	1
	Murl	Murl	1

(continued)

Table 1 (continued)

Criticality	Asset class group	Asset class strategy	Generational level
Low	Signals and OCS	Power supply distribution	1
		SPOT	3
		DISPLAN—MURL	1
		FMP	1
		TIAS	1
		Field communication systems	1
		TNT	1
		Alarms—station security	1
		CCTV	2
	Electrical	Rectification/Auxiliary power supply	1
		Rectification	1
		Structure bonding and earthing	1
		Signal power supply	1
		Earthing system	1
	Track and structures	Rail sidings	1
		Tunnels	1
	Stations and facilities	Carparks and pathways	1
		Electrical	1

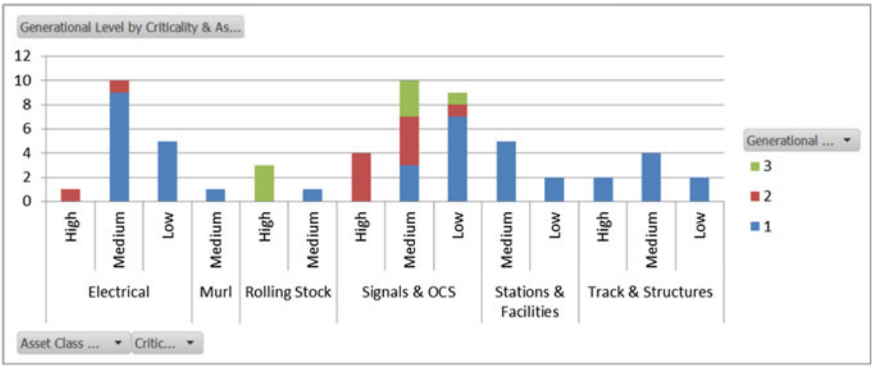

Fig. 1 Generational level by criticality and asset class for the first iteration of the ACS'

Criteria used in version three of ACSGM (Appendix 1) included:

AMO Linkage, Roles & Responsibilities Definition, *Asset Description, Function and Interfaces*, Asset Hierarchy, Information Systems & Data Quality, Accuracy of Condition Assessments & Fault/Defect History, Level of Service Definition, *Knowledge of Criticality*, Depth of Risk Assessment, Group Analysis, *Life Cycle Modelling*, Planning Period.

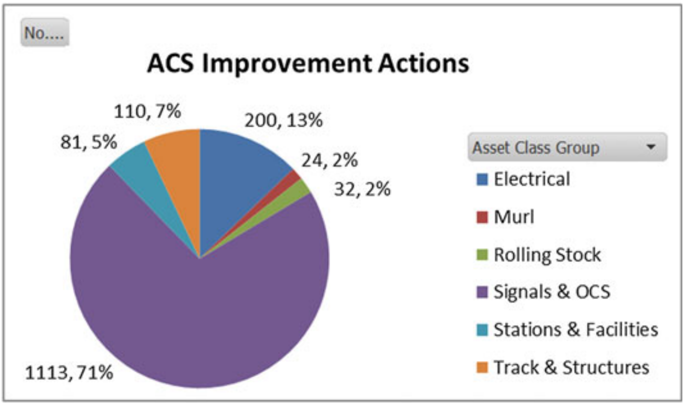

Fig. 2 Improvements actions identified by asset class group

One of the key outcomes using the Generational Model concept in writing ACS is the identification of improvements (aligned with the Generational Level criterion). Figure 2 represents the number and percentage of improvement actions by asset class group. The variations in numbers of actions were heavily dependent on the perspective the Asset Class Strategist as well as the scope in the tackling issues at a higher asset management system level. This behaviour was a result of developing a number of strategies in parallel resulting is improvement actions being duplicated, not raised in higher-level asset management strategies and the eagerness of the Asset Class Strategists wanting to capture all of the issues.

As part of a lesson learnt process, MTM has developed an Asset Management System Improvement Program (AMSIP) set of Guidelines that directs the Asset Class Strategists to ensure that any proposed improvement actions are aligned with the areas of focus outlined in the ACSGM. These proposed actions are then reviewed and synergised into a set of improvement actions. During the development of the first round of ACS, 1560 improvement actions were identified and included in the AMSIP. Through the identification of duplications, common themes, synergy activities, etc. these actions were able to be refined to 500 agreed improvement actions.

5 How the Generational Model Aligns to Asset Management Maturity

As stated, the Generational Model is a set of criteria that enables a more rigid and structured means of gauging the evolution of pertinent asset management documentation, while the concept of organisational maturity lacks a commonly agreed definition. However, most attempts focus on building models of what a ‘mature’ organisation should look like as a construct built up from a collection of specific (detailed) processes and practices and then assessment of maturity as reaching, or exceeding, self-established or defined maturity ‘levels’ for the specific processes and practices (Carpenter 2015).

As also suggested by Carpenter (2015), the concept of Asset Management Maturity is slightly better defined than organisational maturity, in that there are several industry specifications, such as the GFMAM Landscape, the IPWEA framework that forms the basis of the International Infrastructure Management Manual (IIMM) or the WSAA/IWA Aquamark model. He states that maturity, however, is still most often viewed as a construct of grouped processes and practices, and most of the models built to assess maturity against these constructs also have self-established or defined maturity ‘levels’, to the Generational ‘levels’.

Therefore, the link between the Generational Model and the asset management maturity process is apparent in the use of an ‘open system’ that does not explicitly identify every process and practice, but specifies outcomes, objectives, capabilities or coordination/linkages that must exist—the ‘what’, not the ‘how’ and is not subject to structural gaps in the assessment tool, it requires a higher level of base awareness and knowledge of those both building and auditing the system as to what constitutes a complete system (Carpenter 2015).

6 Development of Other Generational Models for MTM

The application of the Generational Model has also been used for the development of MTM’s AMGS. These strategies form a higher-level asset management document than ACS, as they present the metropolitan railway as a network and provide an end-to-end destination perspective (refer to Fig. 3). These documents are currently being prepared for the first time, with the first iteration of these documents due for completion by November 2015.

One aim of the AMGS is to inform the ACS to ensure optimised asset management. The output of the Group and ACS supports the asset management planning and investment prioritisation and ensures that MTM maximises value within the asset management and strategic functions. A draft version of the Group Strategy Generational Model (GSGM), was modelled on version 2 of the ACSGM. The italicised (retained in version 3) and bolded (removed from version 3) highlight items below are common in second version of the ACSGM.

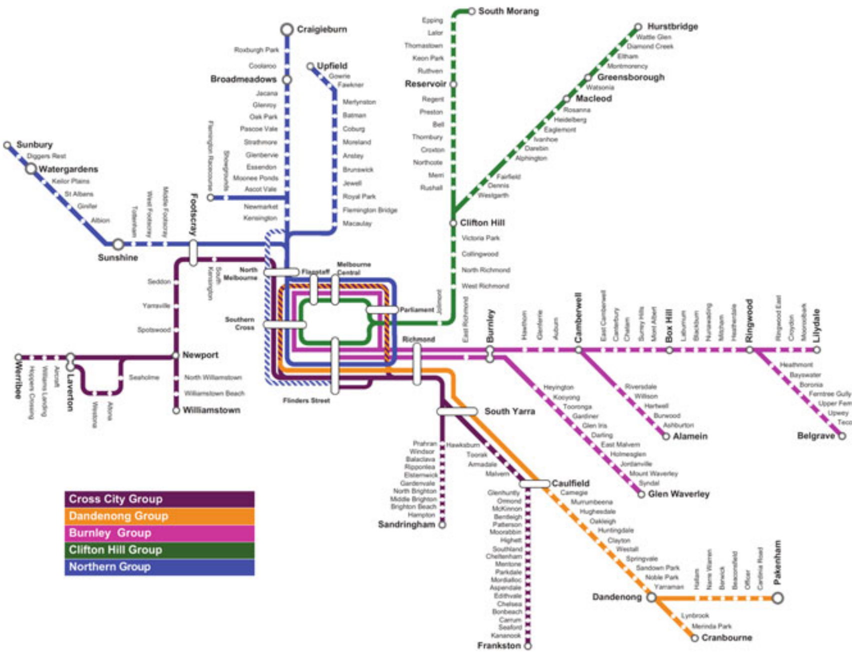

Fig. 3 Five group network map

Criteria used in draft version of the GSGM included:

Asset Management Objectives (AMO) Linkage, Roles & Responsibilities Definition, Information Systems & Data Quality, Depth of Risk Analysis, Route Section Analyses, *Planning Period,* **Confidence, Improvement Planning, Targeted GS Generational Level**, Information Sources and Consultation, Targets and Objectives, Route Criticality, Interfaces, constraints and projects, Accuracy of Target Analysis and Group Strategy.

The revised version is currently under development in parallel to the development of the GS. One interesting outcome is that the ACS will be required to provide information and analysis of assets in the context of a group, route, line and critical section perspective in order to support broader analysis in relation to the group's capability to deliver on the AMO. The GS' look at both the asset and non-asset solutions.

7 What's Next? Moving Forward

In dealing with internal and external stakeholders, the concept of a Generational Level for an ACS and GS and determining what level they are required to be, now provides informed discussion on how to best proceed.

From an ISO 55001 and Asset Management Maturity perspective, the Generational Model plays an important role in providing a framework and path forward for improvement of key asset management documents, as well as building targeted capability and maturity within the organisation.

Generational Models have or are now being developed for other key documents within MTM e.g. RAMS (Reliability, Availability, Maintainability and System), the Asset Information Strategy (AIS) and work is currently being undertaken towards a Generational Model for the Asset Management Capability Plan (AMCP).

The Generational Model is under continual refinement as each time the next series of ACS' are being developed. It is through the experience of those committed to the development of ACS that they become more "mature", and their understanding of the future state of these documents propagates.

Therefore, the production of Generational Models provides a staged framework that aids in the development of pertinent asset management documentation and assists in the development of asset management capability in people, information, processes and procedures; all within the context of Asset Management Maturity.

Appendix 1—Version 3 of ACS Generational Model

Criteria and scoring for evaluating and ascertaining the generational level for Asset Class Strategies including asset class criticality is in Table 2.

The target to what generation each Asset Class Strategy (ACS) should be developed is addressed under criteria titled "Target ACS Generational Level". This is used to first to ascertain the minimum generational level based on criticality of the asset class. The rate of progress through to higher generational levels shall be based on criticality (high criticality asset classes are given higher priority that medium/low criticality asset classes) and other factors that arise from time to time.

Note: For life long assets are reliant on regular condition assessments, the move from one generational phase to the next could take as long as three years. For example, to be able to update the forecasts, the new condition information needs to be compared against the baseline forecast (determined at the previous generational level) to determine the confidence in the forecast and assumptions made in that forecast.

The scoring system is based on whether the asset class strategies comply, partially comply or do not comply with the criteria.

An asset class strategy is deemed:

- 1st generation when the score is between 25 and 44
- 2nd generation when the score is between 45 and 69
- 3rd generation when the score is between 70 and 94
- 4th generation when the score is between 95 and 100

Table 2 Criteria for evaluating and ascertaining the generational level for asset class strategies

Criteria	SCORE	1st generation ACS	2nd generation ACS	3rd generation ACS	4th generation ACS
AM objectives linkage	0—Not comply 1—Partial comply 2—Comply	• Asset Management System targets have not been cascaded to the Asset Class level	• Asset Management System targets have been cascaded to the Asset Class and Asset Subclass (if applicable) levels	• Asset Management System targets have been cascaded to the Asset Class, Asset Subclass (if applicable) and Asset Type levels	• Asset Management System targets have been cascaded to the Asset Class, Asset Subclass (if applicable), Asset Type and Component levels
Roles and responsibilities definition	0—Not comply 1—Partial comply 2—Comply	• Roles and responsibilities for the Asset Class'; (1) data collection and analysis; (2) strategy development, review, and approval; and (3) strategy implementation and management, have not been documented	• Roles and Responsibilities for the Asset Class'; (1) data collection and analysis; (2) strategy development, review, and approval; and (3) strategy implementation and management, have been documented	• Roles and Responsibilities for the Asset Class'; (1) data collection and analysis; (2) strategy development, review, and approval; and (3) strategy implementation and management, have been documented and are embedded	• Roles and Responsibilities for the Asset Class'; (1) data collection and analysis; (2) strategy development, review, and approval; and (3) strategy implementation and management, have been documented, are embedded and continually reviewed and revised to maximise effectiveness
Asset description, function and interfaces	0—Not comply 1—Partial comply 2—Comply	• The asset description is documented at the Asset Class/Subclass level	• The asset description, function and interfaces are documented at the Asset Class/Subclass level	• The asset description, function and interfaces are documented at the Asset Class/Subclass and Asset Type level	• The asset description, function and interfaces are documented at the Asset Class/Subclass, Asset Type and Component level

(continued)

Table 2 (continued)

Criteria	SCORE	1st generation ACS	2nd generation ACS	3rd generation ACS	4th generation ACS
Asset hierarchy	0—Not comply 1—Partial comply 2—Comply	• The asset data attributes and structure have been documented and embedded for the levels of Asset Class, Asset Subclass (if applicable) and Asset Type	• The asset data attributes and structure have been documented and embedded for the levels of Asset Class, Asset Subclass (if applicable), Asset Type and Components	• The asset data attributes and structure have been documented and embedded for the levels of Asset Class, Asset Subclass (if applicable), Asset Type, Components and Failure Modes	• The asset data attributes and structure have been documented and embedded for the levels of Asset Class, Asset Subclass (if applicable), Asset Type, Components, Failure Modes and Causes
Information systems and data quality	0—Not comply 1—Partial comply 2—Comply	• No assessment has been undertaken of the asset information's completeness, quality and normalisation (degree of duplication)	• The first assessment has been undertaken of the asset information's completeness, quality and normalisation (degree of duplication), the information's completeness, quality and normalisation is greater then 80 % and improvement actions have been raised and actioned (if applicable)	• Multiple assessments has been undertaken of the asset information's completeness, quality and normalisation (degree of duplication), the information's completeness, quality and normalisation is greater then 90 % and improvement actions have been raised and actioned (if applicable)	• Business-as-usual assessments are being continually undertaken of the asset information's completeness, quality and normalisation (degree of duplication), the information's completeness, quality and normalisation is greater then 95 % and improvement actions have been raised and actioned (if applicable)
Accuracy of condition assessments and fault/defect history	0—Not comply 1—Partial comply 2—Comply	• Limited condition information, or fault/defect history spanning the lesser of one year or 10 % of the assets expected life	• One condition assessment, or fault/defect history spanning the lesser of two years or 20 % of the assets expected life	• Two condition assessments separated by the greater of one year or 5 % of the asset's expected life, or fault/defect history spanning the lesser of four years or 40 % of the asset's expected life	• Three condition assessments each separated by the greater of one year or 5 % of asset's expected life, or fault/defect history spanning the lesser of eight years or 80 % of the asset's expected life

(continued)

Table 2 (continued)

Criteria	SCORE	1st generation ACS	2nd generation ACS	3rd generation ACS	4th generation ACS
Level of service (LoS) definition	0—Not comply	• LoS (detailed understanding of user/stakeholder requirements of asset) not defined	• LoS (detailed understanding of user/stakeholder requirements of asset) defined for the Asset Class or Asset Subclasses (if applicable)	• LoS (detailed understanding of user/stakeholder requirements of asset) defined for categories within the Asset Class or Asset Subclasses (if applicable) based on their impact on the Asset Management Objectives	• LoS (detailed understanding of user/stakeholder requirements of asset) defined for categories within the Asset Class or Asset Subclasses (if applicable) based on their impact on the Asset Management Objectives and effects of LoS changes on Asset Management System targets understood
	1—Partial comply				
	2—Comply				
Knowledge of criticality	0—Not comply	• The Asset Criticality has been determined for the Asset Class/Subclass	• The Asset and Network Criticality has been determined for the Asset Class/Subclass	• The Asset and Network Criticality has been determined for the Asset Class/Subclass and Asset Types	• The Asset and Network Criticality has been determined for the Asset Class/Subclass, Asset Types and Components
	1—Partial comply				
	2—Comply				
Depth of risk assessment	0—Not comply	• Risk assessment is one dimensional. E.g. assessment considers the Asset Class or Asset Classes (as applicable) as a whole	• Risk assessment is two dimensional. E.g. assessment considers the Asset Class or Asset Classes (as applicable) and the Asset Type	• Risk assessment is three dimensional. E.g. assessment considers the Asset Class or Asset Classes (as applicable), the Asset Type and the asset location	• Risk assessment is four dimensional. E.g. assessment considers the Asset Class or Asset Classes (as applicable), the Asset Type, the asset location and the asset age
	1—Partial comply				
	2—Comply				
Group analysis	0—Not comply	• The Asset Class' impact on applicable Asset Management System targets is understood at the Network level	• The Asset Class' impact on applicable Asset Management System targets is understood at the Group level	• The Asset Class' impact on applicable Asset Management System targets is understood at the Route level	• The Asset Class' impact on applicable Asset Management System targets is understood at the Strategic Route Section level
	1—Partial comply				
	2—Comply				

(continued)

Table 2 (continued)

Criteria	SCORE	1st generation ACS	2nd generation ACS	3rd generation ACS	4th generation ACS
Life cycle modelling	0—Not comply 1—Partial comply 2—Comply	• The Life Cycle Model uses assumptions based on the design life (or field experience if unknown), historical performance and historical maintenance spending	• The Life Cycle Model uses assumptions based on one condition assessment and historical asset performance and historical maintenance spending	• The Life Cycle Model uses assumptions based on two condition assessments, historical asset performance and historical maintenance spending. Comparisons with previous predictions of asset condition and failure rate used to fine-tune assumptions	• The Life Cycle Model uses assumptions based on three or more condition assessments, historical asset performance and historical maintenance spending, and detailed modelling of deterioration drivers. Comparisons with previous predictions of asset condition and failure rate used to fine-tune assumptions
Planning period	0—Not comply 1—Partial comply 2—Comply	• Less than 30 % of the Annual Works Plan associated with this Asset Class, was either not completed or changed, during the previous financial year	• Less than 20 % of the Annual Works Plan associated with this Asset Class, was either not completed or changed, during the previous financial year	• Less than 10 % of the Annual Works Plan associated with this Asset Class, was either not completed or changed, during the previous financial year	• Less than 2 % of the Annual Works Plan associated with this Asset Class, was either not completed or changed, during the previous financial year

Scores are independently verified by Asset Management Systems and Compliance (AM&S).

Some Criteria met for **all** or some of the assets in the ACS (Partial Comply)	**All** criteria met for **all** assets in ACS (Comply)
No criteria met for **all** assets in ACS (Not Comply)	**All** criteria met for **some** assets in ACS (Partial Comply)

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Inequality Indices Based on the Notion of Shannon-Entropy for the Assessments of Industrial Fleets

Vicente Gonzalez-Prida, Marcos E. Orchard, Carmen Martin, Adolfo Crespo and Andrés F. Soto

Abstract The state-of-the-art related to reliability, availability and maintainability (RAM), provides indices that allow to effectively measuring different attributes on single complex assets. However, those methodologies usually present limitations when the aim is to analyse grouping maintenance or the remaining useful life in fleets of assets. The purpose of this contribution is to suggest the advantages of measures based on the notion of Shannon entropy, applied to fleet RAM analysis. Particularly, this research presents a derivation from well-known concepts such as the Gini, Hoover, and Theil indices.

1 Introduction

The isolation of failure causes is usually based on the comparison of the reliability conditions among different pieces of equipment. However, the impact of failures on industrial assets does not necessarily follow an independent nature, and fault events can exhibit sometimes symptoms closer to an epidemic behaviour on a fleet that was already launched to the market and in operation, because an asset is not isolated from the context in which it is being used. Therefore, the study of heterogeneities in

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terms of the reliability of an industrial asset fleet can present the following considerations: Differences in reliability conditions among different groups of the same asset, Disadvantaged groups (older equipment) have a shorter life cycle and present lower availabilities than the more advantaged ones (new assets) and Groups undergoing worse operating conditions present not only a higher unavailability, but also experience a lower performance. From the notion of Shannon entropy, this contribution presents an application of indices for inequality measures (Gini, Hoover, and Theil index) for the analysis of the availability in fleets of industrial assets. This is in order to make possible comparisons among fleets operating under different boundary conditions and usage profiles, in terms of availability and performance. However their availability has certain dependence among the components since they belong to the same system. This aspect is clarified throughout the document.

2 Brief Literature Review

Prognostics and Health Management (PHM) is gaining importance among researchers and practitioners, since it enables predicting the remaining life span or remaining useful life (RUL) of critical engineering assets. Although efforts in this field are significant around the world, real prognostics systems are still scarce in industry (Potes Ruiz et al. 2014). Other knowledge areas (e.g., physic or information theory), have developed tools to provide efficient approaches in order to handle the inherent uncertainty of prognostics that, a priori, is not easy to assure accurately (Jabrouni et al. 2011). Among these approaches, we find the entropy statistics as a suitable theory to analyse evolutionary processes over time, to indicate variety in distributions at particular moments in time, and others applications related to industrial organization and innovation studies. Apart from this, collaborative maintenance management and maintainability can take advantage in the industrial context using approaches based on indicators and specific attributes (Moreu et al. 2012). This sort of indices (based on the notion of entropy) has, among others, interesting properties: do not vary with scale changes (in our case, the dimension of the fleet), incorporate the dimension of the physical asset performance and are easy to interpret. Maintenance, in reference to fleet, can be implemented on a gradual basis since a fleet can be considered as a distributed system, with components that can be interacting among them (Vujanović et al. 2012). Fleet composed of similar or heterogeneous components can be exploited to acquire knowledge or to find relevant information to be reused. Experts basically can determine whether a situation is replicable by a general approach that provides information on some similar characteristics of the analysed component. This improves our insight into component health and status through the analysis of events such as solicitation responses or program participation. A fleet considered as a distribution of complex assets can be observed as an evolutionary system where entropy statistics are applicable to analyse its processes over time (Vujanović et al.

2012; Shannon 1948). With this purpose, it is possible to obtain information on the status of the fleet components that can help managers to update (for instance) the conditions of real-time maintenance service, the current monitoring process, or even considering decision variables in the process of end-of-life dismantling (Godichaud et al. 2011). In a particular case, it is also possible to compare different fleets, with different characteristics in terms of reliability, availability, and maintainability (RAM), as well as performance, productivity, monetary value, cost, operation profile etc. In consequence, it can be possible to obtain a flexible maintenance plan (Ojanen et al. 2012). Consequently, fleet behaviour can show reliable indicators of a component health status, considering the collaborative assessment of their health by its neighbouring components (Potes Ruiz et al. 2013).

3 Theoretical Development

3.1 Shannon Entropy and Related Indices

(a) The Shannon Entropy

As defined by Shannon in 1948, entropy expresses the expected information content according to the uncertainty of a probability distribution. Let p_i be the probability of an event E_i to occur, and let there be n events with their corresponding probabilities $p_1, \ldots, p_n$ adding up to 1 (from the n possible events, at least one takes place). Shannon (1948) proposed a logarithmic function $h(\cdot)$ to express a measure of the information associated with an event E_i; incorporating the concept that an event with smaller probability of occurrence yields more information as it is "unexpected":

$$h(p_i) = \ln\left(\frac{1}{p_i}\right) \tag{1}$$

The function $h(\cdot)$ indicates that the lower the probability of an event to occur, the higher the amount of information of a message when the event takes place. The entropy is here defined as the weighted sum of the n information values $h(p_i)$ by their respective probabilities:

$$H = \sum_{i=1}^{n} p_i \ln\left(\frac{1}{p_i}\right) \tag{2}$$

In addition to this concept, Theil in 1972 remarked that the entropy concept, in this regard, is similar to the variance of a random variable. The main difference is that entropy applies to qualitative rather than quantitative values and, as such, depends exclusively on the probabilities of possible events. Considering S_g

as a subset of events, the probability that an event falling under S_g (where g = 1, …, G) is obtained by:

$$P_g = \sum_{i \in S_g} p_i \tag{3}$$

The entropy at that level of information is then:

$$H_0 = \sum_{g=1}^{G} P_g \ \ln\left(\frac{1}{P_g}\right) \tag{4}$$

Consequently:

$$H = H_0 + \sum_{g=1}^{G} P_g H_g \tag{5}$$

where

$$H_g = \sum_{i \in S_g} \frac{p_i}{P_g} \ln\left(\frac{1}{p_i/P_g}\right) \quad g = 1, \ldots, G \tag{6}$$

H is a measure of the information content being $H \geq H_0$ because both P_g and H_g are non-negative. It means that after grouping there cannot be more entropy (uncertainty) than before grouping the events in disjoint subsets. The mathematical development and the properties application are described in depth in references (Theil 1972). In information theory, this theorem is interpreted as follows: If the first set of events takes place, then, its expected information content is H_0. The subsequent events will occur with expected information content as H_g. Therefore, the total information content results $H_0 + \sum P_g H_g$.

(b) The Shannon Diversity Index

In biology, a diversity index is a mathematical measure of species diversity in a community (Agrawal and Gopal 2013). This concept is usually applied with terms like richness or relative abundances. The Shannon diversity index applied by biologists usually presents the following structure:

$$H = \sum_{i=1}^{S} (-P_i \ln P_i) \tag{7}$$

where the following variables are considered: Shannon diversity index (H), fraction of the entire population made up of species I (P_i) and amount of species encountered (S). This index means that the higher is the value of H, more diverse is the community and abundance of the species (Das et al. 2012).

(c) The inequality indices:

Other authors (Gini 1936; Shannon 1948; Theil 1972) also propose different formulations for inequality (diversity) indices such as:

- Gini Index:

$$G = 1 - \sum_{k=1}^{n-1} (X_{k+i} - X_k)(Y_{k+i} - Y_k) \tag{8}$$

where the following variables are considered: Cumulative proportion of the population variable (X) and Cumulative proportion of the income variable (Y). The Gini coefficient is based on the Lorenz curve. It is mathematically defined as the cumulative proportion of total income obtained by the cumulative proportions of the population.

- Hoover Index:

$$Hv = (1/2) \sum_{i=1}^{n} |p_i - w_i| \tag{9}$$

In this expression, p_i and w_i correspond to the relative variables $p_i = E_i/E$ and $w_i = N_i/N$, where are consider the following variables: Effect in class i (E_i) and Amount of items in class i (N_i)

- Theil Index:

$$T_{sym} = (1/2) \sum_{i=1}^{n} [(p_i - w_i) \ln(p_i/w_i)] \tag{10}$$

In this case, the difference between p_i and w_i is multiplied by a factor of relative contribution referred to each class. This expression corresponds to the Symmetric Theil index, which can be partitioned in two components:

$$T_{sym} = (1/2)(T_T + T_L) \tag{11}$$

where

$$T_T = \sum_{i=1}^{n} [p_i \ln(p_i/w_i)] \tag{12}$$

$$T_L = \sum_{i=1}^{n} [w_i \ln(w_i/p_i)] \tag{13}$$

Summarizing, Hoover and Theil indices are also inequality indices as Gini coefficient. However, Hoover and Theil refer to different measures. But, only the

Theil index is based on Shannon entropy, and can be partitioned into components. This index can also be normalized to a range from 0 to 1 by the expression:

$$T_{Norm} = 1 - \exp(-T). \tag{14}$$

3.2 Approach to the Life Cycle of Industrial Assets

Quantifying diversity (in biology) or inequality (in econometrics) can be an important tool for engineering managers and your industrial assets. For that purpose, it is intended now to adapt the above mentioned expressions into variables related to availability and productivity over a population (or a fleet) of assets. These expressions will be useful, for instance, in order to make comparisons of different scenarios where fleets of the same kind of assets present different behaviours. Let consider the following variables for a fleet of industrial assets: Population (N_i), Productivity (p_i) and Unavailability (UA_i). Where i = 1, …, n refers to the different assets classes which are possible to find or group within the same fleet. Now, we will consider these variables in the formulas already commented. The novelty here is the application of variables related to an industrial context, instead of those ones related to econometrics (salary, poverty rate) or biology, fields where this formulation has been already implemented. Therefore, we take the ratio N_i/N and the ratio UA_i/p_i (or its inverse p_i/UA_i) to calculate indices. The decision about which ratio to use is not a trivial matter, especially since it is assumed they will be applied in the expression of the Shannon entropy. Due to the fact that the aim here is to better understand the relationship between availability (or unavailability) and productivity, it has been considered UA_i and pi respectively in order to represent both characteristics. Under these considerations, and using Eqs. (8)–(13), the associated indices result as follows:

- Shannon Entropy:

$$H = \sum_{i=1}^{n} \left(-\frac{(UA_i/p_i)N_i}{\sum_{i=1}^{n}((UA_i/p_i)N_i)} \ln\left[\frac{(UA_i/p_i)N_i}{\sum_{i=1}^{n}((UA_i/p_i)N_i)}\right] \right) \tag{15}$$

- Gini Index:

$$G = 1 - \frac{\left(\sum_{i=1}^{n} G_i\right) / \left(\sum_{i=1}^{n} N_i\right)}{\sum_{i=1}^{n}(UA_i/p_i)} \tag{16}$$

- Hoover Index:

$$Hv = (1/2)\sum_{i=1}^{n}\left|\frac{(UA_i/p_i)N_i}{\sum_{i=1}^{n}((UA_i/p_i)N_i)} - N_i\bigg/\left(\sum_{i=1}^{n}N_i\right)\right| \tag{17}$$

- Theil Index:

$$T_{sym} = (1/2)\sum_{i=1}^{n}\left[\left(\frac{(UA_i/p_i)N_i}{\sum_{i=1}^{n}((UA_i/p_i)N_i)} - N_i\bigg/\left(\sum_{i=1}^{n}N_i\right)\right)\ln\left(\left(\frac{UA_i/p_i}{\sum_{i=1}^{n}(UA_i/p_i)}\right)\bigg/\left(N_i\bigg/\left(\sum_{i=1}^{n}N_i\right)\right)\right)\right] \tag{18}$$

As shown, the ratio from which all other indicators are calculated is [unavailability]/[productivity]. The reason is to find a strong correlation between the indices and the problem to solve. In other words, the indices should provide appropriate engineering interpretation in the application context. Therefore, with the proposed ratio is clear that lower values are more interesting if what desired are a high productivity and/or low unavailability. Also, if the ratio is based on the assets productivity (instead of economic parameters, for instance), it is easier to interpret and relate the obtained values with maintenance policies.

4 Conclusion

Throughout this document, we have briefly depicted the Shannon entropy, as well as inequality indices such as the Gini, Hoover, and Theil index. They are successfully applied in other knowledge areas as thermodynamics, statistics, biology or econometrics. This paper has intended just to approach such concepts to the physical assets management, in order to find practical and useful applications. The paper is at this stage limited to be purely conceptual and theoretical. However, potential application of the suggested measures could be for example: (i) fleet of mining trucks where productivity is evaluated by the number of tonnes transported per year, thus, the ratio provides a view of the unavailability effect in the fleet at a certain age, with respect to the amount transported; (ii) second-hand car markets where comparing inequality indices enables to detect how the higher is the equality, the easier the foreseeing of the RUL of the physical assets in operation and, as a consequence, the worthwhileness of one fleet in front of the other one. As future research lines, it is proposed to develop more elaborated indices that simplify the choice of preferences from individual or fleet attributes. These new indices can be translated from other fields or by the application of a conjoint analysis.

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Availability Simulation Based on Pseudo-random Failure Rates: A Case Study on Industrial Process

V. González-Prida, L. Barberá, A. Crespo and A. Guillén

Abstract The main objective of this paper is to analyse the availability of different possible configurations for an industrial facility which provides loading and unloading services of LNG (Liquid Natural Gas) at the quay of a plant. Specific service availability is calculated with the support of OREDA database and applying random values for failure rates, which have been obtained from the mean failure rate and standard deviation provided by the mentioned database. As an additional objective, this paper shows a sensitivity analysis for service availability modifying the reliability of involved elements, which helps for example to review the physical stock structure or to readapt maintenance policies in the plant.

1 Introduction

Nowadays, there are many simulation methods that allow us to consider important aspects of the system operation like redundancies, standby nodes, preventive maintenance, repairing priorities etc. (Gonzalez-Prida et al. 2008). Simulation methods are used to assess whether a system fulfils certain availability and reliability requirements, offering realistic estimations that could be expected from the system under study (Crespo and Iung 2007). The complexity of such methods sometimes causes the decision maker reluctance to use them. Therefore, the challenge is not obtaining even more sophisticated software applications (Crespo et al. 2005), but to simplify as possible the calculations in standard data sheets using

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conventional or generic office tools. Following this intention, this paper aims to calculate the service availability of an industrial process system, which will be particularly characterized by the flow of LNG delivered from storage tanks at a regasification facility, to a LNG carrier or tank ship. Furthermore, this research includes as additional targets:

- A sensitivity analysis of the availability of services referred to changes in the reliability of the components of the loading and unloading systems.
- Review the physical stock structure in an industrial plant, regarding the items for loading and unloading (quay and involved equipment for LNG loading and unloading).

The mentioned targets are briefly described in the following pages. With those goals, the paper is structured as follows: Firstly, those elements needed for the calculation of the availability are introduced from the point of view of the quantitative assessment of uncertainty which is involved in the analysis and calculation of the availability. Secondly, the procedure for availability calculation is depicted. It presents therefore theoretical considerations underlying the calculations performed later. Next, it describes the scenario where the case study is developed. Once the results are shown, this paper includes a sensitivity analysis where calculations and considerations are particularized for their implementation under different conditions failure rate values. Finally, the paper concludes highlighting the main results of this research, including also some possible future applications.

2 Application of Pseudo-random Failure Rates

2.1 Uncertainty in the Calculation of Service Availability

The quantitative assessment of uncertainty in the calculation of availability (De Rocquigny et al. 2008) involves the following elements (Fig. 1):

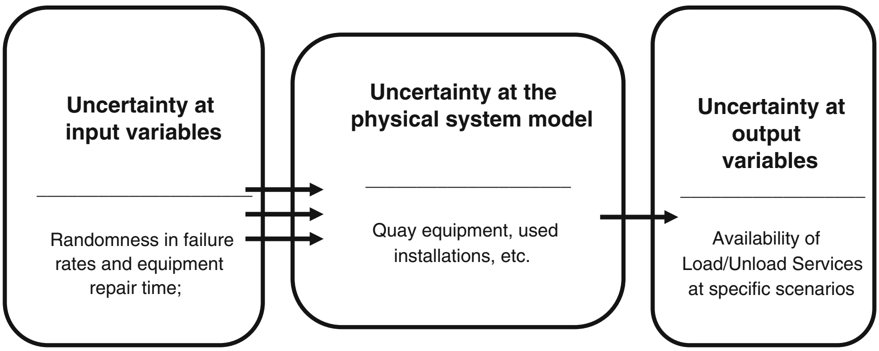

Fig. 1 Items involved in the uncertainty evaluation

According to this scheme, the model represents the physical system behaviour, which in our case study will be the behaviour of those items related to LNG loading and unloading. Particularly, the model for an industrial process system has a certain degree of uncertainty in its design, which decreases as a detailed knowledge of the physical system is acquired. In our case, the model is deterministic in order to calculate availability (as output variable) for a complex system of probabilistic nature. Regarding the uncertainty in the input variables of the model, sometimes it is not possible to obtain sufficient contrasted information on failure rates and repair of equipment considered in the analysis. In this case, this problem is solved using the data base OREDA (Offshore Reliability Data) (SINTEF, 2002). Regarding the uncertainty in the output variable, the availability evaluation for loading and unloading service considers modelling the uncertainty in the output variable of study, for certain modes or scenarios in which the plant operates (Apostolakis 1999). With the above considerations, the study of uncertainty is designed for availability of loading and unloading services within defined risk limits values. The values obtained for the availability of these services will support the subsequent decision making process in the industrial company.

2.2 Application of Pseudo-random Failure Rates

The value of failure rate (λ) is obtained in OREDA by an estimator, using data from multiple different installations. Minimum and maximum values are also given with an uncertainty range of 90 %. As for the Mean Down Time (MDT), it is noteworthy that in this analysis we have used the data provided by OREDA on the "Active Repair Time" to avoid considerations of logistics, inventory etc. This "Active Repair Time" is defined in OREDA as the calendar time required to return the equipment to a state in which it is ready to operate, excluding time to stop the equipment, time spent on work orders, time waiting for materials and parts, start-up time after repair. Considering all the above, it has been assumed in the calculations different analysis in order to observe each system behaviour in reference to its availability. In the case of applying a pseudo-random failure rates, the analysis takes the data related to average failure rate and its standard deviation. With these two parameters, it is possible to calculate the inverse of a normal accumulative distribution. For this calculation particularly, in the case study has been applied a probability associated to the normal distribution as a random number between 0.5 and 0.95. Applying just this formulation is not enough, as far as it could be possible to obtain values under the minimal failure rates provided by OREDA. Therefore, for our case study it has been considered the maximal value between the minimal failure rate provided by OREDA, and the result obtained by the inverse of a normal accumulative distribution. Besides the above commented calculations, it is possible to perform a sensitivity analysis of the complete system. That means that altering data on the components (i.e., penalizing or favouring the hypothetical failure rate), one can observe how the different systems and subsystems behave.

3 Case Study

3.1 Scenario

Regarding the system to be analysed, the following subsystems are considered as indispensable for the unloading service: Drainage tank, Hooks and winches system, Common systems, Active-passive safety. On the other hand, the not-indispensable subsystems are the following ones: Instrumentation associated with the unloading line, Safety valves, Ship approaching system, Auxiliary systems. The mentioned categorization was decided in agreement with the industrial plant experts who depicted the availability of providing such a service even under extreme conditions. Figure 2 illustrates the diagram for LNG ship unloading. According to the items involved in the uncertainty evaluation (Sect. 2), model inputs are here the failure rates λ_i of each component from the mentioned subsystems, as well as their Mean Down Time, MDTi or active repair time. These inputs may take different values for each simulation. Fixed inputs also exist, which correspond to those hypotheses considered constant for the performance of the simulations. Furthermore, for the calculation of availability A, we apply the formulation shown in Table 1. Therefore, our model is defined by the following function:

$$\mathrm{Ai} = 1 - \mathrm{UA_i} = 1 - \mathrm{MDT_i}/(\mathrm{MTBF_i} + \mathrm{MDT_i}); \quad \text{where: MTBFi} = 1/\lambda_i$$

Therefore, using as a direct source for uncertain input data, the values provided by OREDA, we will make two calculations:

- With mean failure rate and MDT;
- With random values for failure rate obtained from the mean failure rate and standard deviation provided by the database and mean MDT.

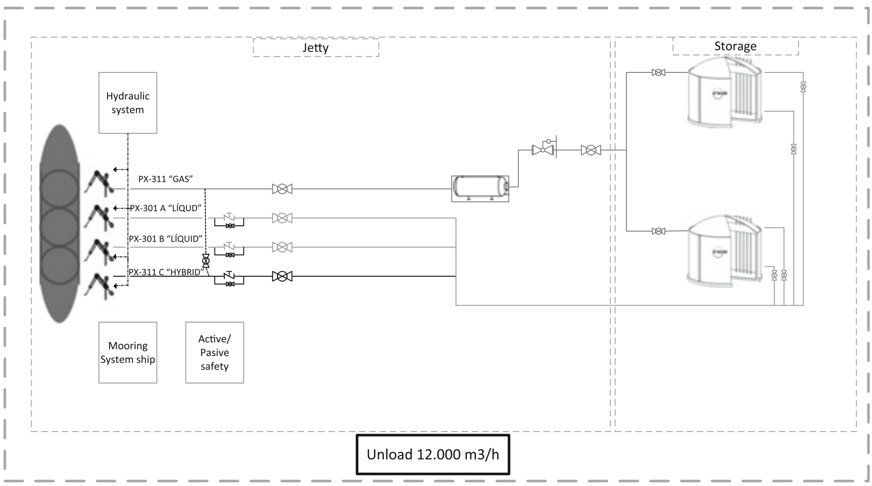

Fig. 2 Diagram for LNG ship unloading at 12,000 m^3/h

Table 1 Results for unloading at 12,000 m^3/h

	λ mean	MTBF	MDT	UA	A (%)
Unload system	97.54	0.01025	55.320	0.0053	99.46
Arm assembly	59.47	0.01681	31.226	0.0018	99.81
Nitrogen valve	10.90	0.09174	5.8000	6.3E−05	99.99
Blowdown arm joint	11.50	0.08695	14.200	0.0001	99.98
Valve to arm	18.00	0.55555	3.5000	6.2E−06	99.99
Hydraulic unit	13.87	0.07209	7.0000	9.7E−05	99.99
Drainage tank	17.66	0.05662	6.4000	0.0001	99.98
Hook and winches	0.479	2.08909	1.5588	7.4E−07	100.0
Winches	0.039	25.8553	7.9159	3.0E−07	100.0
Hook remote desk	0.440	2.27272	1.0000	4.4E−07	100.0
Active-passive safety	27.81	0.03595	12.254	0.0003	99.96
Common systems	244.50	0.00408	57.008	0.0137	98.62
Complete system	387.99	0.00257	130.329	0.0481	95.18

In both cases, the opinion of experts in the plant has been considered in order to distribute functionally the elements, following a series-parallel configuration so it has the most realistic and possible behaviour. The above calculations (analytical calculation using mean failure rates and random failure rates), are applied to an unload mode of 12,000 m^3/h, as far as the quay of the industrial company under study is designed to operate in this scenario. In that case, our variable of interest (plant availability) will be quantified.

3.2 Calculations

In order to calculate the availability in this mode, it has been taken into account some general considerations in the operation mode (for example, the case of systems consisting of "n" identical subsystems in parallel where the system is considered to fail if "m" or more subsystems fail). In addition to this, it has been also considered the calculation of failure rate and active repair time for different configurations of the arms in the quay. Applying the mean failure rates that provide the database OREDA, the following results are obtained (Table 1). On the other hand, considering the same mean failure rate and the standard deviation also provided by OREDA, it is possible to obtain a pseudo-random value for λ from the inverse function of the cumulative normal distribution for the specified mean and standard deviation. In this function, the probability associated to the normal distribution is a random number between 5 and 95 %, as commented on Sect. 2. With these values for λ and performing 100 simulations, results are obtained and shown in the value histogram and the distribution function for the availability of our case study scenario, with an operation mode according to the unloading service at 12,000 m^3/h (Fig. 3).

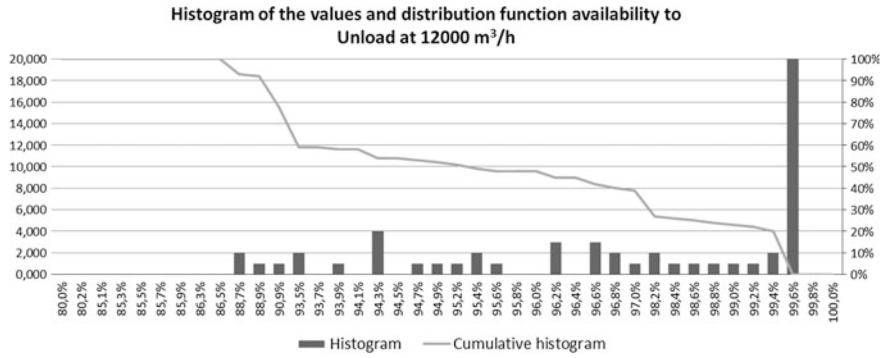

Fig. 3 Histogram and distribution function for availability in unloading service at 12,000 m^3/h

Table 2 Comparison chart of availabilities in the unloading service

	Λ	MTBF	MDT	UA	A (%)
λ mean	387.99	0.00257	130,329	0.04813	95.187
λ min	8.85	0.11297	125,477	0.00110	99.889
λ max	1334.90	0.00074	128,949	0.1468	85.314

3.3 Results

Table 2 shows a comparative chart with the values obtained for mean failure rates in the unloading configuration of 12,000 m^3/h.

It also adds the result obtained replacing the value of the mean failure rate, by the minimum and maximum which are also provided by OREDA data base. In the same way, by matching these results with experts' opinion (industrial company), it results that maintenance policies in the plant approach its behaviour in the case of a lower failure rate (in terms of availability).

4 Sensitivity Analysis

4.1 Clarifications

The stage of sensitivity analysis classifies the system availability according to the importance of a variation in the input variables (Saltelli et al. 2004). In other words, this study analyses the importance of different uncertain input variables in reference to a given quantity of interest in the output (in our case, the system availability). In this model for our case under study, sensitivity analysis provides the ability to assess the impact on the availability, varying input values in the applied deterministic mode, resulting this method suitable as a tool that makes easier the decision making process.

These changes eventually fall to the decision maker, which may require, for example, higher reliability on a given load or unloading system, whose specifications show that they can play a key role with respect to a final choice.

4.2 *Application to the Case Study*

In the present analysis, once obtained the expressions that relate the RAMS variables of components, we proceeded to provide a quantitative assessment with the help of the database OREDA. With this quantitative assessment, it is possible to observe the availability of subsystems as well as for the entire system, achieving overall results shown later in this section. The results obtained in terms of subsystems, allow establishing a ranking from higher to lower availability under certain assumptions and boundary conditions, which would allow (together with a reliability analysis) the possibility of making a preliminary list of recommended spare parts. Although this paper has been focused on the availability calculation of a system with one specific operating mode (unloading service at 12,000 m^3/h) from this research is also possible to obtain other interesting results as those ones from the case of a sensitivity analysis. In this sensitivity analysis, performing variations in failure rates allow us to observe how the availability of the complete system varies, so it is possible to rank subsystems according to this effect on the output variable. Figure 4 shows an example of spreadsheet with our specific operating mode, considering the calculation of mean failure rates. In that exercise, one of the subsystems is altered each time improving 10 % in the respective failure rate percentage, which can be indicated in green cells. With this procedure, each time we obtain a certain (and different) value for the total availability. Proceeding in this way, it is possible to obtain a ranking that illustrates where is appropriate to improve maintenance policies if the goal is to increase the availability of the plant for a given operating mode.

	λ MEAN	MTBF	MDT	UA	A
UNLOAD 12000 y λ MEAN	387,9948737	0.002577354	130,3298173	0.048133328	95,187%

UNLOAD SYSTEM	0%
DRAINAGE TANK	0%
HOOK AND WINCHES	0%
ACTIVE PASSIVE SAFETY	0%
COMMON SYSTEMS	0%

	SYSTEM λ	MTBF	MDT	UA	A
complete system	387,9948737	0.002577354	130,3298173	0.048133328	95,187%

Fig. 4 Spread sheet example for sensitivity analysis in unloading service

In other words, if every time is reduced by 10 % the failure rate of a particular subsystem, and leaving the rest equal, we obtain the following availability for the operation of unloading service at 12,000 m^3/h (it is ranked from highest to lowest availability obtained):

- Common systems: 0.954766
- Unload system: 0.953029
- Active passive safety: 0.952202
- Drainage tank: 0.952079
- Hook and winches: 0.951850

With these results, it is easy to observe how decreasing the failure rate of common systems; it is possible to obtain a higher improvement in the entire system availability.

5 Conclusions

Throughout this paper, we have described a case study where an availability analysis has been applied, considering pseudo-random failure rates for its calculation, as well as a sensitivity analysis in order to detect elements or subsystems where an improvement in its maintenance policies may cause an increment in the availability of the whole system. It is important to notice that failure rates come from a database (OREDA) that considers a steady state of operation and normal elements. Therefore, results must be seen as an approach. That is reason why this analysis is mainly a good starting point in the understanding of the systems behaviour regarding its availability (Gonzalez-Prida and Crespo 2014). Thus, the more experience and detailed knowledge on the systems, the more refined could be considered the analysis and more adjusted to reality, using historical data of the plant itself, which will allow providing more particularized and accurate conclusions.

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Standards as Reference to Build a PHM-Based Solution

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Abstract PHM (Prognostics and Health Management) is key factor for reaching more proactive maintenance models. Its applicability depends, among others, on the development of general methodological approaches to guide the design process of new maintenance strategies where the potential of PHM can be exploited. Despite there are few specific standards that treat PHM is possible to use current standards of maintenance and diagnostic as the bases of the development of this general methodologies. This paper offers a revision of some of the available standards that can serve as guidelines to develop such solutions including a proposal of methodology to design and implement PHM solutions that combines current standards.

1 Introduction

Under the term of PHM (Prognostics and Health Management) a body of knowledge is included that nowadays is considered as an engineering discipline (Cheng et al. 2010). This covers all methods and technologies to assess the reliability of a product in its actual life-cycle conditions to determine the advent of failure, and mitigate system risks (Haddad et al. 2012). PHM is fundamental in today evolution of maintenance function. PHM, along with other trends like e-maintenance—term that serves as conceptual support to general use and applications of ICTs in maintenance—appear as the key factors in achieving higher maintenance efficiency levels and the life cycle cost reduction (Lee et al. 2006). Example of current and future importance of PHM (Cheng et al. 2010) the U.S. Department of Defense (DoD) 5000.2 policy document on defense acquisition, which states "program managers shall optimize operational readiness through affordable, integrated, embedded diagnostics and prognostics, embedded training and testing, serialized item management, automatic identification technology, and iterative technology refreshment". This points out to a new generation of CBM application based on

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PHM skills. It is sometime referred as CBM/PHM maintenance solutions (Vachtsevanos et al. 2006).

PHM technology is still very much in its infancy (Sheppard et al. 2008). So in many sense PHM systems have yet to be discovered or developed. Among others development, general methodological approaches have to be proposed to guide the design process of new maintenance strategies where the potential of PHM can be exploited. Despite there are few specific standards that treat PHM, owing to the close ties between PHM and traditional diagnostic and maintenance issues is possible that current standards of maintenance and diagnostic can be applied to PHM as the bases of the development of this general methodologies. In this sense standardization of PHM elements is one of the main interesting development lines in this research field. This paper offers a revision of some of the available standards that can serve as guideline and information sources to develop such general methodologies. The aim is to present a practical way to combine information from different standards as base of this development.

2 On the Role of PHM in Maintenance Evolution. The Necessity of Methodological Proposals

Nowadays maintenance concept is suffering a revolution. Firstly, maintenance becomes more and more part of the integrated business concept (Crespo 2006). So the competitiveness requirements that are been imposed over companies are been translated to harder demands over maintenance results: lest maintenance costs, more reliability levels and life-cycle extension. Other hand, the technological development has introduced new challenges and opportunities for maintenance performance. Challenges mainly come from the necessity to deal with new complex and engineering system (Jardine et al. 2006). Other aspect to consider is the large number of new technologies that are being introduced. These opportunities are related with new capabilities that are possible to incorporate to maintenance function as consequence of new technologies apply to maintenance. So, in this scenario is possible to change the maintenance models through ICT (Information and Communication Technologies) and PHM skills, providing more proactive maintenance models.

Design and implementation of PHM-based solutions are very complex tasks. Mainly owing to great level of interaction between the various technical disciplines that make up PHM solutions. So, despite the benefits that can be achieved, this complexity imposes significant entry barriers, both from technological and economical views (Guillen et al. 2014). General methodological approaches have to be proposed to guide the design process of new maintenance strategies where the potential of PHM can be exploited. This is one of the current gaps that must be addressed to extend the PHM application. Despite the lack of an accepted general methodology there is a lot of background and information that can be used as starting references. The problem is how to combine and use all these references in an orderly manner. Summarizing, it is possible to classify this references in three types:

1. Frameworks for maintenance design. There are different frameworks and methodologies to organize maintenance management in an industry, facility or system. The most important reference is the RCM and its posterior evolutions as the RCM II (Moubray 1997). Others interesting approaches have been exposed by Waeyenbergh and Pintelon (2002) or Crespo (2006).
2. Standards. The standards analysis is the main point of this paper. It will be treated in sections below.
3. PHM technical frameworks. Finally, a lot of references in the specialized literature of PHM introduce frameworks to help PHM system developers and integrators for faster system development and deployment. These frameworks address the problem of implementing a PHM solution from a technical point of view, but not the maintenance management issues.

3 Standards Related with PHM Applications. Classification and Practical Use Proposal

Standards are needed for harmonized terminology, consistency of the PHM methods and tools, and compatibility and interoperability of PHM technology. Standards also help provide guidance in the practical use and development of PHM techniques (Mathew 2012). Within the standards that can be related to the treatment of PHM solutions, there are references from different international organization. The main organizations are:

- International Organization for Standardization (ISO)
- Machinery Information Management Open Standards Alliance (MIMOSA)
- International Electrotechnical Commission (IEC)
- Institute of Electrical and Electronics Engineers (IEEE)
- Others: SAE, United State Army (US army) and the Air Transportation Association (ATA).

The proposed analysis in the sections below is focussed, mainly, on ISO and IEC standards, which are the most internationally accepted and, in many cases, the more known standards, especially in industrial sector. The aim of this paper is not to list the standards exhaustively but to introduce how is possible to combine different standards in appropriate way to support the complicated process of develop a PHM-based solution and its integration within maintenance function. For more comprehensive review of current available standards the following references are recommended by the authors: Sheppard et al. (2008), Vogl et al (2014) and Mathew (2012). Classification of the analysed standards according with technical fields of PHM solutions.

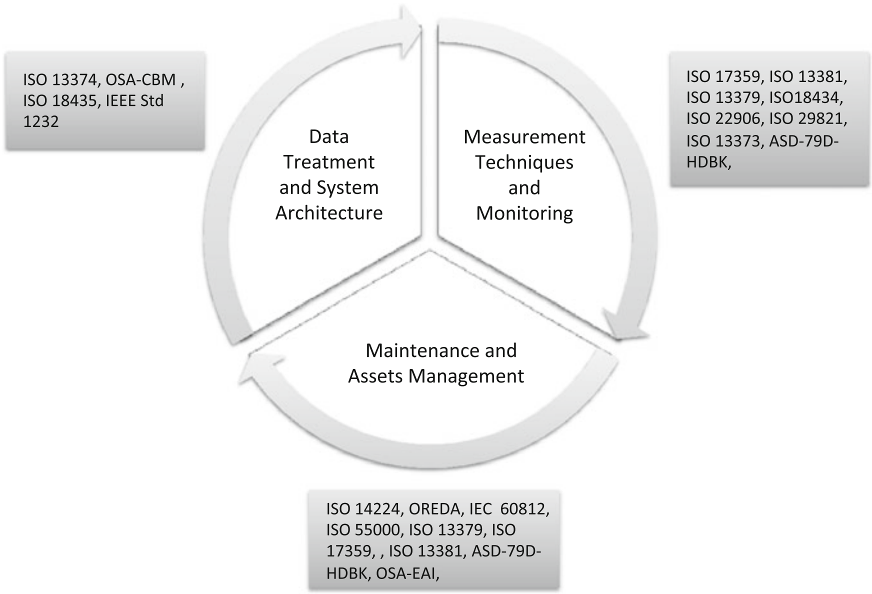

Fig. 1 Technical fields involved in PHM-based solution design/implementation and some of standards related

There are three technical fields that must to be combined in any PHM application (Fig. 1).

Data treatment and system architecture. The aim of this field within PHM-based solution is to provide the logical support (software, application, data bases) and physical support (hardware, communications) to be able implement and use this solution (Vatchevanos 2006). It is necessary to deal with the problem of compatibility between different technologies, integrating a wide variety of software and hardware components (MIMOSA 2012). This type of solutions implicitly includes a complete process, from the capture of the raw data up to the utilization of the information obtained within decision-making (maintenance, logistics, equipment design, etc). This process has been well depicted by ISO 13374, standard that has been adopted by other as OSA-CBM and ADS-79D-HSBK.

Measurement techniques and monitoring. PHM solutions require monitoring a large number of product parameters to evaluate the health of a product (Cheng et al. 2010). These parameters include operational and environmental loads as well as the performance conditions of the product, for example, temperature, vibration, shock, pressure, acoustic levels, strain, stress, voltage, current, humidity levels, contaminant concentration, usage frequency, usage severity, usage time, power, and heat dissipation. There are specific standards for every specific measurement technique. These standards help to use and harmonize the results of the concerned technique and facilitate the integration of its results within maintenance.

Maintenance and assets management. This area includes specific standards related to maintenance issues and the standards that address the functional conception of the system and the relation with the rest of the business. Also is possible to connect the aims of PHM solution with of asset management strategies and with rest of business areas and the business general aims (ISO 55000). This approach aids to make the cost-benefit analysis of this PHM solutions, whose profitability has to be evaluated considering the impact along the entire life-cycle of concerned assets, value management consideration and cost-risk-benefit analysis.

3.1 Proposal for a Practical Combined Use of Standards for a PHM-Based Solution

This section shows how is possible to propose a general methodology for design PHM solutions for maintenance with the supporting of the interpretation of different available standards. In Fig. 2, the flowchart proposed is depicted jointly with the corresponding phases of the schema of the ISO 17359. This standard is one of the main industrial references for the design of condition monitoring program, so this element has been included in the schema in order to aid to understand the relation of these PHM techniques with the classical view of condition monitoring in the industry. The figure also includes the standards that can be used as reference in each specific phase.

ST1. The first step is the definition of the indenture levels, from plant or installation levels to the maintainable items and the description of operational contexts.
ST2. Criticality analysis is made to choose the most important systems within the installation, plant or business that are being studied. The criteria use in this phase allows to interpret the business aims in order to connect with this aims the rest of the decision.
ST3. The two main outputs of the RCM analysis are the failure mode definition and the election of maintenance activities over every failure mode. In order to do this RCM have to different stages: (i) FMECA, to describe the functional analysis of the system and to establish the failure mode. It also included the evaluation of the relative relevance of the failure mode that have been described; For PHM solution design is convenient to know the functional description of the system, which is provide by FMECA. Other result is the prioritisation of failure modes according its consequences, information that allows choosing the failure modes that are candidates to a PHM application. (ii) RCM logic, to determine the maintenance policies over every failure mode. With the final results of ST4 and ST5 it is possible to define the maintenance actions required by the failure modes that have been decided to control by using PHM solutions.

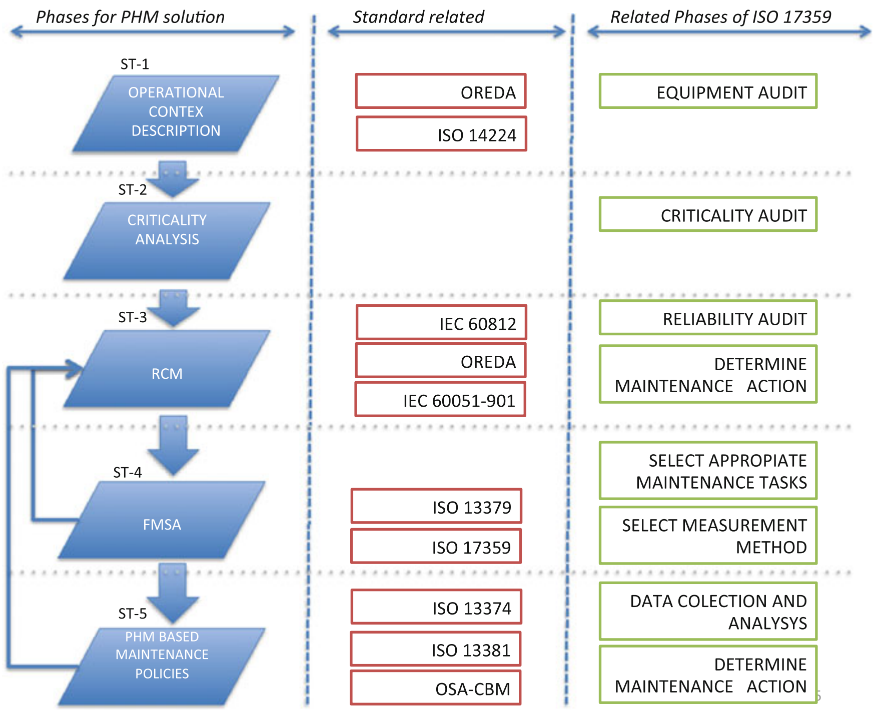

Fig. 2 Practical combined use of a set of standards to build a PHM-based solution

ST4. In this phase the symptoms of the failure are described and the way to obtain measures of this symptoms. A process named Failure Mode Symptom Analysis (FMSA) is performed.
ST5. In this phase, PHM policies, including their algorithms and uses, are designing using the information provides by ST4 analysis. The result of this phase is reintroduced in ST3 to be used in RCM logic to redefine the maintenance plan considerations.

4 Description of Main Analysed Standards

ISO 14424. "Petroleum, petrochemical and natural gas industries—Collection and exchange of reliability and maintenance data for equipment". This standard includes comprehensive basis for the collection of reliability and maintenance data in a standard format for equipment in all facilities and operations within the petroleum, natural gas and petrochemical industries during the operational life cycle of equipment: (i) Data requirements for the type of data to be collected for use in various analysis methodologies. (ii) Standardized data format to facilitate the exchange of reliability and maintenance data between plants, owners, manufacturers and contractors. This standard provides a well-organized reference to interpret the installation/system physical structure (physical tree) correctly. This step is essential to define adequately the indenture levels (IEC 60051-901) and has a critical influence on failure mode definition and description.

IEC 60812. This standard is focused on the reliability technique Failure Mode and Effects Analysis (FMECA). FMECA is a powerful tool deeply used by the industry in various phases of life-cycle management, as a design-phase tool, a support for maintenance planning and also a very useful tool for selecting the best technique for selecting the best monitoring variable or technology. The IEC 60812 is a guide to perform the FMECA analysis, so it has the main guidelines for an FMECA facilitator. The standard is divided into three parts: planning, execution and documentation of the analysis.

ISO 17539 and rest of ISO-TC 108 technical reference of specific measurement techniques. ISO 17359 mainly provides a general process or guide to build a condition monitoring (CM) program. This standard can be understood as general framework for guide the use of a series of ISO standards dedicated to condition monitoring and diagnostics. These main standards are also listed in the ISO 17359 (Table 1)

ISO 13379, **ISO 13381**. These are the more directly related standards to PHM within ISO family. ISO 13379 is focused in diagnosis and ISO 13381 in prognosis. Both use the reference of ISO 17359 to connect their result to CM and CBM. ISO 13379 develops the FMSA process that allows describing the failure modes through its symptoms and them the symptoms through its descriptors. This is the gateway between failure modes, the measurement techniques and the definition of the parameters required by the diagnostic and prognostic algorithms. ISO 13381 presents the main guidelines and aspects to consider in order to perform failure prognostics.

Table 1 Specific ISO standard referred to measurement techniques

Measurement technique	ISO reference
Vibration	ISO 13373-1:2002
	ISO 13373-2:2005
	ISO 16587
	ISO 18436–2
Thermography	ISO 18434-1:2008
	ISO 18436–7
Acoustic emission and ultrasound	ISO 22906:2007
	ISO 29821-1:2011
	ISO 18436–6
Tribology and lubricant	ISO 14830–1
	ISO 18436–5

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Adaptive Transient Event Detection for Industrial Applications

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Abstract Foreign elements may destroy sensitive parts of mobile industrial machines such as harvesters. When such undesired transient events shall be detected, varying machine noise scenarios demand adaptive algorithms that allow for a robust detection performance. Moreover, a detection system that is too responsive reduces the machine's speed of operation. We have evaluated three algorithms that are capable of detecting transient events, and that allow for timely precautionary measures. Two of the methods apply a fixed and adaptive threshold to the short-time energies of the high-pass filtered sensor signal, respectively, while a new method employs linear prediction-based filtering and an adaptive frame-energy threshold, and incorporates the variance of the high-frequency frame content enabling the distinction between events resulting from foreign elements and events originated by the machine. The algorithms were applied to four types of transient events that were combined with a set of machine noise recordings at different signal-to-noise-ratio (SNR) levels. Our results show that the new method provides 95 % correct detections down to a SNR of −1 dB, and that all methods provide a very low rate of misdetected events.

1 Introduction

In the feeding process, harvesting machines can seriously be damaged by foreign elements that are collected together with the crop. To avoid such an undesired failure, a detection system is needed to allow for an early detection of these foreign

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elements, thus enabling an automatic machine stop on time. The objective of this work was to develop an adaptive algorithm that allows for the detection of transient events due to foreign elements based on knock sensor signals. This adaptive algorithm should tolerate potential transients resulting from the cropping process, and thus avoid false alarms.

This paper is structured as follows. Section 2 briefly reviews related work in the field of transient detection. In Sect. 3, we present three algorithms for transient detection which we will experimentally evaluate and compare. The evaluation setup is described in Sect. 4, and the results are presented in Sect. 5. Finally, we conclude our findings in Sect. 6.

2 Related Work

The problem of detecting transients has been explored in various fields. Wang and Willett (Wang and Willett 2000) tested the performance of different approaches to detect transients in noise in the realm of process-monitoring by acoustic emission. The authors have tested the performance of the detection of unknown transient signals in white Gaussian noise. Their results suggest that unsophisticated methods such as “Nuttall’s Power-Law Detector” (Nuttall 1994) give reliable results. As an example for transient detection in the biomedical area, Nenadic and Burdick (2005) tested a spike detection algorithm based on the Continuous Wavelet Transform. Their method allows for nearly real-time performance. In musical signal processing, Masri and Bateman (1996) presented a technique to cope with transient phases in analysis-resynthesis models. Time-scale modification of audio requires the detection and particular processing of transient events, especially if large modification factors are used. Bonada (2000) proposes to detect fast changes and keep them as they are. His system for change detection involves bank filter energies, Mel cepstrum coefficients and their deltas. Verma and Meng (2000) extended spectral modeling synthesis (Serra and Smith 1990) by a model for the transient parts of sounds. Their transient modeling system first analyzes the sinusoidal parts of the sound signal, resynthesizes those components and detects transients based on the energies of the resynthesized signal and the first-order residual signal, i.e. the original signal minus the resynthesized signal. Nsabimana and Zölzer (2007) use a transients plus sinusoids and noise approach. They detect transients by applying a linear prediction error signal and an adaptive threshold based on the envelope. Gnann and Spiertz (2009) use the absolute discrete group delay as a measure to detect transients in sounds. In combination with a maximum order filter, their method works well both on percussive and tonal-percussive sounds. Glover et al. (2001) compare seven algorithms for musical onset detection. These algorithms are based on signal frame energy differences, spectral difference of consecutive frames, a detection function using combined magnitude and phase information, three detection functions that are based on linear prediction, and a method that is based on the differences of peak amplitudes using a sinusoidal model.

3 Transient Detection Algorithms

The aim of this work is to develop a transient detection algorithm that provides reliable detection results in a computationally efficient manner. In this section, we present two variants of a simple transient detection algorithm (SITRA). In the first implementation, a fixed threshold is used, while the second implementation features an adaptive threshold. Then, we introduce a more sophisticated algorithm that incorporates linear prediction-based filtering, an adaptive threshold and the incorporation of the variance of the high-frequency content of candidate frames.

In each of these algorithms, the sensor signal is sampled at 20 kHz and divided into frames of 256 samples that overlap by 50 %.

3.1 SITRA with Fixed Threshold

As a simplest means of transient detection, an algorithm called SITRA (Simple transient detection) has been developed. This algorithm is schematically shown in Fig. 1.

As the machine noise mostly consists of low-frequency energy, the framed sensor signal is high-pass filtered at 200 Hz first (3rd-order Butterworth). Then, the frame energy is calculated. If the energy level exceeds a certain fixed threshold, a foreign element is detected.

An example for this variant of SITRA is given in Fig. 2. The upper plot shows the energy of the filtered sensor signal frames, while the bottom plot illustrates the detected events and ground truth data. The last three events cannot be detected due to their low energy.

3.2 SITRA with Adaptive Threshold

Varying operating conditions require an appropriate degree of flexibility with regard to the threshold level. Hence, we have extended the previous method by introducing

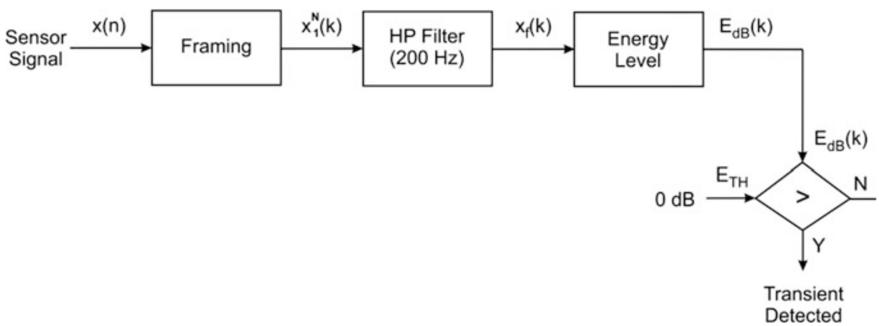


Fig. 1 SITRA block diagram (fixed threshold)

an adaptive threshold which is derived by calculating the median of the previous 20 frame energy levels and adding a fixed threshold offset (10 dB). Again, a transient is detected as soon as the energy level of the actual frame exceeds the threshold. This procedure is depicted in Fig. 3.

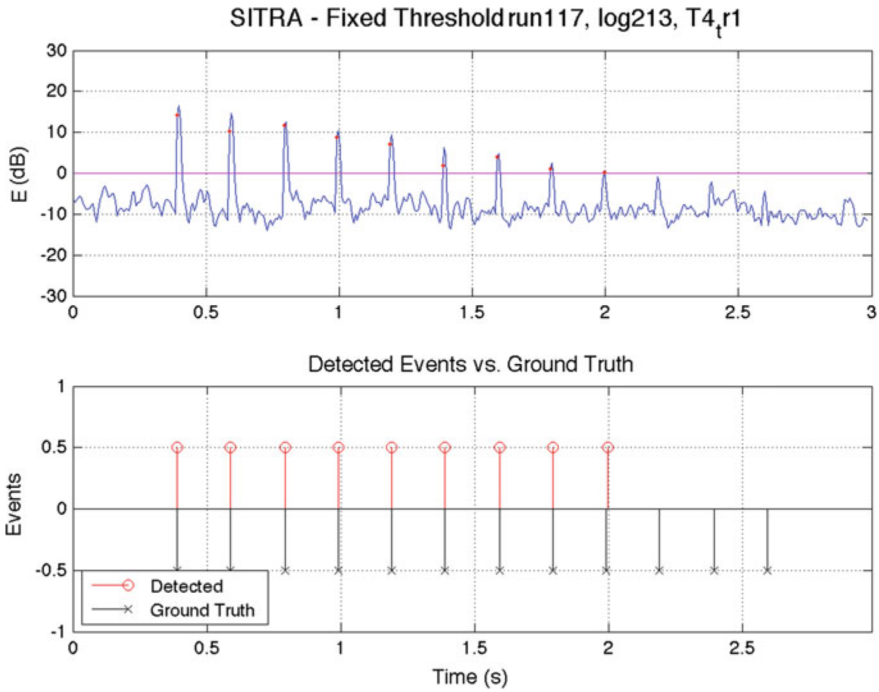


Fig. 2 Example for SITRA transient detection with a fixed threshold

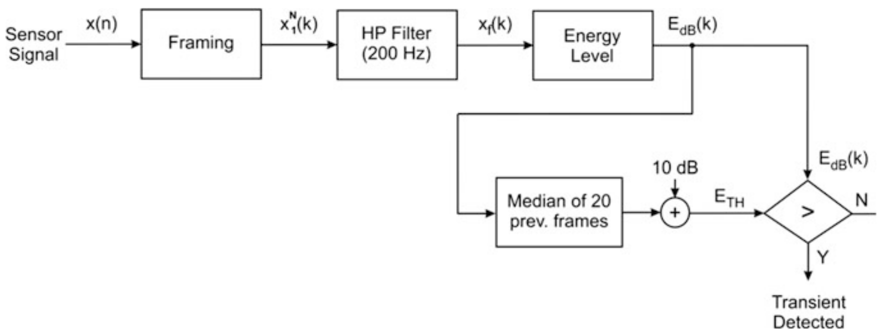


Fig. 3 SITRA block diagram (adaptive threshold)

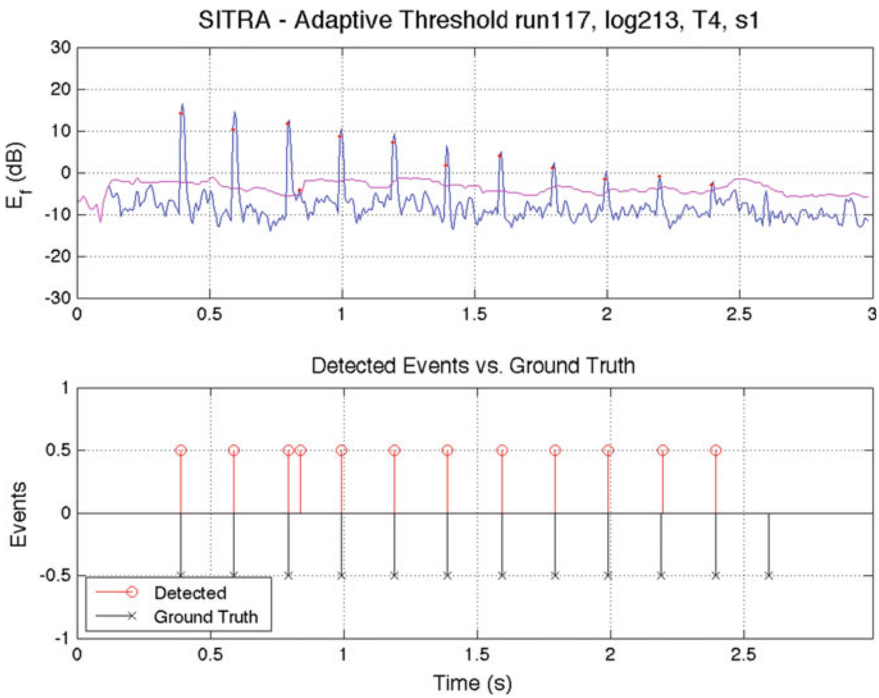


Fig. 4 Example for SITRA transient detection with an adaptive threshold

Figure 4 presents an example of the adaptive version of SITRA using the same signal as before. Again, the upper plot illustrates the signal frame energy, while the bottom plot shows the detected and ground truth events. While this algorithm detects almost all transients, a misdetection occurs after the third event.

3.3 Linear Prediction-Based Method

Except for a certain amount of cropping noise, the spectral characteristics of the harvester machine noise usually remain stable within a certain operation mode. Therefore, we utilize linear prediction (LP), (Makhoul 1975), to remove this kind of noise as illustrated in Fig. 5.

First, the input sensor signal is windowed, the LPC-coefficients $A(z)$ are calculated using the model order of 128, and the frame is FIR-inverse-filtered by directly applying $A(z)$. This results in a residual signal in which the machine noise has been removed to a great extent. In the next step, the signal frame energy is calculated and a threshold $E_{TH}(k)$ is derived based on previous energy values as described in the following.

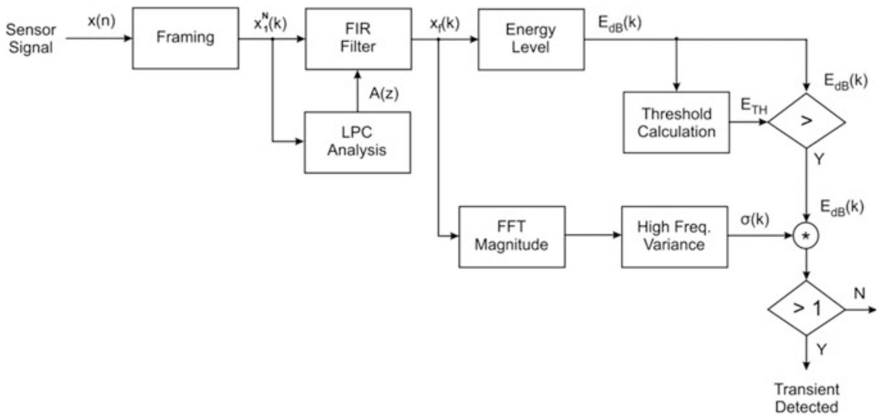


Fig. 5 Block diagram of the LPC-based transient detection algorithm. The calculation of the threshold energy is described in the text

As a basis, the median of the frame energy levels of the previous 20 frames (including the current), $\tilde{E}_{20}(k)$, is calculated:

$$\tilde{E}_{20}(k) = median\{E_f(k - 19...k)\} \tag{1}$$

Then, $\tilde{E}_{20}(k)$ is subtracted from the current filtered frame energy level $E_{\mathrm{f}}(k)$

$$\delta E(k) = E_f(k) - \tilde{E}_{20}(k), \tag{2}$$

and the standard deviation $\sigma_{\delta \mathrm{E}}(k)$ of the previous five level differences (excluding the current) is derived as follows:

$$\sigma_{\delta E}(k) = std(\delta E(k - 5...k - 1)). \tag{3}$$

Finally, the energy threshold $E_{\mathrm{TH}}(k)$ is calculated:

$$E_{TH}(k) = \tilde{E}_{20}(k) + 2 \cdot \sigma_{\delta E}(k) \tag{4}$$

Threshold $E_{\mathrm{TH}}(k)$ is compared with the actual frame energy level in order to identify transient *candidates*. If the actual frame is a candidate, a novel Transient Detection Function (*TDF*) is derived by multiplying the candidate frame energy level with the variance $\sigma_{\mathrm{HF}}(k)$ of its high-frequency energy content (5–10 kHz).

$$TDF(k) = E_{TH}(k) \cdot \sigma_{HF}(k) \tag{5}$$

If $TDF(k) > 1$, candidate frame k is defined as a transient event.

This detection process is illustrated in Fig. 6. The top plot shows the energy level $E(k)$ of the unfiltered sensor signal frames. The second plot presents the filtered frame energy $E_f(k)$ and the adaptive energy threshold $E_{TH}(k)$. For each frame of which the filtered frame energy exceeds the threshold, the high-frequency variance is calculated (third graph). The fourth plot shows the *TDF* and its threshold. In the bottom plot, the detected events and the ground truth events are presented.

In Fig. 7, we present the result of the LPC-based filtering in terms of the spectrograms of an original signal (top) and its filtered version (bottom). These plots illustrate the elimination of the machine noise while preserving the low-frequency transient information. In the SITRA methods, this information is highly reduced by the use of the high-pass filter.

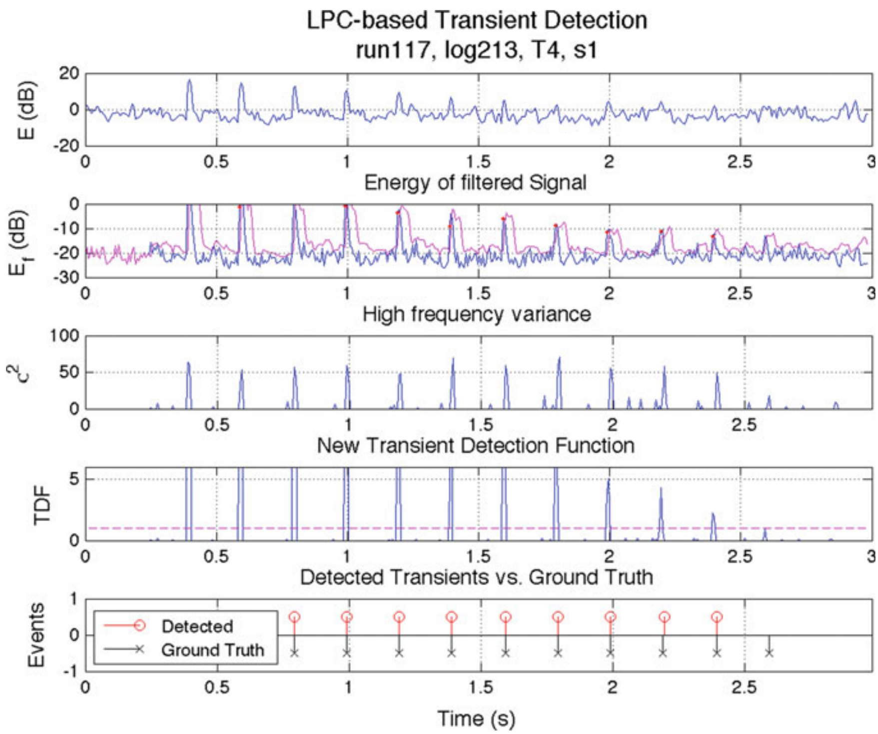


Fig. 6 Example for linear prediction-based transient detection

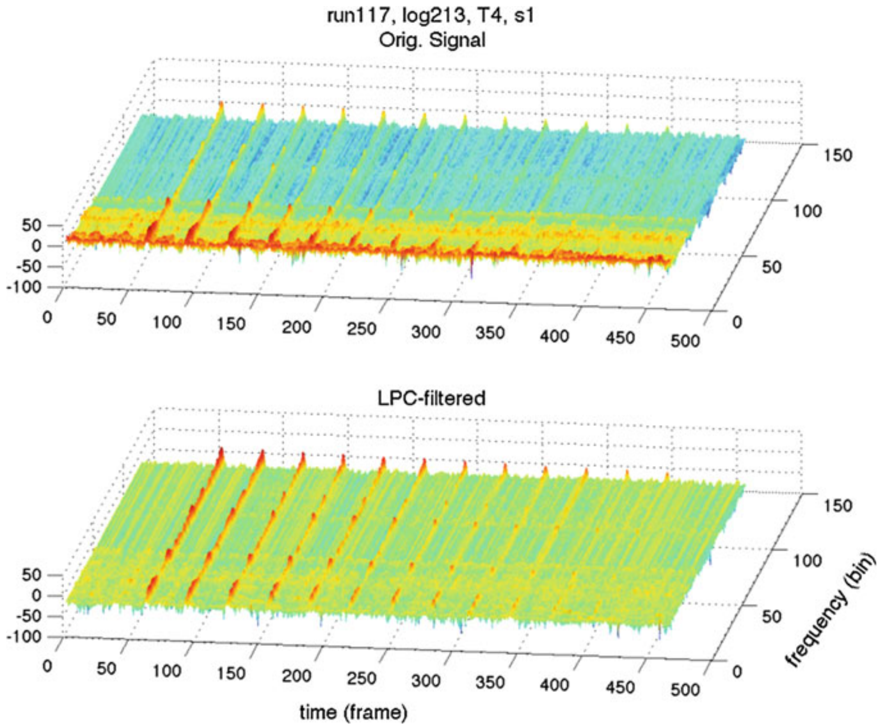


Fig. 7 LPC-based transient detection: spectrograms of original (*top*) and filtered (*bottom*) signal. Low-frequency transient information is preserved

4 Evaluation

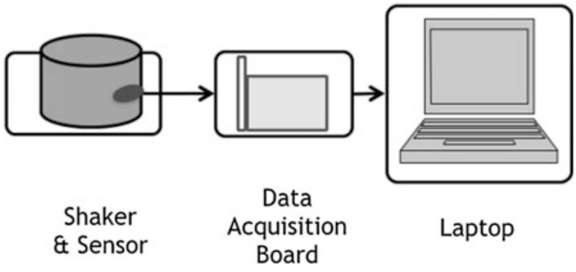
In order to be able to carry out a structured evaluation of the detection algorithms, we have combined two types of signals, namely (i) transient signals and (ii) feeding noise signals. The transient signals were acquired in the laboratory using the test setup schematically illustrated in Fig. 8, while the feeding noise signals were logged at a harvesting machine.

As transient events may exhibit different spectral characteristics, we have used the following objects to generate the test signals:

- Rubber hammer (low frequency bumps)
- Book back (low/mid frequency bumps)
- Stone (broadband noise)
- Metal object (broadband noise)

The knock sensor was mounted on the shaker and connected to a data acquisition card by which the sensor data has been recorded. The four objects were hit upon the

Fig. 8 Experimental Setup for the acquisition of the transient signals



shaker using different levels of force. From the resulting signals, we have extracted five transient events per object for further processing.

For our study, we have combined 16 fragments of the harvester noise signal (three seconds duration) with the four types of transient signals by adding 12 repetitions of a particular transient every 200 ms starting at 400 ms with the amplitude energy decreasing by 2 dB per repetition. In addition, 20 implementations of these repetitions were generated by consecutively adding a time shift of 20 ms to the transient events per implementation. Hence, the total number of samples is 16 noise samples × 4 transient types × 5 transients per type × 20 implementations = 6400 samples containing a total of 76,800 transients.

As the transients exhibit varying decay behavior, we have calculated the SNR levels of the individual transient signals based on the first $N = 100$ signal samples $E_t(n)$, and the respective samples of the noise signal $E_n(n)$ as follows:

$$SNR = 10 \cdot \log_{10}\left(\frac{\sum_{n=1}^{N} E_t(n)}{\sum_{n=1}^{N} E_n(n)}\right) \tag{6}$$

Considering a minimum occurrence of 500 realizations at SNR steps of 2 dB, 97 % of the transients ranged between an *SNR* of −31 and 33 dB.

The samples were fed to the three transient detection algorithms and the detection performance was evaluated by means of a confusion matrix. Transients that were detected one frame before or after the ground truth transient position were tolerated. The performance with regard to the correctly detected transients (true positives) was analysed in detail and the respective cumulative distribution function has been calculated as a function of the SNR level.

5 Results

Figure 9 presents the results of the evaluation of the three transient detection algorithm in terms of the cumulative distribution functions (cdfs) with regard to the true positives, i.e. the correctly detected transients, versus the SNR level.

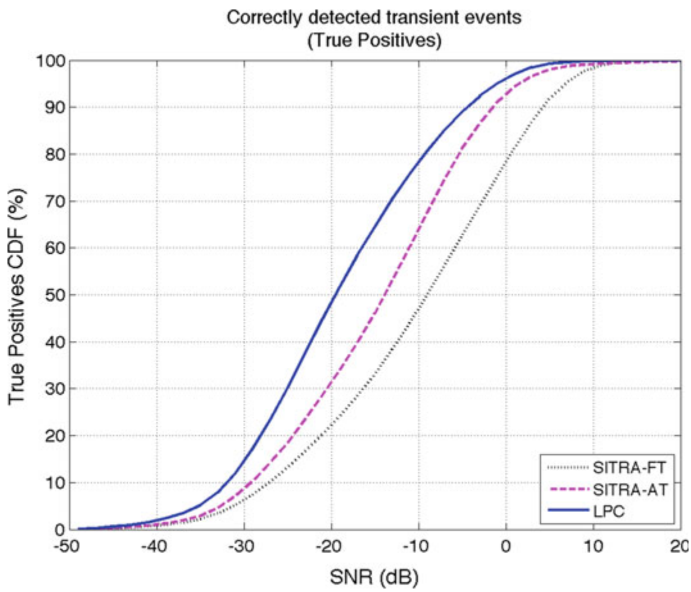


Fig. 9 Cumulative distribution function (CDF) plots with regard to the correctly detected transients (true positives)

The SITRA method with a fixed threshold provides 95 % correctly detected transient events down to an SNR of 7 dB, while the corresponding SNR level equals 3 dB for the adaptive SITRA version. The novel method performs best, providing at least 95 % true positives down to an SNR of −1 dB. From an SNR perspective, at an SNR level of 0 dB, fixed SITRA, adaptive SITRA and the LPC-method provide 78, 92.7, and 96 % correctly detected events, respectively.

Finally, Table 1 presents the confusion matrix of the overall performance of the algorithms based on the entire dataset. The rate of correctly detected events (true positives) increases from 48 % for the fixed threshold SITRA to 61 % for the adaptive SITRA method, and to 72 % for the new linear prediction-based approach. In turn, the rates of actual transients not being detected (false negative) are decreasing from 51 % (SITRA-FT) via 38 % (SITRA-AT) to 27.6 % (LPC). As the false positive rates suggest, misdetections rarely occur in general. Hence, in this respect, all of our methods provide a high degree of robustness.

Table 1 Confusion matrix of the overall performance

Rate (%)	SITRA-FT	SITRA-AT	LPC
True positive	48.15	61.82	72.36
False negative	51.85	38.18	27.64
True negative	99.76	99.22	99.74
False positive	0.24	0.78	0.26

6 Conclusions

We have presented three frame-based algorithms for the detection of transient events and evaluated their performance based on four different transient types. Our results show that the novel LPC-based algorithm provides 95 % correct detections down to an SNR level of −1 dB. Taking the simplicity of SITRA into account, it provides good results, especially when an adaptive threshold is employed.

In future work, the detection algorithm may be designed in a more tolerant way regarding consecutive transient events as to prohibit unnecessary misdetections.

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Strategic Asset Information Management: Experiences from Finnish Companies

Jyri Hanski, Jere Jännes, Ville Ojanen and Pasi Valkokari

Abstract Decisions on strategic asset management are crucial from the perspective of improving the sustainability of companies. The new ISO 55000 series of AM standards is a means of improving the AM strategies and practices of companies, and thus their sustainability performance. For this study, three Finnish companies were interviewed about their asset management, especially related to their asset information management practices and sustainability. The results are compared with the asset information management guidelines given in the AM standard. The goal of the research is to find best practices and areas of improvement in asset information management, and thus to improve asset management related decision-making and the sustainability of companies. All the interviewed companies gather and analyse data from their machinery and infrastructure and the analysis and utilization of asset related information is considered important. The economic perspective of AM is seen crucial in decision-making, but also sustainability reporting, maintenance and operating information, value of assets and fault data are utilized. The asset information is scattered in different systems and behind different organisational barriers. Companies, however, strive towards unified asset information management systems.

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1 Introduction

Strategic perspectives of asset management (AM) have earlier received less attention, but their importance at corporate level is increasing (Wilson 2002; Hastings 2009). Laue et al. (2014) argue that current AM related maturity models focus primarily on operational and technical level neglecting the strategy, policy, social and governance perspectives. Some dimensions of AM decisions have been based more on intuition and visions in comparison to structured and well-tooled analysis (Komonen et al. 2012). Brown et al. (2014) list the new issues that AM and AM models have to face i.e. sustainability, interaction between built assets and natural environment, resilience, life cycle management, community demands, information management and new types of governance arrangements. Production assets may have long life cycles and major changes occur in endogenous and exogenous factors during their life cycles. Thereby, decisions on strategic AM are crucial from the perspective of improving the sustainability of companies.

The new ISO 55000 (2014) series of AM standards is a means of improving the AM strategies and practices of companies, and thus their sustainability performance. The standard aims to represent the best practices of asset management worldwide. ISO 55000 (2014) defines AM as “coordinated activities of an organization to realise value from assets”. Realised values are dependent on the goals, characteristics and objectives of the companies and its stakeholders. The standard emphasises the role, determines the central terms and concepts of AM and its interfaces to other activities of a company. It gives guidelines to creating and developing a sustainable AM system. Processes and strategies of information management are a central part of AM. The standard gives guidelines for management of asset information.

To improve the level of asset information management and sustainability in companies, there is a need for more information on their current level. Thus, the main research question of this study is as follows: “What kind of asset management practices can be found in Finnish companies and how they compare with the guidelines of ISO 55000 series of AM standards?”. The focus of research is especially on asset information management, strategic AM and sustainability. The goal of the research is to find best practices and areas of improvement in asset information management, and thus to improve asset management related decision-making and the sustainability of companies. For this study, three Finnish companies were interviewed about their AM, especially related to their asset information management practices. The results are compared with the asset information management guidelines given in the AM standard.

2 Methodology

The research is qualitative in nature and based on the results of interviews. Qualitative research methods were selected due to the newness of the research field. The research is based on six semi-structured interviews in three industrial companies. Altogether 14 persons were interviewed. The persons interviewed work in service, production or finance departments. Two companies were interviewed once and the third company four times in different business units. The interviews were recorded and transcripted. All of the companies are large Finnish companies with revenues of over 200 million euros. The interviews were aimed at finding the level of AM in the interviewed companies, focusing especially on their asset information management practices and strategies. The data was analysed by comparing it to the guidelines given in ISO 55000 series AM standard. Because of the limited number of the interviews, the data is mainly analysed as a whole, representing some of the best practices found in Finland.

3 Results

In this chapter, the results of the interviews are presented. The observations represent the opinions of the interviewees regarding AM and sustainability.

3.1 AM Strategies and Sustainability

The state of the interviewed companies' AM strategies and processes varies from several processes and strategies to no specific strategies in place or at least no strategies that the interviewees are aware of. In addition, there are departmental variations in the AM strategies inside the companies. There is an exchange of information with stakeholders, however the communication with customers is emphasised. Long-term relationships with customers are accentuated. Stakeholders are also communicated through sustainability reporting which increases the transparency of the companies. The need of consistency is stressed in management and reporting. Sustainability shows in the strategies in forms of energy efficiency demands, emissions monitoring and in selection and procurement of machinery and materials. Supplier selection may also include sustainability criteria. Production and environmental goals set standards for AM. Sustainability can also be seen in increased number of repairs and reduced number of replacements, and in new ways of inspections and acceptances. Moreover, often components are changed instead of replacing larger items such as equipment, modules, devices, etc.

3.2 Collecting AM Related Information

Data is collected from machinery and/or infrastructures in all the interviewed companies. Data collection has developed considerably with decreasing costs of instrumentation, development of data collection technologies and reduced number of people working at the facilities. The interviewed companies collect wide varieties of information depending on the type of the facility and the used components. For instance, process information, remote control and performance monitoring data, key performance indicators (KPI's), criticality ratings, storage information, asset values, lifetimes and estimates of replacement needs, production volumes, maintenance related information, authority reporting based data needs, waste and emissions, discharges, etc.

The collected information is also dependent on the fact if the company has service contracts with their clients. Clients might demand that the supplying companies bring new ideas to their AM processes. Reaching a holistic perspective on the impact mechanisms of particular systems is seen as a specific information need among some of the interviewees. There is no systematic quality control or standard for the information needs, apart from the quality standards set by the authorities for the authority reports. The goal of improving the quality of information is to prevent the disturbances in activities. Chaining of the utilisation of information and the lost connection to the original data are considered problems in quality control. Common information and information retrieval systems are considered a solution to this problem by the interviewees. Interviewed companies have methods and systems to support the various parts of information management process, for instance to support production, maintenance and process management. The most problematic areas related to the information management process are information standardisation and the end-of-life activities.

3.3 Analysis and Utilisation of Asset Information

The information collected from machinery and infrastructure is analysed in the interviewed companies. The needs and wishes to the specification of the analysis are partly received from customer feedback questionnaires. Different energy efficiency and availability criteria and the fulfilment of quality criteria are followed especially. Other mentioned targets of analysis include machinery and component specific costs, asset value and cost per assets. Improvement in measuring technology helps information collection, analysis and utilisation. The management and ownership of the information infrastructure, for instance related to cloud services, is contemplated by the companies. Currently, the information is scattered in different systems. Data management is considered a problem, especially from the perspective of who can and has time to manage the data. Automated systems can already partly provide solution to this problem. The interviewees think that condition based maintenance is going to become more common as the measurement technology develops.

Utilisation of information is considered important. If the machinery or infrastructure is maintained at a right time, the lifetime costs are usually reduced. On the other hand, some maintenance activities can be performed less often when they are deemed less critical and move into real condition based maintenance. AM decisions need supportive reasoning, and purely statistics based decision support might not be good enough in industrial setting (in comparison with insurance companies). The interviewed companies mentioned examples of utilising the information, for instance reports made on the basis of the measurements and analyses and methods offered to the customer to utilise the produced information. AM information is used mainly on operational level, but it is also utilised to create the higher level performance indicators. In some cases, customer invoices ensure that the quality of the AM information is high enough for it to be sent it to the customers. Condition monitoring and process related measurement information are separated from the invoicing information and other information sources. All in all, the information used for invoices is better summarised but does not provide a holistic perspective on the level of AM, for instance the state of the critical components. In AM related decision-making the determining of the profitability of investments from the monetary perspective is crucial. However, also other types of information are used, for instance sustainability reporting, maintenance and operation information, value of assets and their depreciation, long-term maintenance programs, and failure and cost information.

3.4 AM Risks, Roles and Responsibilities, Processes, Information Exchange, and the Quality and Availability of Information

The interviewed companies have identified the risks related to ownership and there are processes for risk management in place. The most important risks, their consequences and probabilities are listed. The demands from insurance companies are a major driver in charting the risks. Clients are also informed by the existence of risks and criticality assessments are made for them. A company assesses unavailability costs in different scenarios related to, for instance, capacity requirements, planned running times and usability. There has been a shift from reactive actions based on the results of the analyses to predicting risks and doing predictive actions. As an example of the changing mindset, the managers have the courage to make predictions about the machine failures on operational level. However, on the higher level there are deficiencies in assessing the significance of risks and in predicting the machinery and infrastructure failures. Local risk assessments are made on facility level to determine the critical components. Efficiency monitoring strives towards consideration of reasons and further measures, and understanding the figures instead of just reporting them.

AM roles and responsibilities are highly standardised, but some companies are aware of the need for clearer definitions to increase flexibility and improve work rotation. AM related maintenance responsibilities are defined in external customerships. AM processes and activities are described separately for each type of facilities, because of the different machinery and components. There is a considerable variance in information exchange with the most prominent stakeholders. Remote service systems enable the access to clients' information systems and, thus, make the information exchange easier. In this case, however, the confidentiality between the company and the client is crucial. Companies have plans for the communication with clients. Because of the customer driven approach to the business, the companies have less exchange of information with other stakeholders, but when it is necessary, it is described on project level. Companies gather information on its stakeholders through feedback, customer surveys and events. There are also some joint programs for, i.e., reducing the environmental impact of companies. In some of the companies the quality and availability of information and its meaning to support the company's decision-making is considered. They are conscious of the uncertainty and incompleteness of information. Their own assets are a source of reliable and accessible information. The operational environment is thought to be the challenging part of asset information management, even though it is considered at the corporate level. Risk charts are used to manage the risks of incomplete information.

4 Discussion

The guidelines given in the ISO 55000 (2014) series of standards are presented in *italics*. Conclusions based on the interview results follow the guidelines.

4.1 AM Strategies and Sustainability

Environmental, economic and social pillars of sustainability and the fulfilment of sustainability based organisational objectives are emphasised. The role of stakeholders and their requirements and expectations are also highlighted. Based on the characteristics and operational environment of the organisation, an organisation should create a strategic AM plan, which is consistent with organisational objectives. This plan sets criteria for AM decision-making. Different stakeholders may have conflicting objectives for AM from the sustainability perspective. Thus, the AM system should be transparent and consistent (ISO 55000 2014).

There are many developments that are increasing sustainability. However, AM strategies are not necessarily based on sustainable thinking, even though they might increase the sustainability of the company. The reasons behind this indirect improved sustainability include process development, energy and resource efficiency and the resulting cost savings or increased capacity. The role of stakeholders is emphasised. Customer is the most important stakeholder. Also government, society, suppliers and partners are mentioned. There is a big variation in the level of AM strategies and processes between and inside the companies. Sustainability reporting is practised in the companies. These indicators increase the transparency of AM system and the consistency of its development.

4.2 Collecting AM Related Information

Requirements and the necessary information items are set for the information needs and the documentation of information. These include, for instance, user requirements, descriptions of assets and their purpose, various asset attributes, performance targets, key performance indicators, details of historical asset failures, etc. Information needs of the organisation should be determined through a formalised approach to meet its organisational objectives. Value and quality of information should be taken into account relative to its costs and complexity of collecting, processing and managing. Availability of appropriate AM related information to assist in decision-making should be determined. Processes for collecting and managing asset information should be defined to ensure the accuracy, efficiency, traceability, auditability and timeliness of business processes and reporting. In addition, the methods for measurement and collection of source information, the frequency and verification of measurement, its storage and approval for further analysis should be defined (ISO 55000 2014).

Formalised approach for determining information needs was not found in the interviews. However, because of a limited number of interviews, there might be formalised approaches for determining information needs in place. Value and quality are taken into account and some problems in managing the information are recognised. Information collection is sometimes demanded by the clients. All the companies collect information from their assets. A wide variety of information is collected and it is used to support AM related decision-making. Methods and processes exist for collecting and managing asset information. For instance, customer feedback questionnaires, energy efficiency, and availability and quality criteria are followed. More holistic methods for AM might, however, be needed.

4.3 Analysis and Utilisation of Asset Information

Organisation should define, implement and maintain the methods for analysis and evaluation of information, and processes for managing its information. There are differing information needs in different levels of organisation and a differing ability *to have horizontal and vertical alignment of the information. Organisation should consider the complexity of its processes for managing its asset information. Asset related data can reside in many systems and, thus be very expensive to gather and maintain. Unnecessary duplication of data should be avoided and the data should reside in the most appropriate system. Processes for where and how the data is reworked into usable information and how it will be communicated should be defined* (ISO 55000 2014).

The information collected from machinery and infrastructure is analysed in the interviewed companies. Purely statistical analysis is thought to be inadequate in industrial setting and is often complemented with condition based information. Based on the interviews, it would seem that there is a need for methods for the evaluation of information. The different levels of information have been recognised and some examples of alignment are found. A lot of information is produced but the state of critical components may not always be provided, because of the emphasis on the invoicing information. The companies have recognised the need for unified systems and the expensiveness of duplicating the data. Actions have been taken towards better asset data management.

4.4 AM Risks, Roles and Responsibilities, Processes, Information Exchange, and the Quality and Availability of Information

The organisation should include consideration of the significance of the identified risks, the roles and responsibilities for AM, the AM processes, procedures and activities, exchange of information with its stakeholders, including service providers, and the impact of quality, availability and management of information on organizational decision making. Organisation should consider the need to align its information requirements to suit the level of risk that an asset poses. The information should be easily exchangeable with service providers. The use of common terminology increases understanding between stakeholders and inside the organisation. To ensure the completeness, accuracy and integrity of AM information, collaboration amongst relevant stakeholders is needed. There is a need for a quality of information that is relative to its use (ISO 55000 2014).

Processes for risk management are in place and the significance of identified risks is considered. The interviewees give some examples of predictive risk management. Risks related to ownership are identified and there are processes for risk management in place. There has been a shift from reactive actions based on the results of the analyses to predicting risks and doing predictive actions and managers have the courage to make predictions about the machine failures on operational level. On the higher level there are deficiencies in assessing the significance of risks and in predicting the machinery and infra failures. Local risk assessments are made on facility level to determine the critical components. It was not found out in interviews if the criticality of components affects the information requirements, but it should. All in all, the risk management is at a good level, even though there are development needs in corporate level asset risk assessment.

AM roles and responsibilities are highly standardised, but some improvement areas are recognised such as need for clearer definitions to increase flexibility and improve work rotation. AM related maintenance responsibilities are defined in external customerships. AM processes and activities are described separately for each type of facilities, because of the different machinery and components. Exchange of information is practised mainly with customers. There is a considerable variance in information exchange with the most prominent stakeholders (reasons: remote service systems, confidentiality). Companies gather information on its stakeholders through feedback, customer surveys and events. There are also some joint programs for, i.e., reducing the environmental impact of companies. Customer's role was emphasised in the interviews, however, also other stakeholders were taken into account. In some companies the impact of quality, availability and management of information on organisational decision-making is considered in the companies. The operational environment is thought to be the challenging part of asset information management, even though it is considered at the corporate level. Uncertainty of information is also considered and risk charts are used.

5 Conclusions

All the interviewed companies gather and analyse data from their machinery and infrastructure. However, data management is seen as a challenge. The analysis and utilization of asset related information is considered important. The economic perspective of AM is seen crucial in decision-making. Also sustainability reporting, maintenance and operating information, value of assets and fault data are utilized. Companies also help their value network to utilize the asset information better. The state of the interviewed companies' AM strategies and processes varies; some have several processes and strategies and some have no specific strategies in place or at least no strategies that the interviewees are aware of. At the moment, AM strategies are not necessarily based on sustainability, even though they might increase the sustainability of the companies. Process development, energy and resource efficiency, capacity increase and cost savings are the most important drivers behind the AM activities. The interviewed companies have all considerable asset base and benefit from sustainable strategic asset management practices.

Decision-making is still based on intuition, expert opinion and experience and the asset based information is used mainly on operational level. There are still several points of improvement in asset information management and information systems. AM related information is still scattered in many systems and controlled by various agents in the network. The companies are, however, aware of this and strive towards integrated information systems as presented in the ISO 55000 (2014) AM standard series. Integrated approach to the management systems enables the use of existing systems (quality, environmental, safety, etc. systems) and, thus, reduces the need of developing new systems. This development enables more sustainable AM systems to be developed.

Adopting sustainable development as a guideline can be considered as a strategic decision, especially if sustainability has not been a part of company's values before. To demonstrate the sustainability transparently, sustainability perspectives (environmental, social and economic) should be taken into account in the reporting and management of the company. The companies have recognised this and are striving towards a more sustainable future. AM strategies are in a key role when improving company's performance from the sustainability perspective. Sustainability of companies could be improved by using more AM based sustainability indicators, and using the asset information to support the decision-making more extensively. Emphasising sustainable development enables the companies to create new services and internally develop their processes and activities. Three proposals to improve the sustainability of the AM include (1) better linking the AM information to management systems, (2) predicting and visualising the development of the sustainability and AM indicators and (3) increasing transparency and the use of real time information. Further research is needed to determine the benefits of these suggestions.

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Renewal of Manufacturing Firms Through Innovation

Jussi Heikkilä, Pooja Chaoji and Miia Martinsuo

Abstract Renewal of manufacturing firms in the advanced economies is necessary to keep them competitive in the international field. Renewal of manufacturing is caused by internal factors and involve incremental changes, or by external forces, such as economic crisis or market changes involving radical changes. The purpose of this study is to analyse the role of innovations, types of innovations and scope of innovations in the renewal of manufacturing. The goal is increased understanding of innovations as means for manufacturing renewal, and activation of novel empirical research. We reviewed literature for innovations that are linked with manufacturing technologies and renewal, featuring keyword search, article categorization, and full text analysis for selected articles. The results indicate that research on this topic is spread across four research domains: organization science, operations management, economic geography and innovation literature. Innovation has been studied on the level of firms and regional or national manufacturing clusters. It has been seen both as a catalyst and an inhibitor of renewal on the firm level. Four modes of innovation were identified: innovation related to diversification of customer base, increased efficiency, added value to end products, and interactions in the value chain. The re-bundling perspective is suggested as an interesting opportunity for future research, indicating a shift in the location of innovation from within the firm to the network of firms.

Keywords Innovation · Manufacturing · Renewal

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1 Introduction

The growing competitiveness of manufacturing firms in the emerging economies and globalization of markets have increased the challenges for manufacturing firms in advanced industrial economies (Theodorakopoulos et al. 2014). The recent major economic crisis of 2008–09 further accentuated the challenges. To solve the challenges, new policy initiatives have been introduced for the renewal of manufacturing using advanced technologies and innovations (MacBryde et al. 2013). However, only a few empirical studies observe the transformation activities at the level of manufacturing firms in this context (Bathelt et al. 2013; MacBryde et al. 2013; Theodorakopoulos et al. 2014). In this study we analyse previous research on the types and scope of innovations in manufacturing companies in order to guide upcoming empirical research on this transformation.

The structure of the paper is as follows: Sect. 2 describes the method and the choices of articles for this conceptual study. Section 3 discusses the theoretical constructs that emerge from the selected studies and Sect. 4 describes the empirical context and findings from these studies. Section 5 provides discussion of our observations and concluding remarks to suggest possible future empirical research.

2 Research Methodology

The relevant literature for this paper was selected as follows. Initially, a systematic keyword search in the ISI Web-of-Knowledge database was conducted. Multiple combinations of the keywords *renewal, strategic renewal, resiliency, recovery, re-birth, decline, manufacturing firms, radical innovation, value-added manufacturing* and *process innovation* were used to identify relevant literature. This preliminary review revealed that research on the chosen topic is spread primarily to four research domains: organization science, operations management, economic geography and innovation literature. Studies from these four research domains differ in their keywords and emphases, while sharing the decline of manufacturing firms and efforts for renewal as the common context. The diversity in the observed literature presented an opportunity to generate a set of constructs for understanding the involvement of innovations in manufacturing renewal.

Table 1 describes the articles selected for this study and the information about their source journals and keywords. The primary research interest for this literature review was in the study of innovation modes, types and scope. Therefore, state-of-the-art literature from mainstream innovation research was also selected for the study. Overall, the search process revealed that literature studying the area of innovations involved in the renewal of manufacturing has been empirically investigated only to a small extent.

Table 1 The identified research domains in the study of renewal of manufacturing firms

Research domain	Authors	Journals	Keywords
Organization science	Barker and Duhaime (1997), McKinley et al. (2014), Agrawal and Helfat (2009), Huff et al. (1992)	Organization Science, Strategic Management Journal, Academy of Management Review	Strategic renewal, organization decline, turnaround
Operations management	MacBryde et al. (2013), Theodorakopoulos et al. (2014)	International Journal of Operations and Production Management, Journal of Manufacturing Technology Management	High-value adding manufacturing
Economic geography	Bathelt et al. (2013), Rutherford and Holmes (2014)	Regional Studies, Cambridge Journal of Regions, Economies and Society	Resiliency, manufacturing sector
Innovation research	Kalafsky and Macpherson (2006), Yinnon (1996)	Research Policy, Technovation	Innovation, manufacturing, rebirth, shift

Empirical research studying the innovations in manufacturing firms (mostly observed within innovation research domain) and on strategic renewal of manufacturing firms (mostly observed within organization science domain) present very few investigations at the firm-level in the context of decline of manufacturing. Research in economic geography presents empirical studies on this context, but the analyses and emerging theories on renewal of manufacturing are focused on the region-level. We decided to follow an eclectic approach to arrive at a combination of studies that would provide a sufficiently rich conceptual and empirical basis on the innovations involved in the renewal of manufacturing firms in advanced economies.

Our interest was in analysing empirical studies that observe the innovations in manufacturing at the firm-level, in the context of decline of manufacturing in advanced industrial economies. Six studies including MacBryde et al. (2013), Theodorakopoulos et al. (2014), Bathelt et al. (2013), Rutherford and Holmes (2014), Yinnon (1996) and Kalafsky and Macpherson (2006) were selected for review. Literature informing of existing theories on the role of innovations in strategic renewal (e.g. McKinley et al. 2014; Barker and Duhaime 1997), regional renewal (e.g. Bathelt et al. 2013; Rutherford and Holmes 2014) and significance of innovation modes (Clausen et al. 2013) were selected to support the analyses.

3 Role of Innovation in the Renewal of Manufacturing

3.1 Strategic Renewal of Declining Firms

Agrawal and Helfat (2009) define strategic renewal as the process, content and outcome of refreshment or replacement of attributes of an organization that have the potential to substantially affect its long term prospects. Strategic renewal signifies the type of strategic change in firms that grows out of the current situation (Huff et al. 1992), and alters the path dependence of the firm (Volberda et al. 2001). Organization decline is an important context trigger for strategic renewal activities within firms. McKinley et al. (2014) define organizational decline as successive, year-after-year decrease in an organization's resource base that lasts for at least two years.

Empirical studies on firm decline and turnaround support two opposing views regarding innovation in firms. According to the first view, decline is a catalyst for adaptation and innovation in firms, whereas the second standpoint suggests that decline is an inhibitor of innovation activity in firms (McKinley et al. 2014, p. 88). According to the 'catalyst view', innovation in products and processes is an excellent revitalization solution for firms experiencing decline. The key role of innovation in successful firm turnarounds is to realign the organization with its external environment (Barker and Duhaime 1997). According to the 'inhibitor view', engaging in resource and capital absorbing innovation activities in a declining firm could further exhaust the firm by adding to the amount of challenges that the firm is already tackling, diluting its renewal efforts. In essence this implies that firms respond to decline by not taking up any novel ideas, described as 'rigidity' by McKinley et al. (2014), and focus on reducing costs, improving efficiency and increasing accountability of existing operations (Barker and Duhaime 1997). The dichotomy between innovation as means for successful turnaround, and rigidity as an inhibitor for change is well-established in organization decline and turnaround literature.

Barker and Duhaime (1997) suggest that the inconsistency in empirical findings regarding the major role of innovation in successful turnarounds can be predicted based on the level of need for strategic change in turnaround case studies. When the causes for decline are at the industry level, many of the other firms in the industry suffer decline, and turnaround is possible by surviving the phase of the industry-level crisis based on efficiency and retrenchment measures. On the other hand, when firm level problems are the root cause of decline, strategic change is a prerequisite for recovery from decline. Such analysis of the causes of decline on the firm and industry levels, and its implications on the role of radical innovations in firms is important in the discussion of decline of manufacturing firms. In addition, a third level of analysis, that is the location-level, is relevant. The location-level perspective is, however, missing in the discussions in organization studies, and can be observed from studies in the economic geography domain.

3.2 Revitalization of Declining Regional Manufacturing Clusters

The contemporary discussions and policy debates over renewal of manufacturing at the level of regional clusters and national economies focus on the context of the decline of manufacturing and how advanced technology based innovations may provide a route for survival (e.g., Theodorakopoulos et al. 2014). Regional resiliency is an area of research on how regional economies can withstand the impact of economic crises and restructuring. One of its objectives concerns whether employment and investment in older manufacturing regions can recover, and how public policies might facilitate reindustrialization (Rutherford and Holmes 2014).

Manufacturing performance has a link with the location-level factors. Rutherford and Holmes (2014) discuss that production costs, innovation capacity and access to highly skilled labour are among the important location-dependent inputs to competitiveness of manufacturing firms. Also, problems arising from regulation, policies, currency and energy price fluctuations are common to manufacturing firms at the region-level. Some research presents policies for stimulating innovations in manufacturing sectors in decline (e.g., Yinnon 1996).

Regional ruptures and re-bundling form a part of discussions in economic geography research regarding regional economic development paths. Re-bundling is the process through which existing resources are used in novel ways to serve a new purpose. The concept of re-bundling rests on conceptualization of a firm's resources being capable of rendering a variety of services based on the context of use (Bathelt et al. 2013). Then, regional ruptures or crises provide the basis for de-contextualizing and then re-contextualizing different forms of resources and their specific uses in four possible re-bundling scenarios (Fig. 1).

3.3 Innovation Modes and Types

An important area of empirical investigation is how different firms innovate. One type of the research outcomes are emerging taxonomies of innovation modes in firms. Research on innovation modes suggests that a firm's abilities to innovate are, at least partly, a function of their resources and their ability to renew their resources. Clausen et al. (2013) suggest that the innovation mode of a firm can be defined based on the level of preference between exploration versus exploitation and open versus closed innovation within firms.

Empirical studies on innovation reveal problems related to heterogeneity in innovation activities. Damanpour et al. (2006) suggest studying innovations based on a typology of firms. McKinley et al. (2014) present a typology to analyse the innovation activities in the context of organizational decline and turnaround. They propose that innovations can be characterized as flexible and inflexible. The degree of flexibility is observed as the extent of modifying the innovation once

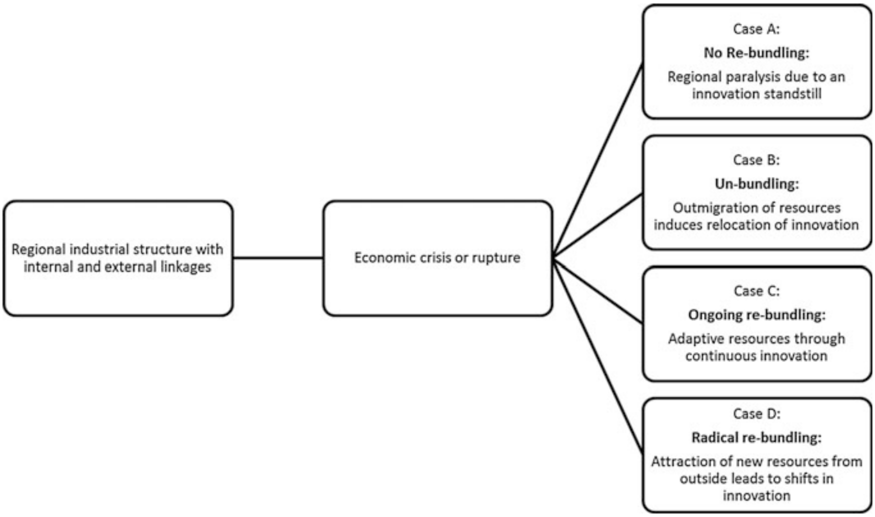

Fig. 1 Renewal trajectories at regional level: ruptures versus rebundling (Bathelt et al. 2013)

implemented and the speed at which it can be modified. Flexible innovations have a wide range of possible post-introduction configurations and the speed of transition between those configurations is rapid. An inflexible innovation has fewer post-introduction configurations and the speed of transition between them is slower. These innovation characteristics are mentioned with respect to production equipment and processes. McKinley et al. (2014) hypothesize that flexible innovations are to be adopted whereas inflexible innovations are to be avoided to maximize chances for successful turnaround of declining firms. Therefore, defining innovation modes and identifying innovation types are regarded as helpful approaches in exploratory studies on innovation activities in firms.

4 Innovation as Means for Manufacturing Renewal

Selected empirical studies are reviewed in this section to study the transformation of manufacturing industries and whether any commonalities emerge in the nature of innovation activities within firms in the context of advanced economies. This analysis is based upon six empirical studies described in Table 2, consistent with the paucity of empirical studies investigating the transformation of manufacturing (MacBryde et al. 2013; Theodorakopoulos et al. 2014).

The existing empirical investigations of manufacturing transformation are covered under such topics as high-value added manufacturing (MacBryde et al. 2013; Theodorakopoulos et al. 2014), knowledge-intensive production (Yinnon 1996) and renewal of manufacturing competitiveness in high-cost economies (Rutherford and Holmes 2014). In order to shift to knowledge-intensive production, firms have to

Table 2 Industries and locations of sample firms in renewal of manufacturing studies

Case firm(s)	Industry	Country	Authors
Longitudinal study of small apparel manufacturer	Textile	UK	Theodorakopoulos et al. (2014)
Small and medium sized enterprises	1. Electro/mechanical engineering and construction (e.g. aerospace, electronics), 2. Chemical and pharmaceuticals (e.g. Petrol, cosmetics, plastics etc.), 3. Textiles (apparels and textiles), 4. Food-based products and miscellaneous (e.g. printing, stationary etc.)	Scotland	MacBryde et al. (2013)
Traditional manufacturing firms of all sizes	1. Plastics and rubber 2. Fabricated metal products 3. Machinery 4. Electrical equipment 5. Transportation equipment	Canada (Technology Triangle region of Kitchener and Guelph metropolitan areas)	Bathelt et al. (2013)
Firms of all sizes	Automotive	USA-Canada (Great Lakes region automotive industry firms)	Rutherford and Holmes (2014)
Firms of all sizes	Machine tools	USA	Kalafsky and Macpherson (2006)
Firms of all sizes	Plastics	New York, England (and Israel)	Yinnon (1996)

shift their activities beyond what is traditionally viewed as production. This typically means involving design and service related activities (MacBryde et al. 2013). In addition, high-value added production involves a shift in manufacturing strategy from production of commodities for mass markets to the production of enhanced products for high-value niche markets. They are typically enabled by the use of new technology, new materials and innovation (Theodorakopoulos et al. 2014).

There are some fundamental differences in the empirical cases of firm decline in these six studies. First, the research methodology and unit of analysis varies. For example, Theodorakopoulos et al. (2014) have studied only one case firm going through the transformation into a technical textile manufacturer from traditional apparel manufacturer. Kalafsky and Macpherson (2006), on the other hand, have gathered empirical data on all firms making machine tools within the US. Furthermore, the studies do not focus on a single incidence of decline of manufacturing firms or on a single time-period. Several studies in this sample focus on contemporary competitive challenges created by manufacturers from low-cost economies (Theodorakopoulos et al. 2014; MacBryde et al. 2013). On the other hand, Kalafsky and Macpherson (2006) study the challenges created for US based manufacturers by competition from manufacturers based in Germany and Japan.

The empirical findings from these studies about firm responses to decline include discussion about the innovation activities within firms in the context of strategic renewal. Based on the review of these innovation activities, four modes of innovation emerge as active in the case of manufacturing firms' strategic renewal in the traditional industrial sectors in advanced economies.

4.1 Innovation for Diversification of Customer Base

In the diversification-oriented mode of innovation, firms make purposeful innovation decisions to steer away from the challenging situation in their existing markets. Innovations are intended for renewing their strategic focus and capitalizing upon their accumulated experience and expertise. It was observed that in response to the decline of the automobile supplier firms in US and Canada, many suppliers of big US automobile manufacturers started innovating new products and solutions to shift their focus from earlier main customers to new customers in growth industries or broadening their global customer base (Rutherford and Holmes 2014; Bathelt et al. 2013).

Another example of such a diversification strategy is the case study of a UK based apparel manufacturer; the firm actively tried to develop its technical clothing division in order to renew its declining apparel business. This decision implied mastering radically new production and testing technologies in the company's production. It implied a change in manufacturing strategy since focus of the company's production moved to a requirement for a new type of expertise, quality and speed. (Theodorakopoulos et al. 2014).

In the case of shift of plastic product manufacturers in New York state and UK, radical technology innovations involving production of advanced polymers, processing methods and computer integrated manufacturing technology were adopted as a part of the companies' renewal in the decline around 1970s (Yinnon 1996). Firms in the plastic manufacturing industry adopted innovations with a purpose of diversifying their growth path towards customers in need of technologically sophisticated plastics, such as in the automobile industry. Strategic renewal of these firms involved adoption and mastery of new production technologies and investing in high skilled labour. This further led to changes in the scope of business from subcontracting to producing own brands to capitalize investments in production of speciality products (Yinnon 1996). Innovation for the diversification of customer base emerges as one of the renewal strategies for manufacturing firms in decline and involves radical innovation in manufacturing.

4.2 Innovation to Increase Efficiency

The efficiency-oriented mode of innovation involves activities for increasing time and cost efficiency of firms in decline. Some of the efficiency-oriented innovations observed among the US machine tool manufacturers in their recovery around 1990 included reduction in cycle time and decrease in unit costs by reducing the number of parts (Kalafsky and Macpherson 2006).

Innovations for reducing costs of manufacturing emerge to be of less priority for strategic renewal of firms in decline. According to Kalafsky and Macpherson (2006) research on rebound factors for US machine tool manufacturers, shorter cycle times were on the fourth rank and reduction of unit costs on the eighth rank, compared with customer service performance and product quality as the top two rebound factors. Similar findings were noted in the case of Scottish SMEs across different manufacturing sectors that ranked high quality, innovative products and aspects of customer service above reducing price (MacBryde et al. 2013).

4.3 Innovation to Add More Value to End Products

The value-oriented mode of innovation involves increasing the value added by the manufacturer to the end product. A typical example of this mode is a small fabricator that expands its offering from a fabrication workshop to a complete system seller. Some of the US auto parts suppliers underwent renewal by taking up new activities and becoming system integrators that design, engineer and build complete modules, and assume downstream coordination functions previously undertaken by automakers (Rutherford and Holmes 2014). Similar examples of firms that built up their knowledge from being fabricators to development of own research and design capabilities were observed in the study of firms in Guelph-Kitchener region of Canada (Bathelt et al. 2013). The value-oriented mode of innovation is suggested as an example of ongoing re-bundling at the firm level. This leads to constant re-configuration of resource base and provides manufacturing firms with a capability that enables recovery from decline. Results from the study of SMEs in Scotland show that in their transition to high-value production small manufacturers move beyond only production activities to increasingly design and customer service related activities (MacBryde et al. 2013).

4.4 Innovation Through Interactions in the Value Chain

The network-oriented mode of innovation involves interaction with agents from organizations in the value chain and communities of practice in an industry through opportunities such as trade fairs, trade magazines etc. Such interactions played a key role in the creation of new meaning and identity related to technical clothes manufacturing for the case firm in Theodorakopoulos (2014). The boundary interactions mode is also observed to be a significant mode of innovation for SMEs in the traditional manufacturing industry in the Canadian technology triangle region (Bathelt et al. 2013). The network-oriented mode of innovation in manufacturing maximizes opportunity for re-bundling at the time of industry level crisis and increases the chances for novel product development. Furthermore, a shift to knowledge-intensive manufacturing requires support of a broader technological network, comprising experts in design, R&D facilities, databases and specialised trading companies. Yinnon (1996) observed that since most SMEs cannot afford to host an expensive R&D infrastructure, the shift to high-value added manufacturing is accompanied by the shift of location of innovation activities from within the firm to the network of partners.

5 Discussion and Conclusions

In this study, the research domains of organization science, operations management, innovation management, and economic geography were identified as relevant for the study of renewal of manufacturing firms through innovation. The domain of organization science has covered studies on organizational decline, turnaround and strategic renewal (McKinley et al. 2014; Barker and Duhaime 1997; Agrawal and Helfat 2009; Huff et al. 1992). They present alternative views on firms' responses to decline, and role and types of innovation involved in successful manufacturing renewal. The operations management research domain presents some empirical studies on the changing nature of manufacturing in advanced industrial economies (MacBryde et al. 2013, Theodorakopoulos et al. 2014). The innovation research domain has provided empirical evidence on the transformation of manufacturing through innovation activities (e.g. Yinnon 1996; Kalafsky and Macpherson 2006). Economic geography studies the decline of manufacturing sector in selected advanced economies (Bathelt et al. 2013; Rutherford and Holmes 2014).

Earlier empirical research suggests four alternative innovation modes through which firms can pursue the renewal of manufacturing:

- Innovation for diversification of customer base
- Innovation to increase efficiency
- Innovation to add more value to end products
- Innovation through interactions in the value chain.

Based on the empirical information from the selected studies, renewal of manufacturing in advanced economies is seen as a response to environmental challenges, wherein competition from overseas manufacturers is a major challenge (Kalafsky and Macpherson 2006; Yinnon 1996; Theodorakopoulos et al. 2014; MacBryde et al. 2013). There are common challenges that manufacturing firms face, and the reviewed empirical research offers some generalisations on the firm-level and regional or national-level cluster responses to the challenges. These suggestions present an opportunity to analyse the transformation and strategic renewal processes of and within manufacturing firms facing the threat of decline.

The re-bundling perspective offers an interesting opportunity for future research, suggesting a shift in the location of innovation from within the firm to the network of collaborative firms. Investigating these value-added manufacturing networks would be valuable, including institutional partners and firms. The framework presented by Bathelt et al. (2013) provides one research opportunity to associate radical innovations with the exchange of agents and knowledge across broader geographic and firm networks.

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Simulation as a Tool in Evaluating Combat Aircraft Shock Absorber Condition

Arttu Heininen, Jussi Aaltonen, Kari T. Koskinen and Juha Huitula

Abstract A simulation model for an oleo-pneumatic shock absorber of a combat aircraft is presented. System equations are presented incorporating the effects of friction, gas spring and damping. The model is validated with experimental data. The objective is to use the model as a tool to improve the shock absorber condition monitoring and fault detection methods. As a part of that a new measuring instrument is discussed.

Nomenclature

ρ	Density
μ	Dynamic viscosity
δQ	Heath exchange with surroundings
A	Orifice cross-sectional area
A_{mp}	Metering pin cross-sectional area
A_L	Lower chamber cross-sectional area
A_{PH}	Primary piston head cross-sectional area
b	Covolume
c_q	Flow coefficient
d_c	Clearance between envelope and piston
d_p	External piston diameter
dp	Piston diameter
dr	Piston rod diameter

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f_{in} Force at input port
$F_{\mu 1}$ Primary piston assembly friction
$F_{\mu 2}$ Viscous friction due to leakage
$F_{\mu 3}$ High pressure chamber friction
F_C Coulomb friction force
F_E External force
F_S Static friction force
g Gravitational acceleration
h Enthalpy
l_c Contact length
m Mass of gas
m_{sa} Shock absorber mass
p Pressure
P Pressure
P_{HP} High pressure chamber pressure
P_U Upper chamber pressure
P_L Lower chamber pressure
P_{ph} Pressure acting on primary piston head
r Specific gas constant
T Temperature
v Relative speed
v Specific volume
v^- Piston velocity
v^+ Envelope velocity
V Volume
X_{ref} Inertial reference position

1 Introduction

Every common aircraft, military or commercial, has a shock absorber in its landing gear. The most used type of shock absorber is the oleo-pneumatic shock absorber (Currey 1988). An oleo-pneumatic shock absorber has gas, commonly dry air or nitrogen, acting as a spring and two chambers containing hydraulic oil. The hydraulic oil flow is forced through an orifice between the two chambers and is controlled by a metering pin, which has a varying cross-section so that the designed load-stroke curve is achieved. During the compression, the energy of the shock is dissipated by the restricted hydraulic fluid flow and a part of it is stored in the compressed gas, which is released during the rebound, as the gas pushes the piston back to the extended position. In this study a simulation model of an oleo-pneumatic shock absorber is presented and validated with experimental data and its use as a tool in condition monitoring and fault detection is discussed. The model is built with LMS Imagine.Lab AMESim Revision 13.

2 State of the Art

Oleo-pneumatic shock absorbers have been a target for simulation and modelling for a quite some time, as simulation is a common tool in the aircraft industry. According to Currey (1988), oleo-pneumatic shock absorbers have the highest efficiencies and the best energy dissipation of all shock absorber types. He also stated that the gas can be modelled isothermally during ground handling and polytropically during landing. Milwitzky and Cook (1953) presented a theoretical study of the kinematics of a conventional oleo-pneumatic shock absorber during landing. The compression was modelled as a polytropic process. The main conclusions were that the discharge coefficient of the orifice has a notable effect on the damping of the shock absorber. This is confirmed by Yadav and Ramamoorthy, who analysed the nonlinear behaviour of a landing gear at touchdown (Yadav and Ramamoorthy 1991). They carried out a simulation using the heavy-pitch model they created for a small fighter-trainer aircraft and it was noticed that the damping effect is increased, when the orifice discharge coefficient is decreased. Daniels (1996) modelled and simulated an A6-Intruder attack aircraft landing gear, which was validated using data from static and dynamic tests. Friction was modelled using the Karnopp friction model and the results were considered accurate. Horta et al. (1999) extended the model with active controls and they found out that there were high friction levels that hindered the performance of the landing gear. In conclusion, modelling the gas, friction and the flow through the orifice are the most important phenomena to model, as they have the most effect on the operation of the shock absorber.

3 The Shock Absorber

The main parts of an oleo-pneumatic shock absorber are shown in Fig. 1. The primary piston assembly (a) is filled with hydraulic fluid, which is forced through the orifice between the primary piston assembly and the orifice support (d). The fluid flow is restricted with the metering pin (b) with varying shape. The orifice support and the cylinder surrounding it are filled with hydraulic fluid and gas. The high pressure chamber (c) is filled with gas in high pressure that cushions the greatest impact loads. The shock absorber is attached to the landing gear with lugs located on the both ends of the shock absorber. A piston is attached to the primary piston assembly that has orifices, which restricts fluid flow. Also, a snubber plate is attached to the bottom of the orifice support. Under the plate, there are orifices, which are closed during compression and open during rebound.

The stroke of the shock absorber can be divided into two parts. In the first part of the stroke, which is approximately 68 % of the overall stroke, only the primary piston assembly is in motion, moving through the secondary piston assembly. The impact load is controlled by the flow through the orifice. After the first part is

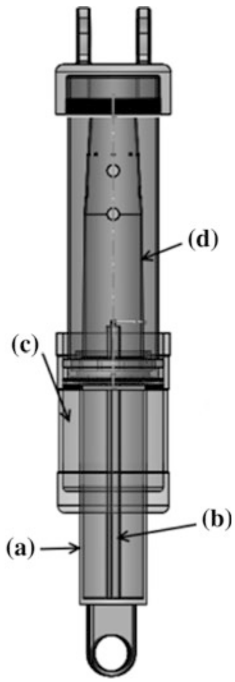

Fig. 1 Main parts of the oleo-pneumatic shock absorber. **a** Primary piston assembly; **b** metering pin; **c** high pressure chamber; **d** orifice support

finished, the primary piston assembly hits an end stop. If the impact load is high enough, the secondary piston assembly engages and the second part of the stroke starts. During this part, the secondary piston assembly moves together with the primary piston assembly, until the impact is fully cushioned or the maximum stroke is reached.

3.1 System Model and Governing Equations

Figure 2 shows the forces acting on the mass of the primary piston assembly, metering pin and the high pressure chamber. Balancing the forces acting on the mass of the shock absorber yields the following equation:

$$m_{sa}\ddot{X}_{ref} = m_{sa}g - p_U A_{mp} - p_L\left(A_L - A_{mp}\right) - A_{ph}\left(p_U - p_{ph}\right) - A_{HP}p_{HP} - F_{\mu 1} - F_{\mu 2} - F_{\mu 3}, \quad (1)$$

where m_{sa} is the mass of the parts listed previously. Other symbols are explained in the nomenclature. The pressure inside the orifice support, p_U, is defined by the gas. The temperature and pressure time derivate are evaluated by resolving the following system of two equations (User's guide 2013):

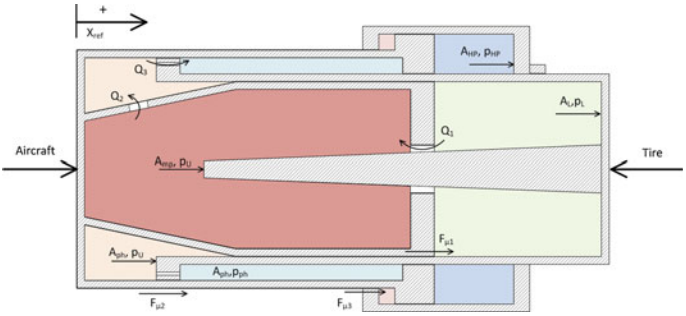

Fig. 2 Schematic of the oleo-pneumatic shock absorber

$$\begin{bmatrix} V\left(\frac{\partial \rho}{\partial P}\right)_T & V\left(\frac{\partial \rho}{\partial T}\right)_P \\ m\left(\frac{\partial h}{\partial p}\right)_T & m\left(\frac{\partial h}{\partial T}\right)_P \end{bmatrix} \begin{bmatrix} \frac{dp}{dt} \\ \frac{dT}{dt} \end{bmatrix} = \begin{bmatrix} \sum_i \frac{dm_i}{dt} - \rho \frac{dV}{dt} \\ \sum_i \frac{dm_i}{dt} h_i - h \sum_i \frac{dm_i}{dt} + \delta Q \end{bmatrix} \tag{2}$$

The density and enthalpy partial derivatives depend on the equation of state. In this study, Peng-Robinson equation of state is used (Peng and Robinson 1970):

$$\left(p + \frac{a \cdot \alpha(T)}{v^2 + 2bv - b^2}\right)(v - b) - rT = 0 \tag{3}$$

The viscous friction, $F_{\mu 2}$, is calculated from:

$$F_{\mu 2} = -\Delta p \pi \frac{d_p - d_c}{2} r_c + \mu l_c (v^+ - v^-) \pi \frac{d_p - d_c}{r_c}, \tag{4}$$

and for the frictions, $F_{\mu 1}$ and $F_{\mu 3}$ the Karnopp friction model is used (Koskinen and Aaltonen 2013):

$$\begin{aligned} F_{fric} &= \min(|F_E|, F_s) sign(F_E) \quad and\, v = 0\, if\, |v| < dv \\ F_{fric} &= \left(F_C + (F_s - F_C) e^{-\frac{3|v|}{v_s}}\right) sign(v) + F_V v \quad if\, |v| > dv \end{aligned} \tag{5}$$

The simulation model is built using LMS Imagine.LAB AMESim Revisivion 13. The model is built with submodels that form a Bond graph of the system. The Bond graph of the oleo-pneumatic shock absorber is shown in Fig. 3. The inside volume has been divided into smaller volumes, represented by the numerals in the figure. Volumes (1), (2) and (3) are thermal-hydraulic volumes, which forms the primary piston chamber and the orifice support, and volumes (2) and (5) pneumatic

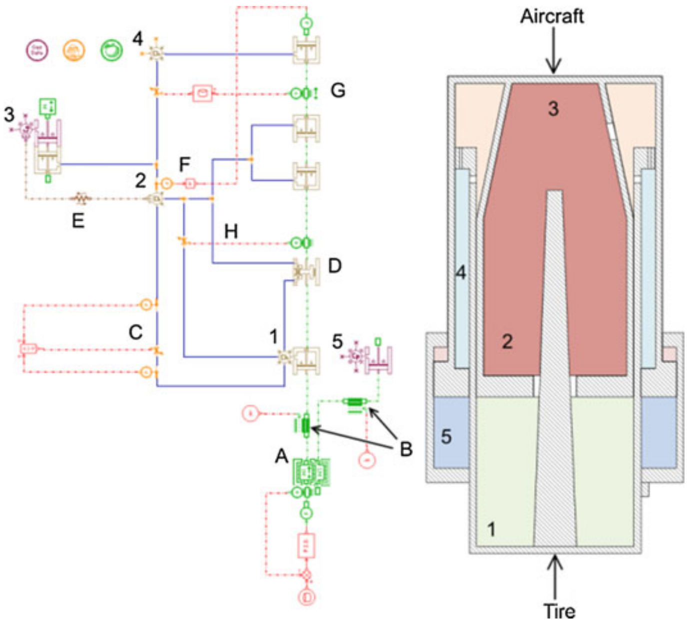

Fig. 3 The bond graph of the oleo-pneumatic shock absorber

volumes, where volume (2) is the gas inside the orifice support and (5) the high pressure chamber. The letters in the figure represent important parts of the model. The mass envelope submodel (A) has the mass, stroke length, and the dynamics between the primary piston assembly and the high pressure chamber incorporated. Two friction models (B) are responsible for the friction forces within the model.

There are three variable restriction submodels (C), (H) and (G), where (C) represents the orifices under the snubber plate (H) is the orifice between the primary piston head and the orifice support, responsible for most of the damping effect, and (G) represents the orifices in the primary piston head. Heat transfer between the gas and liquid inside the orifice support is modelled with a conduction submodel (E) and leakage between the primary piston assembly and the orifice support is modelled with leakage submodel (D). The model is missing forces acting on the metering pin and the primary piston head, which are added to the model with a submodel (F) that multiplies pressure inside the orifice support with the missing areas and converts them to a force signal.

Fluid flow through the restriction submodels are calculated with:

$$dm = c_q A \sqrt{2\rho \Delta p}, \tag{6}$$

where A is the annulus area of each orifice. One or more piston submodels are attached to the volume submodels. The piston submodels are connected in series so that they form a force system. A piston submodel receives force output from another submodel as an input, and the output is calculated from the input with:

$$f_{out} = f_{in} \pm (p - p_{atm})\frac{\pi}{4}(dp^2 - dr^2), \tag{7}$$

where the sign depends on the direction of the positive port of the piston submodel, which is represented with an arrow on the submodel symbol.

4 Validation of the Model

The model has been validated with two sets of reference data. Force-displacement data from a quasi-static test bench and pressure data from a real landing. In both cases, the model has been given the corresponding displacement as an input signal. A normalised force-displacement curve of the quasi-static case is shown in Fig. 4, and pressure inside the high pressure chamber and the orifice support during landing is shown in Fig. 5.

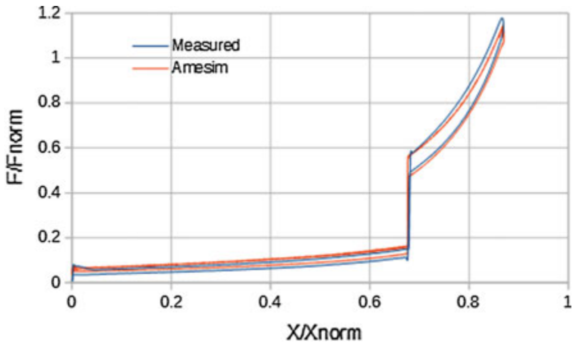

Fig. 4 A normalised force-displacement curve of the quasi-static case

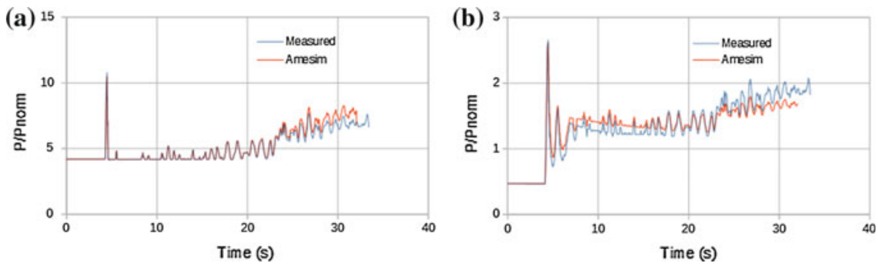

Fig. 5 Pressure inside the shock absorber during landing. **a** Inside the high pressure chamber. **b** Inside the orifice support

In both cases, the simulation is in close agreement with the measured data. The pressure inside the orifice support has the most deviation, but the model predicts the first pressure peaks correctly, which are the most important, as they represent the moment of touchdown. High friction levels were noticed during the quasi-static test bench validation, which need further examinations. It is noted that the model predicts forces and pressures generated by different shocks within an acceptable level.

5 Utilizing Simulation in Condition Monitoring and Fault Detection

The model presented in this article is to be used as a tool to improve the condition monitoring and fault detection methods concerning the shock absorber. With the model, a series of different shocks can be performed and analysed cost and time effective. Also, the model provides means to define normal pressure behaviour of the shock absorber. This could be achieved by analysing the characteristics of the pressure fluctuations inside the orifice support. The shock absorber undergoes service from time to time. During service, the hydraulic fluid is changed, and the aircraft is inoperative during that time. So it is important to develop condition monitoring and fault detection methods that minimises the downtime due to maintenance.

At present, the pressure inside the shock absorber is read from a simple pressure gauge and if the pressure is not at certain level, gas is added to the shock absorber. Adding gas without adding hydraulic fluid changes the gas-liquid ratio. If this is done multiple times, it may lead to a situation, where the shock absorber causes the main landing gear to malfunction, which can have severe consequences. To counter this, a new measuring instrument has been suggested.

The new measuring instrument would measure both pressure and temperature within the orifice support. It would also have a logical component that would perform comparison of the pressure characteristics between data collected during landing and reference data, which is defined by the normal pressure behaviour. If the characteristics during landing deviates from the reference data, the measuring instrument would indicate that the shock absorber is in need of service. As it is infeasible to do measurements with different pressures and temperatures, as the aircraft is used in conditions that can significantly vary, the model can be used to simulate these conditions so that standard operation can be defined.

As the model has only a single degree-of-freedom, it has to be incorporated to a larger model of the main landing gear that has the ability handle multi-DOF, which is required to have the effects of roll, pitch and yawn modelled. Landing is rarely perfect and there are many variables affecting the landing, such as weight of the airplane and sink speed. All these effects must be considered, when the new measuring instrument is designed. Also, a comprehensive model could be used to investigate causes of faulty operation.

6 Conclusions

A realistic analytical model of an oleo-pneumatic shock absorber has been built that has been validated with measured reference data. The model is to be used as a tool in designing a new measuring instrument for the shock absorber. Future work will involve the shock absorber model to be integrated into a larger main landing gear model so that full landing gear dynamics with multiple degrees-of-freedom can be simulated. This landing gear model can then be used to fault detection analysis during landing.

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Decision Making in Asset Management: Optimal Allocation of Resources for Maximizing Value Realization

Christoph Heitz, Lilach Goren and Jörg Sigrist

Abstract Asset Management is about realizing value from physical assets, but formal methods how to do this are still missing. In this paper, we present a formal model for decision making in asset management, based on the general concepts of ISO 55000, in particular the notion of value realization. With this framework, we can first define what optimal decisions are, and second show how to solve these problems in the context of Asset Management. The model describes both the cost and the value contributions of assets in an asset portfolio. The basic policy decision problem is decomposed into a budget setting step, and an allocation problem, where the latter can be solved with standard optimization algorithms. We apply the model to the case of an electrical supply network and find that the supply quality (value) can be increased by about 20 % without spending more money, or the costs can be decreased by 16 % without sacrificing quality, by optimized asset policy decisions with our model.

1 Introduction

Asset Management is about realizing value from physical assets (ISO 55000 2014). ISO 55000 has set the stage for Asset Management but does not specify how to derive optimal decisions. The purpose of the paper is to develop a formal model for decision making in asset management, based on the general concepts of ISO 55000, in particular the notion of value realization. With this framework, we can define

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what optimal decisions are, learn how to solve the decision problem. Thus, the model is a substantial step forward from speaking about value realization to implementing improved value realization in practice.

2 General Model of Physical Asset Portfolio

In this section, we derive a general model of a physical asset or a portfolio of physical assets that is suitable to be used in the context of Asset Management as defined in ISO 55000. We consider a portfolio of technical assets, such as an electricity supply network (consisting of cables, transformers, switches, and other elements), or a production system (consisting of production machines, conveyor belts, and similar equipment). In the framework of physical asset management, an asset is basically an object that creates some costs, and at the same time generates value for the owner by its usage in a specific business environment (ISO 55000 2014). More precisely, it is the technical performance of the asset, embedded in a business process, that generates value for the owner. Any model for asset management should thus include both the cost generation and the value creation. Both cost and value depend on the general business setting and the underlying business process in which the asset portfolio is used. In the following, we assume this business setting as given, and focus on the asset management within this business environment.

From an asset management perspective, the most important aspect for both costs and value creation is the way of managing the assets over their lifetime. Each asset has a lifecycle management policy with which the asset owner chooses to manage the assets. Typical policy questions are the type and frequency of preventive maintenance activities, or the decision on how long to use the asset. In the following sections, we will first define the meaning of cost and value in the present context, and then relate these two aspects of asset management to the third important aspect: the lifecycle management policy.

2.1 Value

The reason why assets are purchased and operated is that they create some sort of value for the owner. It is thus important to define the term value in a precise way. According to the definition of the ISO 55000, in the context of the current paper the term value is used for denoting the business value, i.e. the reason why an asset has been purchased and installed in the first place. This value may be the ability of generating revenues in the case of a production machine, or the ability of transporting electrical energy reliably in the case of an electrical power line. Note that there are other definitions for "value", such as the reselling value or the bookkeeping value, which must not be confused.

The actual meaning and definition of “value” depends on the context and the business environment of the asset owner. Naturally, for different businesses, value is defined differently. For the following, we assume that someone has defined what “value” is in the specific context.

A property of value is that it is created during the operation of the asset portfolio. This means: value is generated over time. Thus, value is, defined more precisely, a value *stream* or value creation rate v(t). For example, a production system that produces items with a specific production rate can be seen as generating value during its operation, and this value might be expressed in units “$ per time”.

Another property of value is that it can typically only be defined on the portfolio level, not on the single asset level. In most cases, a single asset as such has no value at all. Consider, for example, an electrical transformer of an electricity supply network. Taken alone, this transformer has no value at all. It only creates value as a part of a network, i.e. within an asset portfolio. Thus, it is quite natural (and often required) to define value creation on the portfolio level.

Given a specific business environment, the value generation of an asset portfolio is realized by using the technical performance of the asset portfolio in the business process. The technical performance itself depends on two factors: First, there is the *design functionality* of the asset portfolio, meaning the functionality under ideal conditions (no failures, no disruptions, ideal reliability…). In reality, however, there are reductions of the design functionality, manifesting themselves in downtime, quality issues, and the like (see the discussion in RCM literature, e.g. Moubray 1997). Thus, the real performance of the assets is reduced compared to the design functionality, and so is the value creation. Generally speaking, this reduction is a function of the state S_i of the single assets i = 1, 2, … n of the asset portfolio. As the state deteriorates over lifetime, the value creation ability of an asset portfolio will typically decrease over time. So, the value generation rate v(t) can be written as

$$v(t) = v_0 - \Delta v(S_1(t), S_2(t), \ldots, S_n(t)) \tag{1}$$

where v_0 denotes the value creation at design functionality, and Δv the reduction due to the time dependent state of the assets. In many cases, the reduction of the ideal value creation can be attributed to failures and downtime. In such a case, the value function can often be formulated as

$$v(t) = v_0 - \sum_{i=1}^{n} \alpha_i \cdot \lambda_i(t) \tag{2}$$

where α_i is a weighting factor, and λ_i is the (time-dependent) failure rate of asset *i*. The weighting factor α_i is influenced by different factors such as importance of the asset in the portfolio, or the downtime in case of a failure. The higher the importance of the asset, and the longer the downtime in case of a failure, the higher is the value reduction due to the failure, and hence the greater is the value for α_i.

In the context of asset management, we are not that much interested in the momentary value creation, but typically adopt a lifecycle perspective. Thus, Eq. 2 can be formulated in a time averaged form

$$\bar{v} = v_0 - \sum_{i=1}^{n} \alpha_i \cdot \bar{\lambda}_i \tag{3}$$

where the bar denotes time averaging. In this form we can see the general mechanism of value creation: The value is created on the level of the whole asset portfolio (described by its design value v_0), but it is reduced by value reducing terms, where each asset adds its own value reducing contribution. We may thus reformulate Eq. 2 in the following form:

$$\bar{v} = v_0 + \sum_{i=1}^{n} \overline{v_i} \tag{4}$$

with $\overline{v_i}$ is the value term of asset i. Note that this additive form is a simplification—more complex forms are conceivable. However, in many cases this is a reasonable assumption. For example, this is exactly the form that is used in risk management and risk based maintenance, where we would set $v_0 = 0$, and $\overline{v_i}$ the risk contribution of asset i.

2.2 Costs

The structure of the cost dimension is similar to the structure of the value, in that costs also are being created over time, as a cost stream. Typically, at the beginning of the life cycle, there is a large cost component in form of investment and installation costs. Later in the lifecycle, maintenance and repair costs add to the cost structure, and at the end of the lifecycle, disposal costs may arise. Similar to value, we adopt a lifecycle perspective, and consequently reduce the complex cost stream to averaged annual costs, or to annual equivalent costs if we want to include the effect of time value of money. Usually, an additive structure of the total portfolio cost is reasonable: the total costs are calculated as a sum of single asset costs:

$$\bar{c} = \sum_{i=1}^{n} \overline{c_i} \tag{5}$$

where the bar again denotes a time average, with or without discounting.

2.3 Cost and Value Generation and Policy

Both costs and value generation of an asset portfolio depend on the lifecycle management policies for the assets. More specifically, for a single asset i, both the value contribution v_i as well as the costs contribution c_i are directly dependent on the policy. For example, if the usage time for an asset is reduced (meaning an earlier replacement), then typically the average costs increase, because the investment costs are to be distributed over a shorter time period. At the same time, the value reduction is increased: The asset creates more value, but at higher costs. Thus, both cost and value of an asset are not a given property of the asset, but are determined by the lifecycle management policy. Different policies for asset i may lead to different combinations (c_i, v_i). In Fig. 1, this is schematically show: a set of different policies is indicated as a set of dots in a two-dimensional cost-value space. Note that there may be a continuum of operation policies (e.g. usage times can be chosen continuously), but for the sake of clarity we use discrete policies here.

As an example, we consider an asset that costs 1 M$ for purchase and installation, and has a maximal lifetime of 22 years, if no maintenance is made. Alternatively, a maintenance program can be carried out which reduces the decay of the value generation rate and leads to a longer lifetime. This maintenance policy generates average costs of 60 k$/year. The value generation rates v(t) of both policies are displayed in Fig. 2a. In this example, the value generation rate is normalized, assigning a value rate of 1 for a new asset.

In addition to the maintenance policy, the usage time has to be specified as well. In fact, the choice of the usage time of an asset is one important parameter of the operation policy. In Fig. 2b, the resulting plot of v (average value creation rate) against c (average cost rate) is shown for different usage times. Each point corresponds to a specific usage time, while the marker distinguishes between the two maintenance policies.

The cost-value plot shows the performance of the asset in terms of cost and value creation: high cost rates c correspond to a high value creation rate, because a high c means a short lifecycle, and vice versa. It can furthermore be seen that the two

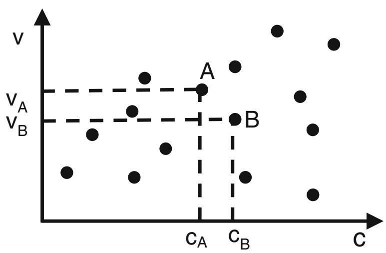

Fig. 1 Model of a physical asset as set of different cost/value combinations. Each possible operation policy is denoted by a point in the two-dimensional cost-value space. For example, the policy A leads to average annual costs c_A and average annual value creation v_A

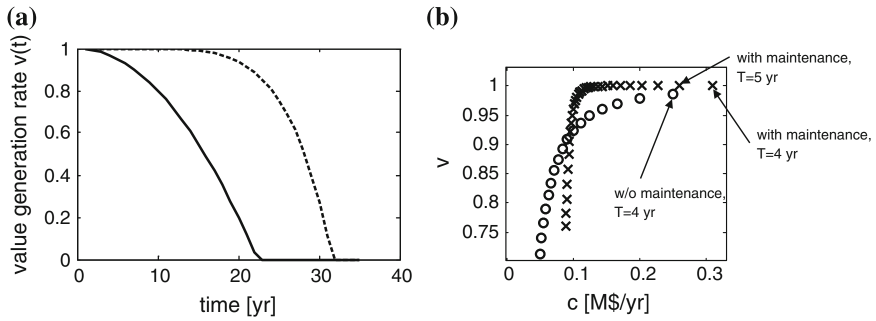

Fig. 2 **a** Value creation rate v(t) over the lifetime. *Solid line* without maintenance. *Dashed line* with maintenance. *Right* Display of different operation policies in the c–v space. *Circles* correspond to the case without maintenance, while x correspond to the case with maintenance. Each marker corresponds to a specific combination of usage time and maintenance policy

operation policies behave quite differently. There is a region where more value is being created with the maintenance program (for average annual costs higher than roughly 0.1 M$/year), where there is another region where the maintenance program essentially leads to an inferior investment performance. For example, if one would like to spend only 0.09 M$/year on the asset, then the maintenance program does not make any sense. This budget constraint would lead to a usage time of roughly 33 years, and an average value creation of 0.8, while in the case of skipping the maintenance program altogether, the same budget would lead to an average annual value creation of 0.91, with a usage time of about 11 years.

3 Decision Making in Asset Management

Decisions making in asset management includes all asset related decisions from the investment decision, over maintenance decisions, until the replacement decision. We denote the set of all decisions during the lifetime by the term "lifetime policy" of the asset. As shown above, any given asset can be modelled as a set of policies in a two-dimensional cost-value space. The fundamental decision problem of asset management is the choice of one of the possible policies, for each asset.

The goal of asset management is to create as much value as possible with as little costs as possible. This goal is set on the portfolio level, but is realized on the asset level: For each asset, a policy has been chosen, such that the portfolio value is maximized while the costs are minimized. Of course, value maximization and cost minimization contradict each other. More value typically incurs more costs. However, the model stated above helps to get a clearer picture of the problem.

First we can state that, on the individual asset level, we have the same tradeoff between costs and value as on the portfolio level. However, there are policies that make no sense at all. For example, in Fig. 1, policy B is more expansive than policy

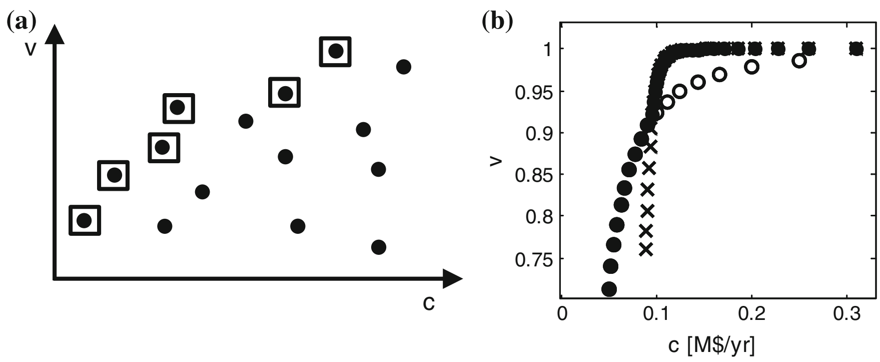

Fig. 3 **a** The Pareto frontier of the asset of Fig. 1. The dominating policies are denoted by *surrounding squares*. **b** Pareto frontier of the asset of Fig. 1, denoted by *black filled circles*

A, and, at the same time, creates less value. So, A is superior to B in both aspects. We can thus reduce the set of all policies to a set of reasonable policies, by finding the Pareto frontier of the policies (e.g. Censor (1977) or Da Cunha and Polak (1967)), see Fig. 3a, b.

However, this does not solve the decision problem: there are still several policies on the Pareto frontier, where more costs always are coupled with a higher value creation. Thus, it is not clear how the optimal asset policies have to be chosen on the asset level.

On the other hand, on the portfolio level, the decision problem can be decomposed in two steps, the first step consisting in the decision how large the total budget for the whole portfolio should be, and the second step consisting in the allocation of the total budget to the single assets.

We will first focus on the second decision problem. For this, we assume that a total average annual budget of B is given for the lifetime management of the asset portfolio. This budget is used to cover the lifecycle costs of the portfolio. Thus, we end up in a well-defined optimization problem:

$$\bar{v} = v_0 + \sum_i \overline{v_i} = \max., \quad \text{subject to } \bar{c} = \sum_i \bar{c}_i \leq B \tag{6}$$

This problem can be solved with standard optimization methods. In practice, a reasonable approximation is to decompose the investment in an asset into partial investments and allocate the total budget such that the Marginal Cost Effectiveness MCE (cmp. e.g., Uddin et al. 2013) is nearly equal for each asset (Heitz and Goren 2014). For the case of a continuous and concave Pareto frontier, the optimum solution is given by the Equimarginal Principle, also known as Gossen's Law (Gossen 1983; Krugman and Wells 2015).

After the allocation problem is solved, for each asset the optimum policy is determined, given the total budget B, and the total average value $\bar{v}(B)$ as a function of B is available. Of course, when changing the budget B, the policies for *all* assets might change, reflecting the fact that when additional money is spent for the system, this is distributed unequally among the assets, with more additional investment on assets that are more relevant for the value creation.

The first decision problem, the determination of the total budget B, can now be tackled. However, since a higher budget always means higher value creation, the function $\bar{v}(B)$ can be interpreted as the Pareto frontier of the full decision problem, where the decision space is the set of all *combinations* of single asset policies. It represents the trade-off between total budget and total value. However, in contrast to the allocation problem, this decision problem cannot be solved without additional criteria. On the other hand, the $\bar{v}(B)$ function may serve as an easily understandable basis for decision making, as it describes the relation between costs and value creation on a system or portfolio level, without the need of explicitely describing the underlying asset management policies.

4 Application: Electrical Supply Network

As an application, we study the case of the network of a Swiss electricity provider, more specifically the low- and medium-voltage network, including all assets such as cables, power lines, transformers, switches, and so on. In total, the asset portfolio consists of 19 different asset categories with about 30’000 single assets. The value creation was defined as the negative of the SAIFI value. SAIFI stands for *System Average Interruption Frequency Index*, which is one of the standard performance indicators for the supply quality of an electrical network (see Council of European Energy Regulators 2014). As for the asset policies, only the lifetime has been considered as a decision variable. Thus, the decision problem was to determine the optimum lifetimes for the single assets, thus focusing on the replacement decision.

Using the information of the geographic information system (GIS), the contribution of each asset to the total supply quality was modeled. The age-dependent failure rate was modeled for each asset category. The allocation problem was solved under the additional constraint of a minimum and a maximum lifetime (specific for each asset category). The result of solving the allocation problem is the set of *individual* lifetimes, depending on the costs and value contributions of the individual assets. In Fig. 4, the cost-value function $\bar{v}(B)$ is displayed, for the case of standard lifetimes (equal lifetimes for all assets in a given asset category—dotted line), and for the case of optimized lifetimes (solid line). The most expansive solution is to set all assets to their minimum lifetime. This results in the maximum value creation. The other extreme solution is to set all assets to their maximum lifetime, resulting in the least expansive scenario with the lowest supply quality. For both extreme cases, there is no freedom left for the budget allocation. However, in between, solving the allocation problem as defined above leads to an increase of quality for a given budget, compared to using standard lifetimes.

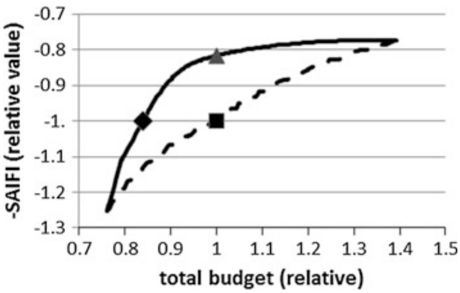

Fig. 4 The cost-value function $\bar{v}(B)$ for an electrical supply network. *Dotted line* standard lifetimes for the asset categories. *Solid line* optimized individual lifetimes, by solving the allocation problem. *Filled square* (■) current policy. *Filled triangle* (▲) value maximization with fixed budget. *Filled diamond* (♦) cost minimization with fixed value generation

The square denotes the reference point of today's asset management policy, which is characterized by equal lifetimes for all assets within the same asset category, and a state-of-the-art lifetime. By optimizing the lifetimes, the supply quality can be improved by about 20 % (▲), at the same costs. Conversely, one might have the goal to decrease costs while retaining today's supply quality, leading to the policy ♦, which is about 16 % cheaper than the reference solution.

Thus, significant cost reductions and/or quality improvement can be gained by using the model as described above. During the last years, we have performed different case studies for electrical networks as well as for water supply networks, and found remarkably similar results. Thus, these figures seem to be representative for existing supply networks.

5 Conclusion

We have derived a new model for asset management decision making, based on a conjoint modelling of both the cost and the value aspect of assets and asset portfolios. Value creation is realized on the portfolio level, and each asset has a specific value contribution. Lifecycle management decisions should tend to minimizes costs and, at the same time, maximize value creation. The corresponding decision problem can be seen as a policy decision problem which can be decomposed in two elements: setting the total average annual budget for the portfolio on the one hand, and allocating this total budget to the individual assets on the other hand. The allocation problem can be solved by standard optimization methods. We have shown that the application of our model to real-world examples may lead to significant cost reduction and/or increase of value creation.

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From CAPEX to OPEX—The Handover Management Paradigm

Malcolm Hide

Abstract Handover management looks at the holistic transfer of assets from a project delivery into an operational environment. While project teams consider the delivery of a working system within the defined budget to be of primary importance, the reality is that from an end user perspective there is a lot more at stake. This paper presents the elements to be considered in order to deliver a system into operation in a way that it can be supported, managed and maintained going forward in an operational environment. It covers the lessons learned and experience gained delivering several baggage systems in two major international airports in the UK, covering new build as well as replacement of existing elements within the baggage systems.

1 Introduction

We all know that in a project environment the primary drivers are time, budget, and quality. Good project managers are however defined by the number of projects they have delivered on time, within budget however quality of delivery is seldom a measure. Operational drivers are cost and throughput, and their managers are defined by their ability to drive operational costs down and deliver a reliable and safe production to meet customer demand. In many cases the fact that there are differing drivers creates tension and potential conflict at the interface.

From a project perspective the operational teams are seen as continually trying to increase or change the project scope by requiring something different from what was originally agreed. Operations teams are also seen as delaying the final acceptance of the project as specified and delivered in order to avoid taking responsibility for an operation they are not yet comfortable with.

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From an operational perspective, project teams are seen as having shot term objectives focused on the handover of the “keys”, and the closer they get to the end of the project the more their focus shifts to the next project. In addition to this when a new system is delivered, it will usually be more complex than the one the operational teams are used to and this complexity leads to uncertainty (Fig. 1).

In our daily lives we manage differing drivers as normal, with examples including when we buy a house or a car. We know what we want and our drivers are clear to us, and the driver for the sales person is also clear—where they have no long term interest in the commitment, only a short term drive to make the sale. We also know how the process works, and if we can’t get everything we want, we agree on compromises whether they are in terms of feature, function or finish.

So, if we exist in a world of differing drivers and apply the concept of compromise on a daily basis, why do we so often find such negativity between the team delivering a project and the operations departments? We believe that the root cause of this is that in most cases both parties do not know the details of what is being delivered[1] and what has been excluded due to compromises made during the project delivery.[2] As a net result of this, assumptions are made by the operations teams, and when the cost or time pressure on the project team is increasing, often you will find short cuts are taken to the detriment of the final operation.

This is effectively where handover management can simplify the process as well as eliminate a lot of the conjecture and negativity around project delivery. Handover management therefore manages the transition from CAPEX to OPEX, making it clear to all parties what is being delivered, how it will be taken into the operational environment while minimising transition impact and managing various stakeholder concerns.

2 Handover Management Overview

The Handover Management process effectively defines a project’s ‘exit strategy’,[3] and when there are clearly identified deliverables and a clearly defined process, it creates a simpler more efficient delivery strategy. Handover isn’t something that is confined to the end of the project, but is defined early in the process in the form of a Handover Management Plan, allowing the delivery to be managed against the plan for the duration of the project.

It also needs to be stressed that this handover management plan is neither the project schedule nor the quality management plan. Project schedule creation and

[1] http://www.pmis-consulting.com/what-goes-wrong-with-projects/.

[2] CHAOS Report—The Standish Group.

[3] “An exit strategy is a planned approach to terminating a situation in a way that will maximize benefit and/or minimize damage.’ http://whatis.techtarget.com/definition/exit-strategy

Fig. 1 CAPEX to OPEX transition incorporating handover management

management is a well-honed skill of many project managers,[4] and is therefore left to the project manager to control. Similarly the quality management plan[5] is in many ways a standard process adopted and managed by a supplier to ensure their quality standards are adhered to. The Handover Management plan is focused on what, where and how the various elements of a specific project will be handed over. For example:

- 'The document delivery list (supplied) defines all delivery documents, and these will be delivered in four phases throughout the project. Once a document is delivered it needs to be reviewed and commented on within three weeks. All comments will be addressed and the final document will be loaded into "X" document repository within three weeks of the comments being received.'

Handover Management feeds off the results of a solid quality management process. If the contractor has a robust quality management system in place where all equipment and functionality tests are clearly defined, it simplifies the handover process. An example of this is a clearly defined ITP (Inspection and Test Plan), which sets out the equipment installation and commissioning process step by step, clearly identifying all tests to be carried out, certification to be supplied, and each of the quality hold points during the process.

Handover Management can be broken up into the nine distinct elements set out below. Each of these are interdependent, however the overall success of a handover will be judged by how well the delivery of each sub grouping is managed.

2.1 Physical Acceptance

Physical acceptance covers the review and acceptance of the tangible components supplied as part of the project delivery. There are usually two separate work streams, namely Hardware and Infrastructure, as shown in Fig. 2. Each of these work streams would go through several tests or inspections culminating in customer acceptance.

[4]Guide to Project Management Body of Knowledge 5th Edition 2013, PMI.

[5]ISO9001 Sect. 8.2.

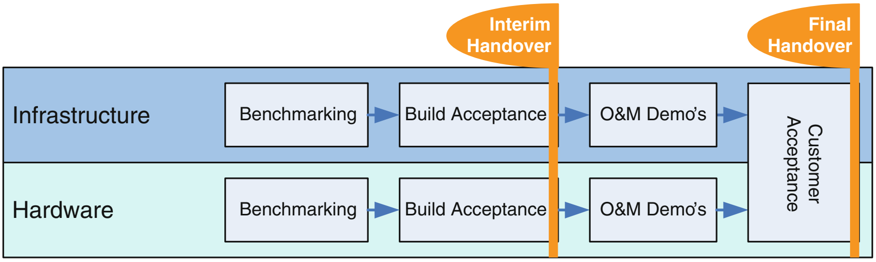

Fig. 2 Physical acceptance process

From a project perspective, the physical acceptance is usually a well-managed element, where defect inspections are carried out with the operations teams and snags are identified and closed out. From a handover management perspective, we are more concerned with ensuring that there is a controlled process in place, and that the defects are closed out.

An area to monitor and be aware of is the potential for scope creep[6] during these inspections, or to allow opinion engineering to interfere. Both of these need to be managed and contained when they present themselves, which comes back to proper stakeholder engagement through the handover management function.

2.2 *Functional Acceptance*

Functional acceptance covers the review and acceptance of the system functionality. It takes the Equipment and Infrastructure delivered as part of the physical acceptance, and turns it into an operating and functional system. In some simple projects the Functional acceptance is almost non-existent as the control systems are extremely simple. Once again there are two separate work streams, namely Controls and Applications, as shown in Fig. 3. Each of these work streams go through several tests or inspections, culminating in the Customer Acceptance.

From a project perspective this element is also fairly well controlled, however it is also an area where short cuts may be taken as this is usually when the project team is under immense time pressures.

As iSAT's (integrated Site Acceptance Tests) are formal acceptance tests they are usually planned and performed over a pre-defined period, as agreed between the project team and stakeholders in the operations team and are co-ordinated by the Handover Manager. This is another area where scope creep or functionality changes can be introduced, and needs to be tightly managed. The majority of these tests are

[6]Scope creep (also called requirement creep, function creep and feature creep) in project management refers to uncontrolled changes or continuous growth in a project's scope.

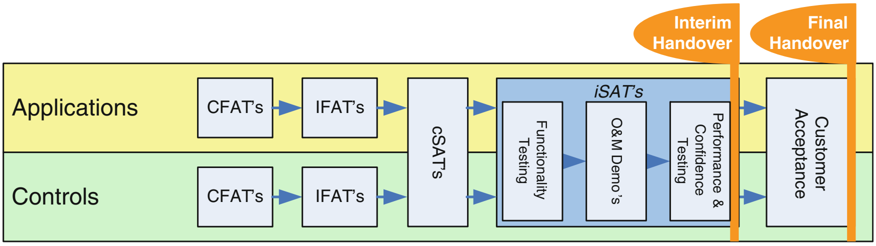

Fig. 3 Functional acceptance process

usually carried out close to the end of the project, and any changes at this stage can result in delays to the project delivery.

While the handover management function would not be responsible for performing or monitoring these tests, it needs to monitor the results of the testing and to manage stakeholder expectations. In addition to this we need to monitor the close out of identified functional deficiencies. This helps to ensure that the system provides all of the required functionality as defined in the URD.

2.3 Documentation

During the delivery of the project, there is a potential that a huge volume of documentation will be generated.[7] While a lot of the documentation will be related to the project itself, some will be required for Operations and Maintenance of the system or for future enhancements to the system. It is essential to identify this delivery documentation as early in the project as possible in the form of a document delivery list, and to ensure that all aspects of the delivery are covered. We have found that there are four classes of documentation that are required:

- As-Built Documentation which covers drawings, schematics and model files. These files will go through several iterations throughout the life of the project, and need to be tracked to ensure all elements are updated to the final delivery status on completion of the project.
- Operations and Maintenance Documentation which covers items such as standard manufacturers literature, residual risk reviews, maintenance method statements, operational instructions, training materials and maintenance instructions.
- Basis of Design Documentation includes elements such as the URD, Detailed Design Specifications, User Interface Specifications, test certification and records of any deviations from defined standards and their justification. This is a

[7]London Heathrow Terminal 5 Baggage System Circa 3500 documents final delivery within 6 months of completion.

particularly important part of the delivery documentation—in most instances the documentation would never be required, however, if there was to be a query around functionality or future enhancements, these documents are the ones you would need.

- Test Certification is quite frequently neglected or not controlled properly, and then results in a mad scramble towards the end of the project to try and get them together. We have found that by having a clearly defined ITP where the relevant certification is defined, and provided with the test plan, and then this issue is limited.

The handover management function is to monitor the documentation delivery, track document review progress and to ensure that the overall delivery list is being managed adequately.[8] Where documents go through several review and update iterations, then it is essential those reviewer's comments are tracked and that they are cleared when the next release is issued.

2.4 *Software Management and Licensing*

Software and control systems have become the norm in industrial applications. As a result when a project is delivered, there will be a plethora of software applications and local bespoke codes or parameters developed as part of the project delivery. All of these need to be backed up and safeguarded as part of the handover process. This allows the operations team to roll back the software and set points to those that were provided when the system was commissioned if necessary.

In addition to this there will be a number of the computers and control systems that will have defined software applications loaded on them, and the licences for the software will need to be controlled in order to ensure they are available to reload onto their replacements should it be necessary, or for audit purposes. Some of these licenses may need to be renewed on an on-going basis, such as anti-virus software or perpetual licensed systems. It is important that the renewal dates are tracked to ensure that they do not expire during the handover and early life phases of the system, and are built into the budget going forward.

Where bespoke software is developed for a system, there might be a requirement for this to be managed under an escrow agreement. This is intended to protect the end user of the system from the supplier going into liquidation, leaving them without access to the source code in the event that modifications are required.

[8]Gatwick Pier Refurbishment Circa 3300 documents final delivery 1 year after completion.

2.5 Training

An essential part of any handover process is the delivery of focused training to ensure that the new system can be adopted into the operation as seamlessly as possible.[9] There are three distinct types of training that need to be covered:

- Familiarisation training
- Operational training
- Maintenance training

A detailed training matrix should be developed to match individual training packages required for the system against defined roles. Each of these training packages needs to be developed to a level required for the identified roles. In existing systems a Training Needs Analysis needs to be performed to assess the current skills and identify what new skills are needed to match the requirements of the new system, and the training adapted accordingly.

2.6 Training Delivery

There should be a mixture of training delivery methods, from classroom based to hands on.[10] The management and delivery of the training to the operational teams will need to be closely monitored and managed, as the success of the transition between CAPEX and OPEX will depend on the operational team being trained well enough to perform their duties correctly.

This is often easier to achieve in new build environments because existing operational teams would already have their own duties, and consequently, training would be an add-on to their existing workload. This usually requires a lot of effort and negotiation with the various stakeholders to ensure it goes off smoothly.

2.7 Maintenance and Operational Integration

There are three elements to the maintenance integration process, which help align the delivery with ISO 55000 requirements:

- Ensure that all assets are registered within a CMMS (Computerised Maintenance Management system).

[9] Provision and Use of Work Equipment Regulations 1998.

[10] http://trainingtoday.blr.com/employee-training-resources/How-to-Choose-the-Most-Effective-Training-Techniques.

- Ensure that the maintenance plans are in place, covering what needs to be done at the required frequency to meet warrantee requirements.
- Ensure that the required spares are available for use when the system goes live.

There are many publications on how to define a maintenance plan, and many people experienced in doing this and as such this paper does not cover it. Suffice it to say that this process can start as soon as the design is complete once all the assets have been identified.

The operational integration process needs to look at how the system will be run and how this fits existing business processes. It is vital that the system designers help the operational team to develop a set of Standard Operating Practices and Contingency Standard Operating Practices, which cover how the system should be run in a normal operational environment, as well as in system related contingency modes. These CSOP’s will also need to be expanded beyond the system, to look at bigger picture contingency modes that are not system related.

2.8 Operational Readiness and Go-Live

Operational readiness is a progressive state indicating the maturity of the project handover. In the run up to the go-live phase of the project, several operational trials should be identified and planned. These trials would require co-operation between all of the stakeholders and as a result, it is vital that they have been engaged with the process every step of the way, and understand their roles in the particular tests being carried out. During this period, both the most suitable system configurations and the contingency operations need to be identified and tested.

Once the operational trials are complete, the system enters a reliability period during the early go-live phase, to ensure that a reasonable level of operational maturity has been achieved. During this period, daily error logs are reviewed, RCA (Root Cause Analysis) is performed on any failures, and assessments made of the system performance.

Once the system has gone through the reliability phase, it enters a confidence period where operational teams run the system with support from the project team. This is the most important phase of the handover, as this is where the results of all the activities monitored by the handover team are put to the test. This is when weaknesses are identified within the operation and corrective actions are set in place to address them.

2.9 Post Go-Live System Optimisation

With the system is in live operation, and a series of corrective actions in place to resolve operational issues, it is time to focus on the system performance. In many

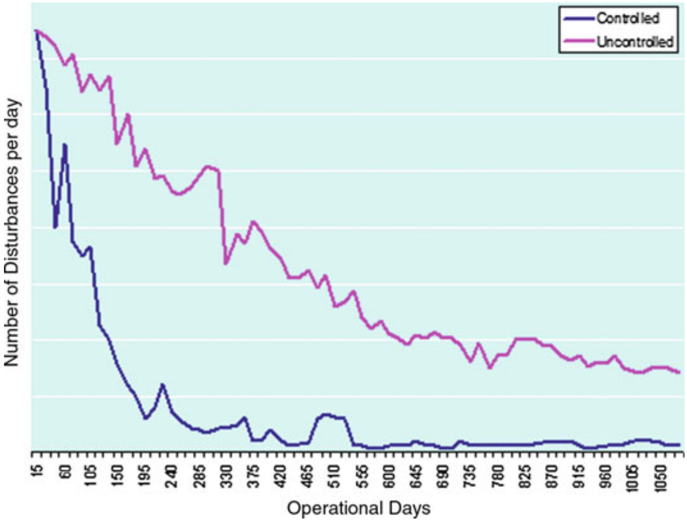

Fig. 4 Controlled versus uncontrolled system disturbance management

industries the system performance will vary from a test environment into real production, and this might result in operating parameters, response times and PID (Proportional-Integral-Derivative) loops that need to be adjusted.

Our experience has shown that the disturbance rate[11] on a system post go-live is invariably higher than it is after a settling in period as shown in Fig. 4. The key, however, as shown in the graph below, is how quickly the system error rate can be brought down to a "normal" level of system related noise as this is directly related to operational cost reduction.

[11]The disturbance rate is related to any stoppages, quality deviations, warnings, extended repair or set-up times and input deviations.

A Pattern Recognition Methodology for Fault Detection: A Circuit Breaker Case Study

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Abstract Maintenance strategies have evolved from standard cyclic maintenance to more advanced approaches like *Condition Based Maintenance* and *Predictive Maintenance* approach. Even if lot of work has been done regarding these methodologies applied on machines or industrial plants, the same care is not applied to other critical devices. In the case of *Low Voltage Circuit Breakers*, in particular for critical applications, conservative approaches are usually applied. That implies a scheduled replacement of devices could occur with a significant *Remaining Useful-Life*. This paper deals with *Pattern Recognition* techniques supporting the first step of prognostics of an electrical circuit breaker. The goal is to develop a methodology for *Fault Detection*, the first phase of a *system of Fault Detection and Isolation*.

1 Introduction

Globalization and more stringent requirements push managers to optimize all systems involved in their organizations. In this scenario, maintenance plays a key role for reaching the KPI needed for equipment reliability and availability. Maintenance approach has changed in the last years, moving from *Repair Maintenance* (RM) to *Preventive Maintenance* (PM) and *Condition Based*

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Maintenance (CBM) which evaluates the equipment health condition by performing a periodic or continuous condition monitoring of the equipment itself, requiring maintenance only when the presence of anomalous behavior, compared with normal operation of the physical system, is detected. As a further evolution, *Predictive Maintenance* (PdM) aims at predicting the future trend of the equipment health conditions, according to prognostics approach (Jardine et al. 2006).

CBM refers to *diagnostic* as the process of detection, isolation and identification of faults when they occur (EN 13306 2001) by monitoring the weak signals of a physical asset so as to extract information characterizing the system state of health (Katipamula and Brambley 2005). The natural evolution of CBM is *prognostic* that attempts to predict faults or failures before they occur and projects the *Remaining Useful-Life* (RUL) (Kothamasu et al. 2009) of a physical system through the use of automated methods. Even if *prognostic* can prevent faults or failures, it cannot completely replace d*iagnostic,* because there are always some faults and failures which are not predictable due to the probabilistic approach of a failure.

Despite the presence in literature of a plethora of works, PdM policy is difficult to apply to critical industrial devices which have a bi-stable behavior (having two stable states, working and not working) such as an electrical Circuit Breaker (CB). In these devices it is more complex to maximize the information content provided by the equipment during the transition from one state to another in comparison with an equipment characterized by a continuous behavior (Fasanotti et al. 2014).

The purpose of the paper moves in this direction, by presenting some experimental results of the use of *Pattern Recognition* (PR) techniques supporting the first step of prognostics of an electrical *Low Voltage Circuit Breaker* (LVCB). The goal is to develop a methodology for Fault Detection, the first phase of a system FDI (Fault Detection and Isolation), using PR techniques.

2 State of the Art

Traditionally, diagnostic methods are classified in *Model Based Methods* and *Process History Based Methods,* depending on the type of knowledge used in the definition of the relative model (Katipamula and Brambley 2005). Figure 1 shows a schematic picture of methods used for diagnostics in industrial equipment.

The *Model Based Methods* are developed from a priori knowledge of the process, which is based on a physical understanding of the same. According to whether information is quantitative or qualitative we can identify Q*uantitative Model Based Methods* and *Qualitative Model Based Methods*. The first methods are based on an analytical redundancy through the use of mathematical models: the idea is to check the actual system behavior against the system model for consistency. Any inconsistency, expressed as residuals, can be used for detection and isolation purposes (Venkatasubramanian et al. 2003a). The second methods express the a priori knowledge of the system in terms of qualitative relations used to draw conclusions about the status of the same. In particular, *Rule Based Systems* derive a set of

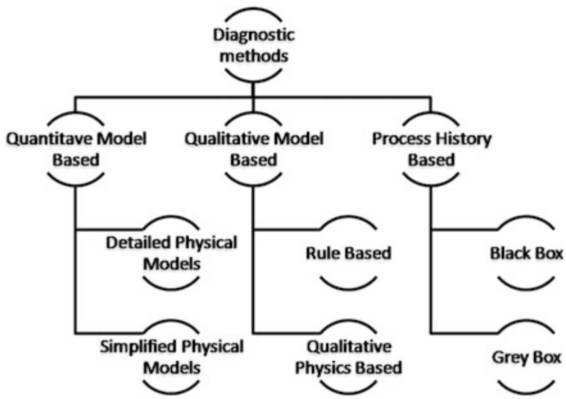

Fig. 1 Schematic state of the arts of diagnostic methods

instructions in term of if-then-else, and *Physics Based Systems* start from the qualitative description of the physical mechanism to build a model and use an algorithm to determine all the behaviors of the system (Venkatasubramanian et al. 2003b). *Process History Based Methods* are developed from a large amount of historical process data because they define a mathematical model that explains the relationship between the measured input and the output (*black-box*). This model has to be descriptive, in that it must derive knowledge from data (*knowledge extraction*), and predictive, so as to make predictions, assuming that in the future data behavior will not be very different from the one observed during data collection (Venkatasubramanian et al. 2003c). At the base of such an approach there is the methodology of *Machine Learning*, which through the use of exemplary data of past experience, obtains the optimized model parameters (Alpaydin 2014). Engineering refers to PR, a methodology whose goal is the classification of *Patterns*, characterized by measurable quantities, said *Features*, in a finite number of classes, said *Labels*, according to the following steps:

- *Data collection* through an appropriate set-up of measurement;
- *Feature extraction* starting from data collected and building new features, using appropriate algorithms (i.e. Kurtosis or Wavelet analysis), able to distinguish the normal operation from a wear-out condition;
- *Feature selection*: filtering these features to identify the most significant ones which allow to discriminate the operational conditions;
- *Classifier design*: training of a classifier aims at discriminating the future operations of the system;
- *Evaluation* of the process put in place.

3 Methodology

As already mentioned, this paper aims at providing the effectiveness in using PR techniques for diagnostic purposes of a bi-stable critical equipment such as a low voltage circuit breaker. Due to the complexity of the functional mechanism of this kind of equipment, hard to be physically modeled, at the base of the diagnostic model for LVCB, a Process History Based method has been used following the steps before described.

3.1 Data Collection

The core of an effective process of PR is the selection of a set of suitable signals in order to get information regarding the status of the system and the relative measurement set-up. In literature, several papers deal with the selection of the more relevant signals and the relative sensorization for High Voltage Circuit Breakers (HVCBs), while for LVCBs there are no significant studies. In particular, the second CIGRÉ inquiry (Heising et al. 1994) on HVCBs reported that the majority of failures has a mechanical or an electrical origin. From the mechanical point of view, HVCBs vibration analysis through accelerometers and the measure of the main contacts position during opening/closing operations (Landry et al. 2008) are the most relevant monitoring techniques. On the electrical side, there are several papers dealing with the application of Electrical Signature Analysis (ESA) (Fumagalli et al. 2010) to the command devices of the CB. Given the lack of specific studies about the major causes of failure for LVCBs, and on the basis of the experience of engineers, it is assumed that the indications found for HVCBs could be applied to this specific case, also due to the similarities in terms of functional blocks and characteristics of the system.

The selected signals and relative sensorization are:

- *Acceleration*: Vibrations caused by the collisions of main contacts and other mechanical parts during closing/opening operations, measured with a tri-axial piezoelectric accelerometer;
- *Current Sensor*: The current absorption of every control electromechanical device, measured with a Hall Effect current sensor.
- *Angular position*: The angular position of the main shaft of the CB, that is proportional to the position of the mobile part of main contacts, measured with an incremental rotary encoder.

3.2 Features Extraction

Starting from data collected during an experimental campaign, it is possible to synthesize the information contained in signals through the generation of significant features (*Features extraction*). The simplest and fastest way to extract features is to find a set of considerable points of a measured time signal, i.e. those attributable to critical aspects or characteristics of the tested device. More accurate methods consider also the frequency domain of a time signal. The basic one is the *Fourier Transform*, usually used in its FFT version. A variation is the *Short Time Fourier Transform* (STFT) (Chikkerur et al. 2007). A different solution is the *Empirical Mode Decomposition* (EMD) (Huang et al. 1998), that is an auto-adaptive decomposition algorithm. *Dynamic Time Warping* (DTW) (Shanker and Rajagopalan 2007) has been developed for voice recognition, but it is currently used in diagnostic techniques for industrial processes.

With regard to the monitored signals:

- For *Acceleration*, that are impulsive signals with some high peaks and a fast decay, three suitable algorithms have been chosen and evaluated: *DTW*, *EMD*, *FFT Slicer*.
- For *Current absorption*, the *Root Mean Square* (RMS) of current value at regime and the time duration have been extracted.
- *Angular position* has been elaborated in order to extract the *amplitude* and the *duration* of the main shaft rotation in opening/closing operations.

3.3 Features Selection

The complexity of the model at the base of the diagnostic system depends on the number of input parameters. To reduce the number of parameters it is usually preferable to perform a *features selection* in order to eliminate irrelevant and redundant features and consider only those that allow a more accurate description of the operating conditions.

From the analysis of literature it is observed that features selection can be implemented through the generation of new features as a combination of those already existing, as in the case of the *Principal Component Analysis* (PCA) and of *Fischer Discriminant Analysis* (FDA) (Chiang et al. 2000), or through the identification of the best features subset through the optimization of an objective function, as in the case of the *Sequential Forward Selection* (SFS) and the *Sequential Backward Elimination* (SBE) (Pudil et al. 1994).

As SFS, SBE and the FDA methods are transformations that require the labelling of the data not available a priori it is necessary the use of PCA. This performs a linear mapping from initial hyperspace to a smaller size hyperspace, aimed to give the dimensions that best encode and represent information, i.e. the one which provides the largest variance of the data. The features values of the collected data are distributed in a very different range, so before using PCA it is necessary a pre-processing (*Normalization*). Applying PCA to LVCB features it is possible to reduce them from *20* to *3*, while safeguarding more than *90 %* of information.

3.4 Classifier Design

To classify patterns whose class is unknown, PR involves the design of a model, called *Classifier*. In the context of diagnostic, a classifier, able to discriminate between normal operation and malfunction, is trained.

In literature, machine learning is divided into *Supervised Learning*, *Unsupervised Learning* (*Clustering*) and *Reinforcement Learning* (Alpaydin 2014).

In Supervised Learning patterns with a priori known label are used as *training set* to train a classifier in order to correctly discriminate patterns whose label is not known. The objective of this method is to identify the surfaces of decision delimiting the classes. It is possible to identify three families: the *Bayesian approach*, in which the a priori probability of belonging a priori to each class is assumed to be known and in which the *rule of Bayes* is used to calculate the probability of belonging a posteriori to these classes. This approach is only possible in theory, since the exact knowledge of the a priori probability and of conditional density is only possible on a theoretical level. In practice, it is better to use the second family, defined *Parametric Approach*, which allows to formulate hypotheses about the shape of distribution, to estimate the key parameters from a training set and then to use the rule of Bayes. Through the third family, defined *Non-parametric Approach*, the information of the training set is used for the classification, based on the fact that similar inputs will have similar outputs. As an example, the *Bayes classifier* (BC) (House et al. 1999) belongs to the first family, *Maximum Likelihood* (ML) to the second, and finally, to the third, tools as *Support Vector Machine* (SVM) (Yang et al. 2007), the *Artificial Neural Network* (ANN) (Yu and Junsheng 2006), the *k-Nearest Neighbor* (k-NN).

In Clustering, a priori labels of patterns are not known and the objective is to identify the intrinsic clusters which are used to discover similarities and differences between the patterns and to create the unknown classes. It is possible to identify two main families of methods: the *Hierarchical Clustering*, which produces a sequence of clusters in ascending or descending order, and the *Partitional Clustering*, wherein the number of groups is chosen a priori. The Hierarchical Clustering is divided into *Agglomerative Hierarchical Clustering* and *Divisive Hierarchical Clustering* (Alpaydin 2014). On the other hand, the technique of *k-means*, in which a centroid, calculated as the arithmetic mean of the patterns belonging to the cluster, is associated to each cluster and in which patterns are assigned in an iterative way in order to minimize the distance between the pattern and centroids, and the technique of *Gaussians Mixtures Model* (GMM), which uses the algorithm of *Expectation Maximization* (EM) to assign the cluster, belong to Partitional Clustering (Bishop 2006).

Reinforcement Learning designs software agents able to determine automatically the ideal actions to perform within a specific context, in order to maximize its performance. However its main applications are in game theory, in control theory and information theory, not in classification context for prognostic.

Relatively to the LVCB case-study, the design has been developed with a Semi-supervised approach in two phases: the first of Clustering, to group the data associated with the CB behavior into families of similar data, so as to assign a label to each pattern and to generate the training set. The second of training, to define the model that identifies the decision-making classes of the problem: normal operation and malfunction. Each switch during its life is subject, as all industrial electro-mechanical components, to a behavior attributable to the *bathtub curve*, in which three main stages of the life of a component are identified: *infant mortality*, *useful life*, *wear-out*. Given that, the algorithms of the k-means and the GMM for a number of clusters equal to three are applied. The results of the two Clustering algorithms are similar, confirming the validity of the choice made regarding the number of clusters in which to make the partition.

With regard to the training of the classifier, a Non-parametric approach is used by the method of SVM. Once defined two classes of multidimensional pattern, the SVM determines the *optimal hyperplane* able to separate the classes, i.e. the hyperplane that correctly classifies the patterns of both classes with the highest margin. Considering that the majority of failures are of mechanical nature, infant mortality phase is neglectable and attributable to normal operation. It follows the training of only one classifier, which separates a class of normal operation (infant mortality and useful life) and a class of malfunction (wear-out).

3.5 System Evaluation

The assessment is made starting from the data, gathered in a second experimental campaign of a new CB. In particular, the analysis of the deviation between the classification indicated by the classifier and the classification expected has been developed, analysis that has shown LVCBs has broken for the same kind of fault. New patterns, whose classification is unknown, are considered as input into the classifier, which returns as output the label corresponding to the class of the pattern. In particular, the label indicates if the operating conditions are related to the class of normal operation or malfunction. The results obtained, shown in Fig. 2, indicate that from the start up to the first occurrence of the intermittent failure, revealed with blocking (dashed line), the classifier associates the conditions of functioning of the LVCB to the class of normal operation (in blue), while from the replication subsequent to the termination of service, the classifier associates the conditions of operation to the class of malfunction (in red). It follows that the developed classifier is capable to discriminate between the normal operations and malfunction.

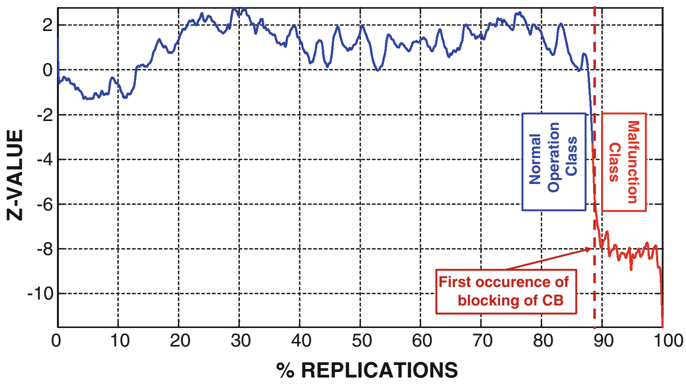

Fig. 2 Results of classification for the first principal component

4 Conclusion

This paper reports the application of a Pattern Recognition methodology applied to the monitoring signals of the operating conditions of a Low Voltage Circuit Breaker. The development of methodology consist of Data Collection, Feature Extraction, Feature Selection, Clustering and Supervised Learning.

The obtained results seem to validate the effectiveness of the work done and the developed classifier, since it is capable to discriminate between the running and useful life operations with wear-out conditions.

From an industrial perspective, the relevance of this approach can be easily understood by considering the importance to rely on prognostics technique able to anticipate the upcoming failure of critical equipment. Moreover, this technique allows an on-line analysis without interfering with the normal operations of the equipment.

It is worth mentioning that this work is a first step of a wider project aiming at developing a FDI system able to develop also the Fault Isolation step in order to evaluate the failure causes, according to prognostics approach. For this second phase, not described in this paper, it will be necessary to carry out further experimental campaigns, designed to consider all possible failure conditions.

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Service Management Models for Railway Infrastructure, an Ecosystem Perspective

Anders Ingwald and Mirka Kans

Abstract Up until 2001 the operation and maintenance of Swedish railway, both the railway infrastructure and the rolling stock, was basically the responsibility of Statens Järnvägar. At this year the operation and maintenance of the Swedish railway was deregulated and as a result the number of actors increased dramatically. Also, during the period from 1990 to 2012 there was an increase in the railway transports of 42 % in train-kilometres. This put great demands on the railway infrastructure operations and service, and indications were seen that the infrastructure was deteriorating leading to delivery quality problems. In order to solve the situation several governmental investigations were initiated. In a governmental report the situation of the railway maintenance is described as problematic due to several technical as well as organisational factors, of which the lack of competition is seen as the most important. Despite several investigations, the desired delivery quality is still not reached. This paper focuses on the Swedish railway infrastructure and describes the background and current state of the Swedish railway service management by utilising a business ecosystem perspective, which lets you capture the complexity and dynamics of the surroundings. By applying this perspective, looking outside the traditional framework of suppliers and customers, important areas in need of investigation or development can be singled out. As a part of the result, the Swedish railway infrastructure industry is modelled as an ecosystem, and directions for future development is pointed out.

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1 Introduction

The responsibility for building, operating and maintaining the Swedish Railways was deregulated in 2001. Before that it was basically the responsibility of one actor, Statens Järnvägar (SJ). The deregulation led to increased numbers of actors involved in different phases of the life-cycle of the railway. The deregulation of the responsibility has generally been identified as the cause for delayed and cancelled trains, but the real reason behind has not been proved. According to an audit report the delay problem was current also before the deregulation process started in 1988, Riksrevisionen (2013). In the same report it is mentioned that the statistics regarding delayed and cancelled trains are of low quality and therefore it is difficult to say if the problem has increased or decreased since the deregulation. This indicates that there are other factors that influence these problems as well. One of the factors mentioned is maintenance, SOU (2010). The usage of the Swedish rail have increased during the period 1990–2012; measured in passenger-kilometres the increase was from 6.6 billion to 11.8 billion, while the usage for transport of goods has increased from 19.1 to 22.0 billion ton-kilometres during the same period, European Commission (2014). The increased use of the railway as a mean of transporting people and goods can be related to several factors, whereof one is the deregulation, Alexandersson and Rigas (2013).

The increased usage together with the complexity of the railway infrastructure increases the demands on the service organisation. Effects of disturbances in one section of the railway infrastructure are multiplied through the entire system, especially if the disturbances take place in a section where the usage is intense. There are still problems regarding delayed and cancelled trains in Sweden. In 2013 the punctuality of passenger train was between 90 and 95 %, depending on type of route, Trafikverket (2014a). For freight trains the punctuality was 77 % in 2012 and 88 % in 2013. Even if the annual figures vary, there have been little changes in these figures the last ten, fifteen years according to the statistics. In some areas there are even negative trends. One such negative trend is within maintenance management: the portion of maintenance that is failure based has increased during the last years, Riksrevisionen (2013). In order to analyse the situation regarding the Swedish railway maintenance services from a wider perspective we use the business ecosystem perspective. This concept was introduced by Moore (1993) and is a mean for putting the subject of analysis into a wider concept. This means that not only suppliers and customers are included in the analysis but also other actors, which are more or less formally connected to the company in focus. The business ecosystem describes the complex, dynamic and often geographically spread reality of a company, where actors come and go, new relations are created and existing ones are broken, Olve et al. (2013).

The purpose of this paper is to describe the background and current state of the Swedish railway infrastructure service management by utilising a business ecosystem perspective, thus, looking outside the traditional framework of suppliers, and customers in order to single out important areas in need of investigation or development.

2 The Business Ecosystem

Companies are often operating in complex, geographically spread and dynamic environments. Furthermore, these environments are dynamic, where new actors enter and others are leaving. Between some of the actors there are formal agreements, between others there are very loose connections, Olve et al. (2013). To be able to describe and analyse this complexity the concept of business ecosystem was introduced by Moore (1993). This concept gives the beholder a wider view of how value is created compared to traditional value chains, value stars or networks, Normann (2001). The purpose with the business ecosystem concept is to describe the complexity in which a company operate, including relations and dynamics in order to better understand how value is created and transactions are conducted, i.e. what customers value and are prepared to pay for, Moore (1993). For the company, in practice, the purpose is to identify, describe and understand behaviour in the environment and thereby being able to develop better business and payment models.

In the business ecosystem, besides suppliers and customers, also other stakeholders are recognised as actors, for example: competitors, companies producing substitute, standardisation organisations, public authorities, customer groups, etc., see Fig. 1. Since the business ecosystem is describing a dynamic environment it is also important to include possible future customers and competitors. Looking at a well-defined part of the business ecosystem it may appear like a traditional value chain or value star, but when zooming out from the narrow view a more complex system will appear. There is no limit built in the business ecosystem concept, and

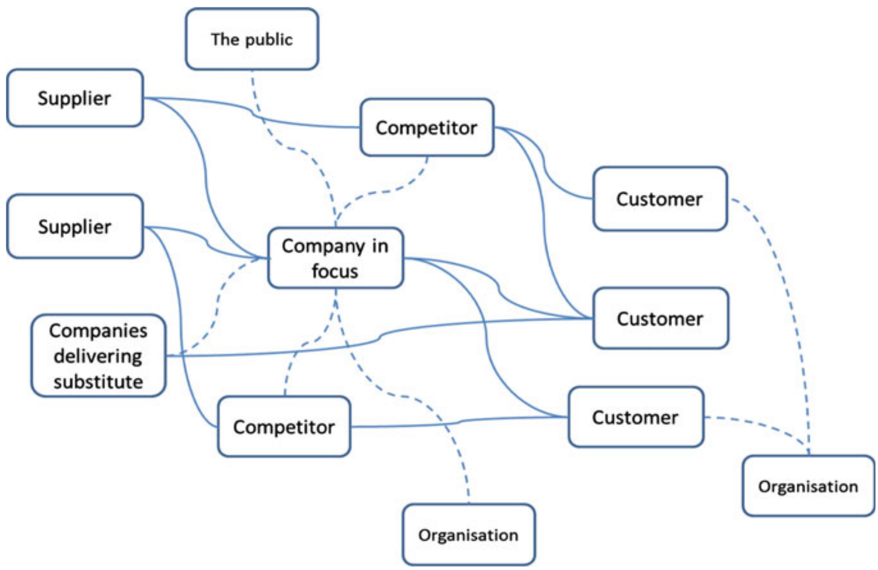

Fig. 1 Business ecosystem, a conceptual example

thus it is crucial in each application to define what part of the ecology that is described and analysed. Depending on the purpose it is possible to describe an environment as one or several business ecosystems, Olve et al. (2013).

3 Development and Current State in Swedish Railway

3.1 Organisational Changes and Current Structure

The deregulation of Swedish railway traffic has been a long journey starting in the late 80s. In 1988 the first step was taken when SJ, Statens Järnvägar, was divided into two separate organisations; SJ responsible for traffic and Banverket responsible for rail and other infrastructure assets. SJ was unbundled in 2001. The freight traffic was deregulated in 1996 and the passenger traffic in various steps from 2006 and forward. Figure 2 illustrates the development of the Swedish railway sector. In 1988 there were in total a handful of actors. Today, the actors are counted in hundreds. In 2013 the number of rail operators was 30 and the bodies in Swedish rail traffic were 42, Trafikanalys (2014). The majority of the bodies are regional public transportation authorities or regional agencies. Banverket was until April 2010 responsible for railway traffic when The Swedish Transport Administration (Trafikverket) took over this role. Trafikverket is today responsible for all types of traffic, as well as for

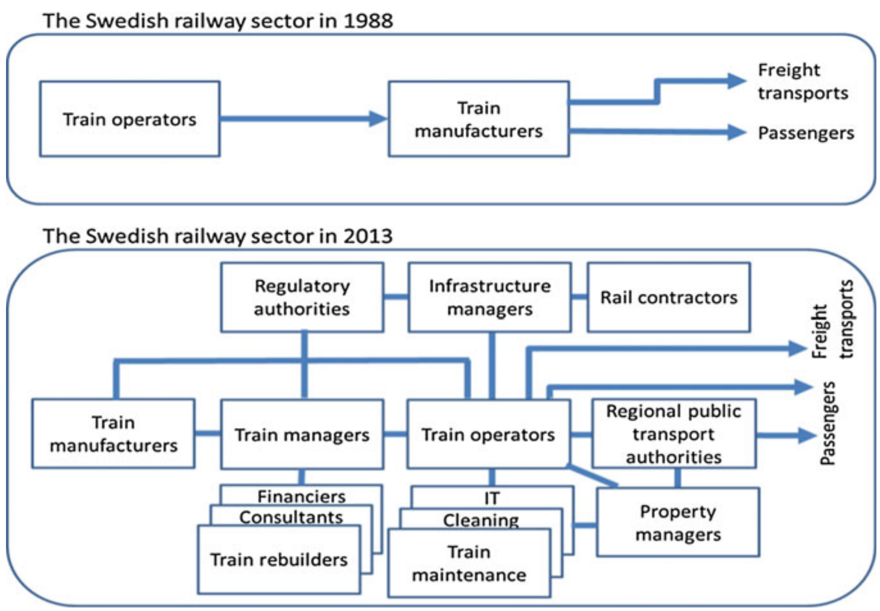

Fig. 2 The development of the Swedish railway sector 1988–2013 (modified from Alexandersson 2014)

building, operating and maintaining public roads and railways. At least three different types of maintenance related actors exist; the train builders, which also offer maintenance services, train maintainers which are specialised in maintenance on rolling parts, and infrastructure maintainers, which takes care of the fixed equipment.

Until 1997, the maintenance organisation of Banverket was decentralised; 20 regional sections were responsible for the maintenance, SOU (2015). The positive aspect of decentralisation was a thorough and personal knowledge of the infrastructure, but the resource utilisation was low. In order to make the organisation more efficient, it was centralised in 1998. This change was turbulent, and both the client and the contractors experienced confusion in their roles. Today, there exist around 10 larger contractors for infrastructure maintenance, but the total amount of actors is much higher, for Trafikverket alone the number is about 900, SOU (2015). Procurement related to railway infrastructure is typically characterised by contractual separation between construction and maintenance. The railway infrastructure life cycle is divided into several parts, and separate contracts for construction work and maintenance are developed. In addition, there are often different actors performing the construction and the maintenance, which means that there is generally no continuity between them. Even the Swedish Transport Administration's organization is organised into two divisions; Investment and Traffic Division, Lingegård et al. (2012). For infrastructure maintenance a total of about 40 different contracts exist between the four main contractors and Trafikverket, SOU (2010). Currently traditional short-term contracts are used between Trafikverket and contractors.

3.2 *Railway Network Usage and Delivery Quality Statistics*

The annual train kilometres in Sweden are around 120–140 million. The total traffic volume in 2013 was 151 million train kilometres, whereof 106 million passenger traffic. The passenger traffic measured in passenger-kilometres has increased the past number of years, see Fig. 3. This is mainly due to an increase in offerings, especially on the regional level, Trafikverket (2014a). While passenger traffic experiences an increase of 19 % in 2008–2013 the freight traffic decreased by 21 % during the same time period, Trafikanalys (2014). The decrease is mainly seen in national transports, while international transports actually increase.

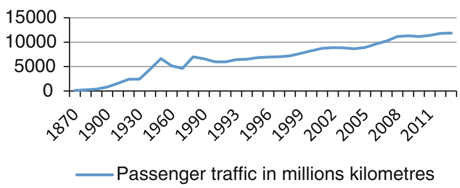

Fig. 3 Passenger traffic in million passenger-kilometres

The transport objectivities in Sweden are expressed in terms of delivery quality, defined as six key indicators: punctuality, capacity, robustness, safety, usability, and environment and health, Trafikverket (2014a). For railway traffic, the punctuality and capacity was improved during the year 2013 while the rest of the measures were decreasing or stayed unchanged, see Fig. 4 (the arrows indicate the trends).

Robustness is expressed in the number of train delay hours owing to faults in the infrastructure, and safety is measured in the number of killed and seriously injured. The Swedish Transport Administration has set a goal of a maximum of 55 deaths by 2020. Usability is a term describing the accessibility for disabled persons, and environment and health is measured in terms of carbon dioxide emissions. Capacity is measured in capacity utilisation, i.e. the percentage of time that a track is in use. Two different measures are used: the capacity for the whole day and capacity during the 2 h of maximum utilisation of the track; see Table 1. High utilisation, i.e. utilisation of more than 80 % creates problems; the vulnerability to disruption is high, and the average speed low. In addition, there is little space for maintenance.

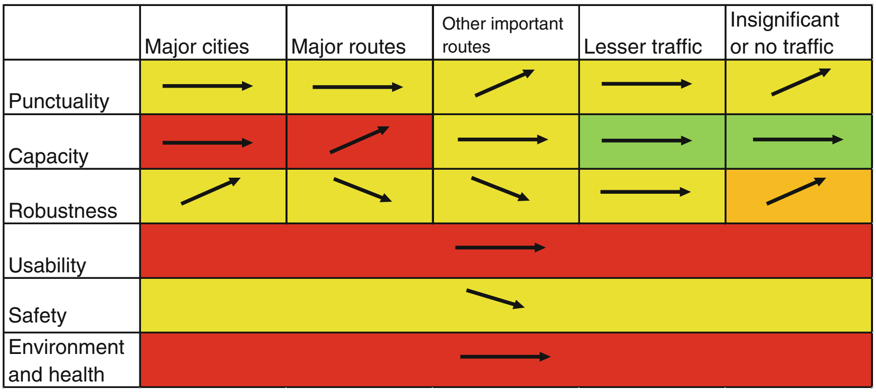

Fig. 4 Summarised results for delivery qualities in 2013

Table 1 Utilised rail capacity, whole days and 2 max hours

Number of line sections with	2011	2012	2013	2011	2012	2013
	Day	Day	Day	2 max hours	2 max hours	2 max hours
Utilised capacity 81–100 %	19	17	22	95	87	93
Utilised capacity 61–80 %	35	37	38	56	63	63
Utilised capacity <60 %	192	189	186	95	93	90
Major track work	3	3	1	3	3	1
Total number of line sections	249	246	247	249	246	247

One of the main reasons to capacity problems is the high amount of single-track routes, SOU (2010).

The arrival punctuality is measured as the number of trains that arrive at their final destination within 5 min of the arrival time according to the timetable. The set goal for 2020 is that 95 % of all trains must arrive within 5 min after the arrival time according to the timetable. In 2013, the punctuality was 91.2 %. The punctuality is higher on the major routes, and lower for the routes with lesser traffic. The punctuality of freight transport is lower than for passenger traffic. There the opposite situation occurs: better punctuality is seen on less trafficked routes while major routes show up lower punctuality. The main reason for punctuality deviations is unplanned emergency maintenance. The main part of train delays are related to infrastructure faults, and the dominating actor held responsible is the Swedish Transport Administration (Trafikverket). 57 % of the total delays in 2013 were caused by this actor, and 58 % of these were directly related to infrastructure failures, Riksrevisionen (2013). The total number of faults reported per kilometre of track is rather stable but increased on all track types in 2013 compared with previous years except for tracks with little or no traffic, Trafikverket (2014a). One possible reason is better reporting of the failures due to new routines.

3.3 Railway Maintenance

The maintenance investments in 2013 was 6238 million Swedish crowns, Trafikverket (2014a). Reinvestments are a part of the maintenance budget, and accounts for more than a third of the total budget. The investments have increased during the past years, mainly due to extensive need of reinvestments in order to solve the problems related to faulty infrastructure. In a report regarding winter preparedness the effects of decreased maintenance costs on train delay was pointed out; a reduction in maintenance costs leads to more delay, SOU (2010). Maintenance costs are moreover affected by accessibility; access to the railway network is a general problem for maintenance. Preventive maintenance is scheduled during night time and weekends but the high rate of failure based maintenance directly affect the availability, as there are no margins in the capacity allocation for unexpected maintenance. The same situation is seen for reinvestments; the total maintenance costs are lower where reinvestment work could be done on closed-down railway, and high for the parts were reinvestments are impossible due to high capacity demand. 90 km of rail was replaced in the year 2013 and 20 km were revised. This is a slightly higher number than previous years, but the damned-up need for replacement is about 1400 km.

In the official operations and maintenance strategy developed by Trafikverket (2014b) the goal is described as: "Operation and maintenance are performed for the traffic to come forward with the promised delivery of quality now and in the future." In practice, this means to meet the set objectives for transports, expressed in terms of punctuality, capacity, robustness, safety, usability, and environment and health. Cost-effectiveness is identified as being one of the strategic areas. For reaching cost-effectiveness in the maintenance, increased cost focus is applied on four areas:

- **Work together** (Operation and maintenance is prioritised and the entire organization contributes to high delivery quality.)
- **Manage towards correct delivery quality** (Operation and maintenance are carried out so that greatest effect in relation to the effort is achieved. Delivery quality for road and rail are co-planned to achieve resource efficiency.)
- **Be a professional client** (Trafikverket affect the development of the construction industry and cooperation well with contractors. Requirements on contractors lead to operational efficiency while ensuring delivery quality.)
- **Choosing the right action** (Trafikverket has required control of the condition on the infrastructure. The deterioration is controlled and the condition is maintained through a cost-effective mix of preventive and corrective maintenance actions.)

4 Previous Studies and Investigations Regarding Swedish Railway Infrastructure Service Management

In this section projects and investigations regarding railway management and maintenance which have been carried out as means to understand the problem area and suggest solutions are presented. Based on these findings the problem is formally described.

4.1 The Infrastructure Service Market

In SOU (2009) it is concluded that actors on the market of railway infrastructure in Sweden perceive that it is not a real market, and because of that there efforts are not fully effective. The report also concludes that there is a need to continue with the market orientation of the railway maintenance and increase the competition amongst the actors. Alexandersson and Rigas (2013) argue that the railway sector, not only in Sweden, need to better follow the needs of the market and become more efficient. Also it is argued that the liberalisation, vertical separation, of the railway sector as a whole is something positive it also has resulted in several problems. They propose that there is a need for more cooperation amongst different actors in the in the transport sector in order to better meet the needs of the market, more elaborated investments and that the sector try to be more active, not only reacting. Nilsson et al. (2013) concludes that the Swedish passenger railway market is well on its way to become completely open. In addition, they point out some critical issues, which need to be solved in order not to slow down the development of a well-functioning market. One of these issues regard access to capacity, e.g. it could, due to the timetabling process be very difficult for new companies on the market to understand how attractive time slots are assigned, thereby increasing the risk. A second issue is access to terminals and maintenance facilities. Two of the largest actors in maintenance has inherited workshops or lease them, thus, making it difficult for new competitors to enter the market. A third issue is availability of rolling stock. To enter the market as an operator, a significant investment is required. This is a large risk for most due to the fact that multiple national railway standards exist, making the market for used rolling stock basically national and thereby relatively small. This can reduce the interest in entering the market. However, there is a trend towards more compatible technical requirements and processes for approval in the EU. A fourth issue is the ticketing system. There is currently no common system for ticket reservations. SJ AB, an operator, has a system, which other operators have bought into. From a competition point of view this is not an optimal solution. Nilsson et al. (2013) state that the Swedish government acknowledges these issues.

4.2 National Investigations Regarding Railway Management and Maintenance

The maintenance of Swedish railway has been a hot topic in national media for several years and a series of investigations regarding the railway management and maintenance has been conducted by the government, Trafikverket and the Swedish National Audit Office. Here we describe the most relevant ones and their conclusions with the starting point in the harsh weather conditions that occurred during the winter season 2009/2010, which resulted in major problems with delays and cancelled trains. An investigation conducted by Trafikverket concluded that about half of the delays during the winter season 2009/2010 were caused by factors that Trafikverket could influence, while the other half falls under the control of the operators. Better cooperation between the Trafikverket, contractors and train operators was seen as necessary in order to limit the problems, Trafikverket (2010). The main causes identified in this investigation were infrastructure, interface and ability of contractors, internal management and processes, and information handling. Amongst the suggestions were increased investments in railway infrastructure and maintenance of infrastructure and trains and enhanced resources in form of vehicles and premises for maintenance. Current contracts regulating traffic should be revised so that they stimulate preventive and proactive actions, and Trafikverket should become better in coordinating and preparing all actors for the winter season through operations management centres, an annual action plan, well defined roles, and standardised reporting and contract processes. In addition, the current maintenance contracts were seen as vague, diverse and not fully covering all types of situations, which lead to interpretation problems. To solve this, the maintenance contracts should specify capacity objectives and be more explicit and standardised.

In 2010 the Swedish National Audit Office concluded that Banverket, who was responsible for rail and other infrastructure assets until April 2010, had failed to produce adequate and reliable documentation for the efficient management of railway maintenance. They also pointed out that the Swedish government had been too passive in their management of the maintenance. Poor information quality and poor reporting procedures, poor understanding of the cause and effect relationships and inaccurate analysis models were amongst the problem areas mentioned resulting in poor understanding of the status of the railway infrastructure, and poor support for decision making and planning. This has led to maintenance plans that did not reflect the real needs and that were too brief. A series of recommendations were proposed to the government and Trafikverket covering developing the analysis and description of the true condition of the railway and its maintenance needs, developing models and methods for cause and effect analysis and for prioritizing of maintenance, and including more detailed information regarding failure causes and maintenance activities made on component level, Riksrevisionen (2010).

Lack of capacity was pointed out as one of the reasons behind delays in a governmental report, SOU (2010). Another report from the Swedish National Audit Office in 2013 came to somewhat other conclusions; the Swedish railway has an unutilised potential in the usage of available railways. The capacity could increase by making planning and management of operations, maintenance and contractors more efficient, Riksrevisionen (2013). The report concludes that the government does not have the required overview and basis for an appropriate management of the different actors. Thus, the government has failed to give conditions and incentives for preventing train delays. The recommendations given in the report covers about the same as the ones mentioned in Riksrevisionen (2010). In addition, the government should review the quality charging system, i.e. the system for charging penalties for actors causing delays, and which changes including law changes that are needed in order to make the system more effective. Also, the quality assurance system and the consequences of its inaccuracy should be investigated, as well as how pricing of transports is made. The railway transports are according to the report under-priced, which is one of the contributing factors for increased railway utilisation. An investigation made by Trafikverket regarding railway fees differentiated fees depending on the impact the train has on the deterioration process of infrastructure are suggested, Trafikverket (2014c). The transportation fees should thus be directly related to the deterioration and the maintenance requirements. The fees should also be changed so they cover at least the marginal costs for operations, maintenance and reinvestments, and the railway fees should cover these costs in full.

A recent report regarding railway maintenance also points out the same areas in need of further development as mentioned above, and it is recommended that Trafikverket develops a maintenance management system that solves the problems referred to above, SOU (2015). In addition, Trafikverket should clarify the responsibilities for the collection of data and for information quality assurance, and for planning and preparation of maintenance. Trafikverket should gain better knowledge about the status of the infrastructure for instance by conducting more condition monitoring. The report recommends Trafikverket to use external contractors for maintenance also in the future and to develop the communication with the contractors as well as the evaluation of the contractor's competence, but until Trafikverket has gained better understanding of the true situation, traditional contracts regulating on activities rather than on performance is recommended. A recent Ph.D. thesis by Linegård also confirms several of the problem areas above. Lingegård (2014) describes the main challenges in Swedish road and rail infrastructure as being lack of communication between different involved actors and projects, meaning that information and experience is not used to improve the performance of current and future assets. A second problem that is described is too detailed contracts, leaving no room or incentives for the entrepreneur to improve performance. A third obstacle that is identified is the conservative culture in the buyer organisation. The buyer is also a very strong actor. Linegård (2014) suggests, contrary to the report SOU (2015), that the road- and rail infrastructure is well suited for integrated product and service offerings (IPSOs) as a contracting form. This would imply a life-cycle perspective which could lead to more holistic considerations when investing in new infrastructure since contractors have to balance construction and maintenance costs. Lingegård (2014) also points out that there are possible synergies between rail and road infrastructure when it comes to construction and maintenance.

4.3 Summary and Problem Description

The situation regarding maintenance services management of Swedish railway could be summed up in three distinct problem areas: maintenance ineffectiveness, maintenance services not fulfilling the market needs, and lack of capacity. The causes behind each of these are several, and some are interconnected, thus causing more than one of the problems. In the following, the most important causes are listed.

Maintenance ineffectiveness is caused due to *low level of competition, or a feeling that the market is not a real market*, which in turn is due to cost models not connected to real needs and obstacles for new actors to enter the market. *Too detailed contracts* are also a reason behind ineffectiveness, which is the result of a conservative buyer's culture and the poor quality charging system. Moreover, ineffectiveness is a result from *poor cooperation amongst actors* due to poor internal management of Trafikverket and lack of suitable IT support, and of *inaccurate maintenance plans*, which is the result of vague contracts, poor information handling and inaccurate or incomplete analysis models (describing the condition of equipment). The reason behind the **inability of maintenance services to fulfil the market needs** is partly due to the same reasons above, especially the *low level of competition* and *poor cooperation amongst actors*. It is also due to the *poor quality* *assurance system* which is a result of passive governmental management. **Lack of capacity** is a result of *inaccurate maintenance plans*, but also the *complicated timetabling process*, which directly affects the capacity planning, and *high amount of degraded infrastructure*. The latter situation is caused by several causes; lack of investments in infrastructure (e.g. due to cost models not connected to real operations and maintenance needs), inaccurate analysis models leading to poor understanding of the condition of infrastructure, and incomplete contractor abilities and competencies.

5 The Problem Area Viewed from an Ecosystem Perspective

Seen as a business ecosystem there are different many types of actors involved in constructing, building, modifying, operating and maintaining the Swedish railway infrastructure, see Fig. 5. The overall responsibility is dedicated to **Trafikverket**, found in the middle of the figure. One group of actors consist of **contractors** for constructing and maintaining the infrastructure, with a formal relation to Trafikverket, regulated by agreements. This group consist of several hundreds of companies according to Trafikverket themselves. Of these approximately ten are larger contractors. In the agreements Trafikverket formulate detailed requirements regarding what each individual contractor should do. A second group consist of **sub-contractors** in the field of construction and maintenance of infrastructure, not

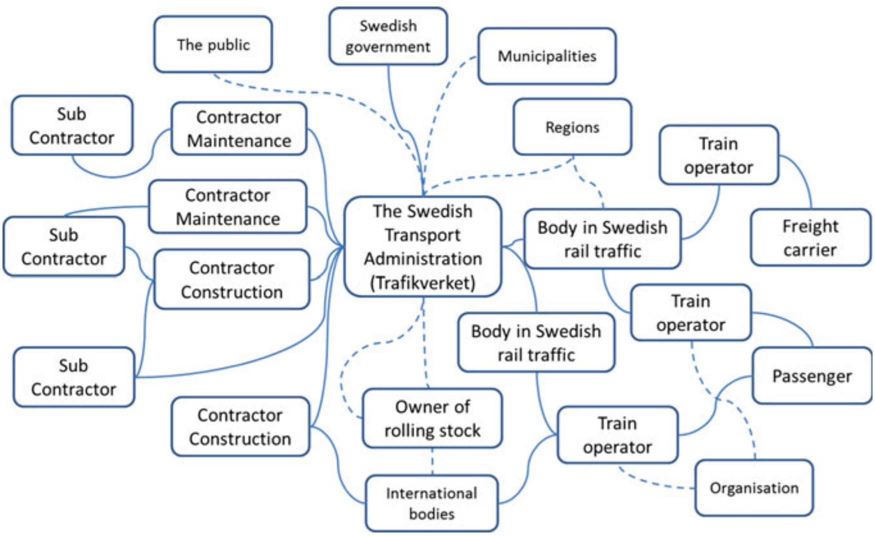

Fig. 5 Business ecosystem, railway traffic in Sweden

directly contracted by Trafikverket. Some of the companies in this group may also be part of the group directly contracted by Trafikverket. A third group of actors consist of **bodies** in Swedish rail-traffic, responsible for the transportation of passengers and goods on the railways. These actors put demands on the quality of the work handled by Trafikverket, especially regarding availability (expressed as punctuality and capacity). The quality of the infrastructure also affects the total quality perceived by thee customers; passengers and freights carriers. A fourth group of actors are **owners of rolling stock**. They also put requirements on Trafikverket regarding quality of their work, e.g. in quality aspects related to the value and life-lengths of the rolling stock. These companies provide the rolling stock to bodies in Swedish rail-traffic. A fifth group of actors are **regions and municipalities**. These actors may have requirements concerning regional and local traffic and cooperate with the regional bodies. This traffic must be coordinated with interregional traffic and also construction and maintenance activities, which is the responsibility of Trafikverket. A sixth group could be **international railway authorities**, because of the will to coordinate railway market internationally, especially in EU. This means that Trafikverket have to consider rules, regulation and standards used in other countries when constructing and maintaining infrastructure in Sweden.

In a business ecosystem there is also a *dynamic dimension*. The actors described are related to Trafikverket in different ways. Some are contracted, e.g. for construction and maintenance, some may have no formal relations at all, e.g. sub-contractors. Some exist in the same area, while others are geographically spread e.g. railways in other countries, etc. The dynamics indicate that actors may come and go, and also that relations may change. This makes it more difficult to keep track of all the requirements to consider. A crucial factor connected to dynamics not considered in the description of the business ecosystem above is the life-cycle-aspect. Because of the life-lengths of infrastructure investments it is essential to consider the entire life-cycle. Today, especially regarding construction and maintenance, there are currently different contracts and often different companies involved in different life-cycle phases of the infrastructure. As a result, there is a clear risk for sub-optimisations and poor information exchange. A characteristic regarding this particular business ecosystem is that not all parts of the Swedish railway are, if looked at from the viewpoint of business economics, profitable. Still these parts should be exposed to competition. Since this leads to a somewhat special market situation, there are several barriers accounted for in articles and official reports for companies to enter this market, among others availability of work-sites and special machines and equipment. Even if this description of the Swedish railway infrastructure in form of a business ecosystem is not complete, it depict a very complex situation, where Trafikverket has a very dominating role and is responsible for planning, coordinating and follow up construction, maintenance and modification, and consequently the actors involved in these activities.

6 Conclusions

The Swedish railway infrastructure is complex for several reasons; there is a very dominant actor, Trafikverket, who is controlling at a detailed level what each contractor involved in construction and maintenance should do, and there is a special market situation, where some actors are not profitable from the viewpoint of business economics, but still undergo competition. The total number of actors is high, but the ones directly contracted by Trafikverket are relatively few. More contractors directly connected to Trafikverket is seen as something positive by Trafikverket amongst others, but in order to make this market attractive for new actors, the barriers identified should be further investigated, and also the reason to low profitability of current actors. One possible way to attract new actors is by contracts that covers larger parts of the infrastructure life-cycle. Extending the scope of the contract might make the contracts more profitable for new as well as current actors. The power of Trafikverket could here be an asset, as they could direct the contracts towards more holistic models.

The complexity that appear when looked at management of Swedish railway infrastructure from a business ecosystem perspective together with the reports highlighting both productivity and quality problems indicates that Trafikverket needs a better understanding of the condition of the infrastructure and how it is related to its use. Furthermore, Trafikverket must better utilise the experience and knowledge available in the contractor's organisations. This requires new types of agreements that include incentives for contractors to actually improve productivity and quality, as suggest by for example Lingegård (2014). Trafikverket are commissioned to plan and coordinate construction and maintenance, and currently do so in detail, there leaving little room for initiative from the contractors regarding productivity improvements. In that way, Trafikverket are also responsible for the improvements regarding productivity. With contracts less built on detailed regulation of content, but instead on performance and quality measures, the quality and efficiency of infrastructure maintenance as well as the market needs could be met. Giving incentives to the contractor to work with improvements both with respect to internal efficiency and external effectivity, the responsibility can be decentralised, while Trafikverket keeps the overall control. These kinds of contracts rely on openness and positive incentives rather than on penalties, which create a win-win situation and positive effects for both contractor and Trafikverket.

Finally, Trafikverket needs to develop better systems for coordinating the individual actors as well as the information that is exchanged in the ecosystem. This was pointed out in several investigations, and the Fig. 5 depicts this need as well. Being the central and dominant actor, and also an actor with long history, makes Trafikverket an excellent driver of this development, but it is important that all actors are taken into consideration, and not only the direct partners of Trafikverket.

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Safety Integrity Under Demanding Conditions: A Study on Permit-to-Work (PTW) Systems in the Marine-Subsea Sector

Shambhu Jayakumar and Jayantha P. Liyanage

Abstract During last few years the oil and gas industry has seen a major evolution of innovative subsea solutions and technological leap leading to novel complex applications such as the 'subsea factory'. Taking this into perspective, the marine subsea industry has become one of the most developing sectors involving many stakeholders with a wide range of background to perform various operations. These operations bring together marine operators, ship owners, subsea asset owners/asset operators, subsea equipment manufacturers, various subcontractors, ship yards, etc., to work together under demanding conditions. Due to high-risk nature of oil and gas business, such operations constitute various critical features requiring specific measures to reduce unwanted events and risk exposure. The permit to work (PTW) system is such a critical measure, which is an integral part of a safe working structure that can help to manage the wide range of activities taking place simultaneously. Risk assessment and risk mitigation, which are core elements for the PTW system, are key contributors for safe execution of jobs. A comprehensive PTW system should not only determine how the work can be carried out safely but also should envisage human factors involved in operations. In addition to generic features that are relevant to normal PTW systems, there are specific needs to account for the nuances of the marine subsea industry. This is to increase the safety as well as efficiency of operations especially under demanding conditions in terms of time, cost, and safety. Years of experiences have begun to question if PTW systems should be applied to all activities since current practices have a considerable potential to lead to many confusions among stakeholders weakening the overall effectiveness. This would require a closer analysis of the current PTW systems and practices to ensure safety integrity as well as to establish an effective work interface between stakeholders.

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Keywords Asset risk · Process safety · Marine subsea industry · Permit to work

1 Introduction

Marine subsea industry is one of the most rising industrial sectors involving many stakeholders with a wide range of operational roles and performance responsibilities. These operations bring together marine operators, ship owners, subsea asset owners/asset operators, various subcontractors, yards, etc., to work together under demanding conditions. Due to high risk nature of oil and gas business, such operations have to be organised meticulously with specific measures to reduce unwanted events and risk exposure. OLF (2006) emphasis on the currently popular practice of integrated operations along with need for mutual collaboration through effectively engineered decisions on the NCS which would lead to seamless integration between the various stakeholders.

Bai and Liyanage (2008) describes that for many decades, production platforms have been the ‘heart’ of complex production systems bearing major operational risks. However in the past couple of years, the central focus has moved more towards subsea applications. This involves a wide spectrum of marine operations with highly specialised state of the art vessels. It could vary from a smaller IMR inspection vessel to state of the art saturation diving vessel.

The assets in North Sea are subjected to a heavily regulated safety management practice. The permit to work (PTW) system is a vital component, which enables such a safe working structure that can help to manage the wide range of activities taking place simultaneously. Risk assessment and risk mitigation, which are core elements for the PTW system, are key contributors to safe execution of jobs. The process in the permit to work system needs to be flexible, yet, robust enough to meet the requirements of all various types of operations. Also the implementation and integration of these systems should be as seem less as possible.

A comprehensive PTW system should not only determine how the work can be carried out safely but also should envisage human factors involved in operations. There is need for a holistic integrated system which provides standardised approach inclusive of all the aspects of the operation. Years of experience have begun to question if PTW systems should be applied to all activities since current practices have a considerable potential to generate confusions among stakeholders weakening the overall safety level.

In addition to generic features that are relevant to normal PTW systems, there are specific needs to account for the nuances of the marine subsea industry. This is to increase the safety as well as efficiency of operations especially under demanding conditions in terms of time, cost, and safety. It should include hazard identification and mitigation, controlling of hazardous operation, lock out tag out isolations, subsystem governing activities including confined space entries, lifting, working at height, hot works, electrical system, machinery etc. The process should be able to lead the operators step by step through the procedures, while highlighting the risks involved and aid them in enhancing control of the job and thereby excluding the risk.

Permit system covering the marine operation should not only cover special or critical operations but also should be capable of covering the planned maintenance programs. When the vessel is operational in sea it is a highly mobile specialised operational unit but when in a dock, during a large maintenance period, it goes into what could be described as a large process plant mode. The system should have features that would cover the work during major maintenance and modification works such as in a yard or in dry dock. The interfaces involved between the various stakeholders becomes complex as the ship with various intricate systems is highly mobile and operates in other geographical locations where a multitude of different companies with different approaches get involved. An integrated approach for PTW should be able to interconnect and achieve synergy between various elements of the PTW system. At the same time, there is a need for a standardised approach due to diverse PTW practices, to ensure efficient operations and effective safety management.

This paper reviews various PTW systems in the same industry, discusses their gaps and differences and specifies requirements for a standardised approach.

2 Features of a General PTW System

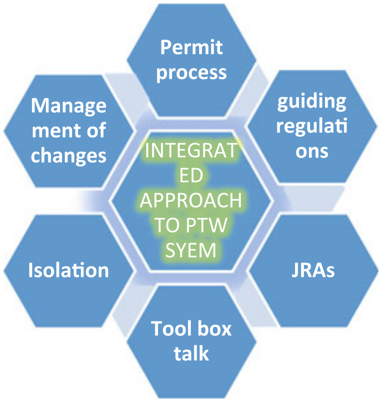
HSE (2005) describes a permit to work system as a formal recorded process used to control work which is identified as potentially hazardous. It is also a means for communication between the management, supervisors and operators with the work team in the hazardous area. A generic PTW system should include

- Clear identification of roles and responsibilities
- Procedures for completing forms, instructions in the issue, use and closure of permits
- Standardised identification of tasks, risk assessments, permitted task duration and supplemental or simultaneous activity and control measures along with the modes of communicating
- Facilitate the flow of information between the various parties involved in the job
- Monitoring and auditing to ensure that the system works as intended

An integrated approach to PTW system should bring all the main components including JRAs, permit process, tool box talks, isolations, managements of change etc. together to a seamless interface (Fig. 1).

- Permit process—Permit process describes the flow for the permit from initiation to approval and finally operation (see Fig. 2). Permit is requested to the permit issuing authority by the person in charge of the job. The issuing authority will look into the job along with the other activities that could be affected and

Fig. 1 PTW system



evaluate whether the permit can be issued. It also describes the approvals, risk assessment along with the type of follow-up that is needed for operation.

- Guiding documents—The PTW system will have various guiding documents which will help the issuing authority to make the decision to approve a permit. These documents will describe the various safety regulations that need to be followed for the task. These regulation are system specific and contents could be unique in each system.
- JRAs—Job risk assessment identifies the potential hazards for the job along with the possible controls and barriers that need to be in place to meet ALARP levels. JRAs are usually performed on the operational procedures by group of key personnel familiar with the job.
- Tool box talk—TBTs refer to the meeting between the work party members where they discusses the JRA and other risk associated with the operation. They will also discuss the various control measures ad safety measures in place.
- Barrier management—Barrier management is key element in the safety of a work place and has to be active throughout the operational time.
- Management of change—This refers to the system of capturing and controlling the changes happening to the planned operation. When there is a change from the plan—they need to be risk assessed and approved by key personnel familiar with the operation.

As DNV (2015) mentions a complete plan-do-check-act engineering cycle gives you a clear and manageable way to improve asset integrity. The PTW system adds additional dimensions to planning and performing an operation to the risk management.

The flowchart below represents a generic PTW sequence showing the main steps involved in the process. A detailed work request will help in ensuring an efficient PTW system. The work requests are evaluated by the Permit issuing officer and granted or rejected based on the circumstances involved during operation. It is

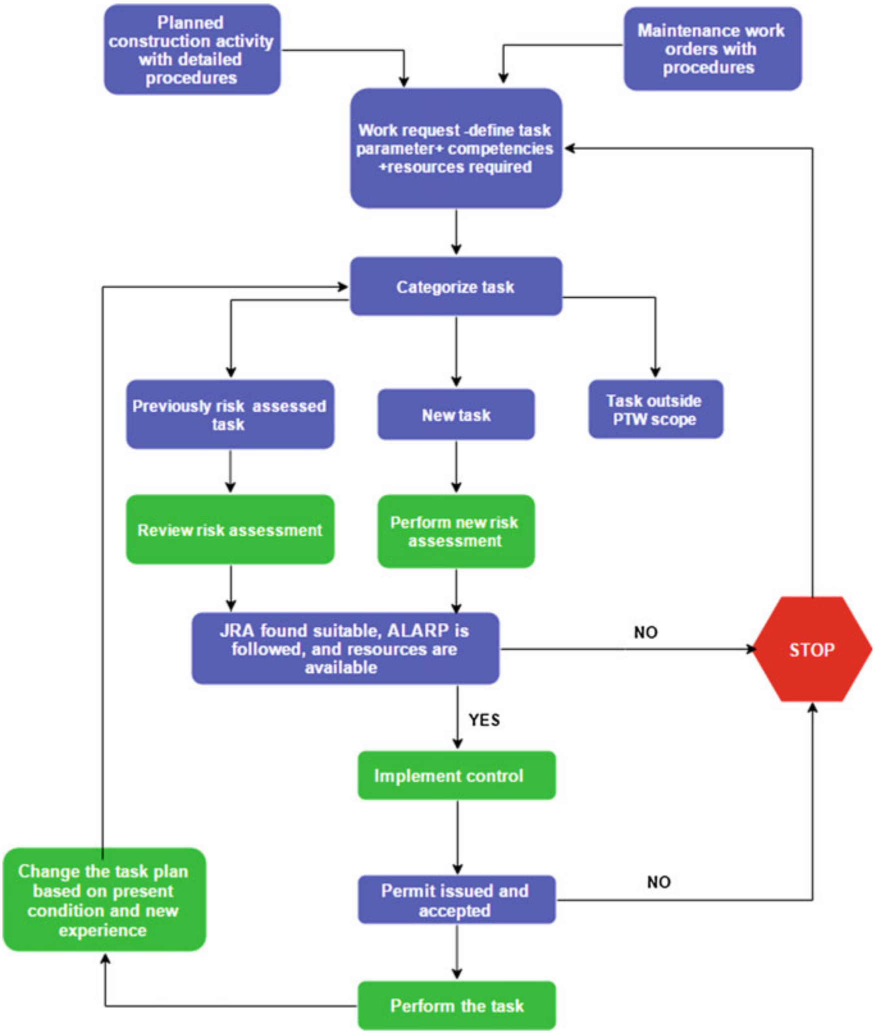


Fig. 2 Flowchart of PTW process

important to ensure that the controls and barriers are in place at all times. Also the continuous monitoring and feedback loop, as highlighted by the flowchart is very critical to ensure and updated safety regime. Based on the operation involved there are subtle changes that will be needed in the flow process to ensure safety and efficiency in the Permit to work administration process. Experience has shown that a simple and easily comprehendible system are the most efficient when many stakeholders are involved.

3 Gap Analysis and Potential Areas for Improvements in Existing PTW Systems

A detailed study has been conducted on permit to work systems that is prevailing in the marine subsea industry. The permit to work system is usually administered on the vessel by either of

1. Marine contractor
2. Ship owner
3. Ship yards (during construction/dry dock periods etc.)

Most of the features are common among various systems and are in line with general permit to work system guidelines. A closer and a detailed examination revealed some notable differences among various PTW systems in use by these stakeholders (see Table 1). These differences changes on a case by case basis.

Practically it is comprehensible that there is a wide variety of marine operations and that there are inherent requirements for fine variances among PTW systems in use. However, due to potential safety and operational efficiency reasons a number of areas in the current PTW practice would probably undergo a detailed review. As it could be observed a relatively good part can potentially be standardized as well. This can further improve current PTW practices by, developing a common understanding, help support mobility of workforce for instance from one ship to another (ex. mobilization of welding operators), aligning expectations of various stakeholders, etc. Some such areas with substantial improvement potential include:

1. Roles and responsibility
   It is noted that the titles and responsibilities are being used loosely depending on the background of the user. The levels of responsibilities for the same title are also described differently in different PTW systems. There is an overlap of responsibilities in certain cases—especially when two or more stakeholders are operating on the same vessel. Not all roles are clearly defined and this causes confusion when personnel are moving from one system to other. The descriptions and responsibilities have to be controlled and regulated properly throughout the industry.
   The industry has to develop a training matrix that would address the training and experience requirements for each of the roles. This will give a generic guideline not only to the work force but also can give a gap analysis report to the management.
2. Planning and operation readiness
   Planning for operation has been a very important forte for the marine subsea industry. Pre audits and pre operations/mobilization meetings have played a central role so far in aligning the expectation and the processes. With the industry expanding these pre operations meetings may not be always possible meaning there is need for more detailed guidelines for all the stakeholders to align themselves. This will help in general agreements for the modes and

Table 1 PTW system of stakeholders

Section	Comments	Marine operator	Ship owners
Roles and responsibilities	Mismatch between the definition and expectations between various stake holders on the roles and responsibilities	Roles and responsibilities defined with required training matrix	Roles and responsibilities are defined
Flow of permit request	Many difference is observed in flow of permit in the system Few examples below		
	Tool box talk	Tool box performed after the permit is issued	Tool box talk is held prior to permit is issued
	Follow up of permit	Requirement for responsible person to sign the permit on site as part of follow up	No requirement for responsible person to sign on-site inspection
	Validity of permit	Permit can be valid for more than one shift	Permit valid for only one shift
Categorization of risk	Categorization of jobs as 'routine' is not uniform in the industry-potential for standardization	Normal crane activities, rigging activities, sampling, mooring etc. fall under routine	Routine activities if any are subjected to judgment of issuing authority
Validity of JRAs	Industry standard could be set for JRA validity	JRAs to be updated when procedures are revised or annually	JRAs are updated only when the procedures are revised
Use of checklist	Industry standard checklist could be developed	Checklist are used extensively	Started using checklist
Working at height	No uniformity on the height above which permit is required. Varying from one company to another and geographical location of operation	Some companies require PTW for all working at height (HSE 2014a, b)	Usually based on regional regulations

(continued)

Table 1 (continued)

Section	Comments	Marine operator	Ship owners
Confined space entry	No uniform requirement identified for gas monitoring	Requires continuous gas monitoring	Mentions about testing the gas before starting the work. Monitoring to be made every 12 h or under captain/issuing authority discretion
	Requirements for initial gas testing	Do not specify 3rd party verification	Requires 3rd party verifications
	No clear consensus found on the requirement of rescue team and placement of rescue equipment		
Isolation	No uniform requirement identified on the procedures for isolation		
	Attachments to the isolation tags	Requirement to attach counter sign foil showing details for tag and relevant information about the system	No clear instruction on what information should be added to the isolation tags
	Standard tags could be developed to be used throughout the industry		

standards of operation avoiding unwanted surprises and will increase the efficiency in the operations. Note: A new mobilization team usually will take about half a shift to be familiar with all the vessel processes (with a typical IMR vessel in the North Sea costing approx. 1 million NOK daily during mobilization).

3. Categorization of risk
   Years of experiences have begun to question if PTW systems should be applied to all activities since it seems to be weakening the overall effectiveness. Some companies have started adding certain activities under ‘routine activities’, which does not fall under the PTW system. This is a step in the positive direction as it will reduce the burden on the PTW system but there has to be good control of which all activities could fall under such a system. As MCA (2010) mentions, there are many types of operation on board ship where the routine actions of one person may inadvertently endanger another or when a series of action steps need to be taken to ensure the safety of those engaged in a specific operation. There has to be a list of activities that can be included in a ‘routine list’ and they cannot be subjective to individual PTW administrators. It has to be accepted and

approved by the industry along with what alternate procedures are to be followed for such ‘routine’ activities.

4. Checklist for each permits

   Checklist is one of the features that is present in certain PTW system in the marine industry. They were found to be suitable and accepted by many stakeholders. These checklists would help tremendously in reducing the human factor errors in the permit to work system. The checklist will differ from vessel to vessel based on operational features of the vessel. These checklists could be included in all the systems as a part of the regulations.

5. Warning system—mapping the dependencies

   Update the permit issuing system with dependencies—If a work permit is taken out on one component in the system the software should be able to inform the issuing authority about all the affected associated systems so as to give precaution/warning for a closer look. This will help immensely to reduce the human factors of judgmental errors or lack of knowledge about the particular system. This mapping can be started during the design phase of any system. These dependencies should be identified during the design phase and should be marked in the FMECA.

6. Validity period for JRAs

   JRAs are the starting points for a safe operation and issuing authorities have to look into the JRAs prior to issuing the permit. It is also important to have an updated JRA during tool box talks with the work party. It is required to update the JRA every year in some systems. This should be a norm across all the PTW regimes by all the stakeholders to update the JRAs every year. This will ensure updating the risk assessment to meet the latest technological advancements and new methodology of operations.

7. Procedure for permits requests and validations

   Processes and procedures for administrating the PTW system are different in different systems. There are also differences in the flow process- for example some systems require the tool box talk to be performed prior to permit application where as in other systems the tool box talk will be held only after permits are issued. In certain systems it is the work party who are filling the forms whereas in certain other systems it has to be filled by the HSE coordinator.

   Confined spaces have been identified as high risk areas and unless proper training, equipment and procedures are in place, workers must not be allowed to enter such spaces. The regulation advices for regular testing of gases in confined spaces. But they are not concrete on the time interval between different testing by 3rd party verification. This is a major point of contention as some of the permit system says the gases needs to be tested every 2 h and some states the officer has the authority to decide based on the circumstances. The guidelines should state the maximum time interval between testing along with the types of testing and test procedures to follow.

8. Duration and follow up of permit
   The maximum duration of permit validity also differs between the various PTW systems. There are also various ways of renewing permits. A uniform guideline system in the industry will definitely help to reduce confusion and misunderstandings in the future.
   Follow up activities are described in the roles and responsibilities section. There could be additional information mentioned in the permit system showing the frequency required for follow up.
9. Attachments to permits
   There are various certificates, drawings, task plans that has to be attached to the permit. There is general lack of consensus seen in this section among various PTW systems. A typical example could be the Gas testing certificate that needs to be attached to the confined space entry permit. There should be industry guidelines specifying the frequency of testing and qualifications for the testing agency.

4 Recommendations

The permit system similar to the HSE systems demands high level transparency. It also calls for a very open arm approach towards each other. Some stake holder like the operators for oil and gas topside have very strict and controlled regime where as some of the older ship yards have not got up to speed on the HSE standards and requirements. A symbiotic attitude could lead to development of all parties involved with a better understanding of each other.

Valuable experiences from across the globe could be collated to develop the guidelines suitable for all the stakeholders. The development group can include

1. Subsea asset owners—oil and gas producers
2. IMCA—International marine contractors associations
3. Association for shipyards
4. Independent experts

We would recommend to develop the specific and detailed industry guidelines to include (but not limited to:)

1. PTW flowchart and process to be standardized
2. Description of the various roles and responsibilities related to PTW system
3. Categorization of jobs into various risk categories
4. Develop standard checklists for each permit
5. Standards for testing/3rd party evaluations—example gas testing for confined spaces
6. Duration of permit validity
7. Permit validation and follow up
8. Data/information sharing platforms—online updates available to all relevant stakeholders in the operation

It is time for the all the major players to sit together and set up a standard that could serve as a good template for the marine subsea industry. The oil and gas industry have to take the initiative to iron out the variations and put forward the expectation. This will definitely help to bring down the quality cost and will increase efficiency of operation, leading to savings of millions of NOK annually.

5 Conclusion

Permit to work system has been a critical element in maintaining the safety and integrity of worksite around the world. To address the specific factors, many industries have developed specific guidelines for the PTW. One such example can be seen in the oil and gas industry when International association of oil and gas producers, OGP (1993) developed together the guidelines for the permit to work system.

There are many unique factors and stakeholders in the marine subsea industry. There is wide variety of PTW system administered by various stakeholders. We have studied many typical PTW systems in detail and have listed and highlighted the major differences existing in this key risk management regime. This paper has also listed the potential action by the various parties to overcome these differences and develop uniform guidelines. The work presented here forms a strong base to develop guidelines for the marine subsea industry. Establishing a common industry regimes will:

1. Give all the stake holders similar understanding and expectations
2. Give the stakeholders framework to modify, improve their PTW system to higher standards
3. Give a common platform from which individual stake holders can build upon to meet their specific requirements.

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Maintenance 4.0 in Railway Transportation Industry

Mirka Kans, Diego Galar and Adithya Thaduri

Abstract Transportation systems are complex with respect to technology and operations with involvement in a wide range of human actors, organisations and technical solutions. For the operations and control of such complex environments, a viable solution is to apply intelligent computerised systems, such as computerised traffic control systems for coordinating airline transportation, or advanced monitoring and diagnostic systems in vehicles. Moreover, transportation assets cannot compromise the safety of the passengers by applying operation and maintenance activities. Indeed safety becomes a more difficult goal to achieve using traditional maintenance strategies and computerised solutions come into the picture as the only option to deal with complex systems interacting among them trying to balance the growth in technical complexity together with stable and acceptable dependability indexes. Industry 4.0 is a term that describes the fourth generation of industrial activity which is enabled by smart systems and Internet-based solutions. Two of the characteristic features of Industry 4.0 are computerization by utilising cyber-physical systems and intelligent factories that are based on the concept of "internet of things". Maintenance is one of the application areas, referred to as maintenance 4.0, in form of self-learning and smart systems that predicts failure, makes diagnosis and triggers maintenance by making use of "internet of things". This paper discusses the possibilities that lie within applying the maintenance 4.0 concept in the railway transportation industry and the positive effects on technology, organisation and operations from a systems perspective.

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1 Introduction

Industry 4.0 refers to a fourth generation of industrial activity as a result of the fourth industrial revolution characterized by smart systems and Internet-based solutions (Lasi et al. 2014). The first revolution took place in the 1800–1900s century, when production was mechanized. This meant that production was moved from the home or small workshops to large factory units and a new social class was born; the working class. The second revolution occurred in the last century when the production was electrified and parts and processes were standardized. The archetype of this revolution is Ford’s assembly line. The digitization of production is usually called the third revolution. Two of the characteristic features of Industry 4.0 are computerization with the help of cyber-physical systems and intelligent factories that are based on the concept of “internet of things” (Ashton 2009). Cyber-physical systems are integrated computer-based or digital components that monitor and control physical devices, also called embedded systems (Lee 2008). These systems communicate over a network usually based on internet technology, and create in other words an “internet of things” (as opposed to social media that could be described as “internet of persons”). Combining these two concepts, we get a distributed network of embedded systems communicating with each other in an ad hoc and dynamic way.

One of the application areas of industry 4.0 is maintenance in the form of self-learning and smart system that predicts failure, makes diagnosis and triggers maintenance actions. These systems have high demands on data access and data quality and use multiple data sources to extract relevant information (Lee et al. 2014). Several research projects have been focused on the cyber-physical approach for developing intelligent maintenance management systems for failure detection, diagnostics and prognostics (Kroll et al. 2014; Sankavaram et al. 2013; Syed et al. 2012). So far, the main application area has been process and manufacturing industries, but the Maintenance 4.0 has a huge potential also in other areas. In this paper the applicability of Maintenance 4.0 in railway transportation industry is explored, and the positive effects on technology, organisation and operations beings will be described from a systems perspective.

2 Maintenance 4.0

Maintenance 4.0 utilizes the advanced technologies for the predictive analytics and provides decisions based on feasibility. Maintenance 4.0 is mainly applicable for the industry 4.0 with emphasis on the prospects of maintenance that involves data collection, analysis, visualization and decision making for assets. Following list of trends for the maintenance revolution compiled by Process Worldwide (http://www.process-worldwide.com/) covers the width as well as the depth of maintenance 4.0:

- *EMaintenance*

EMaintenance is a term covering everything from simple internet based administration systems to advanced diagnostics and maintenance decision support (Galar et al. 2012a). Muller et al. (2008) propose following definition:

> Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. eMaintenance includes various e-technologies (e.g. ICT (Internet and Communication Technologies), Web-based, and wireless) as well as eMaintenance activities (e.g. e-monitoring, e-diagnosis, and e-prognosis), in order to support production and business.

According to Candell et al. (2009) eMaintenance is to monitor, collect, record and distribute real-time data about system health. EMaintenance was introduced before the maintenance 4.0 and applied in broader sense. In practice, the both terms overlap partly or completely. The eMaintenance cloud that provides web services through which information can be exchanged electronically via desktop computers or mobile devices is shown in Fig. 1 (Kour et al. 2014b). EMaintenance could also be described as a form of Business Intelligence (BI) system. The purpose of the BI system is to provide understanding of the business and its environments and decision making capability by advanced information handling and analysis.

- *RFID (Radio-frequency identification)*

Radio-frequency identification (RFID) is a technology for retrieving data regarding an object from distance. The RFID technology is useful for tracking of objects such as vehicles or spare parts, and makes the planning of maintenance activities more efficient by providing valuable timely information regarding the state of the object RFID effectiveness already proved its importance in military, security, healthcare, real time objects tracking. Similarly, RFID can improve railway processes in various ways such as automatic vehicle tracking and identification, operation and maintenance, asset management and others (Kour et al. 2014a).

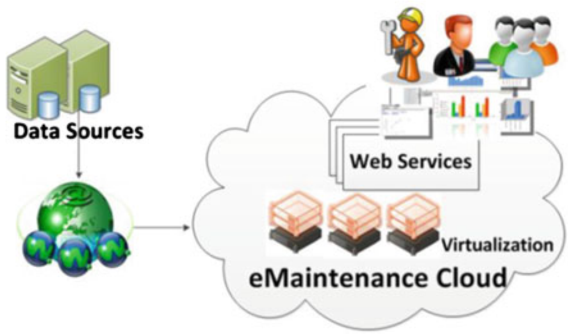

Fig. 1 eMaintenance cloud with web services

- *Virtual or augmented reality*

Virtual or augmented reality is a term describing real time applications that mixes information from the physical world with information from the application. Augmented reality could be applied for simulation, education and training purposes, such as in Manca et al. (2013) or for remote expert guidance of a person through complicated instructions. The cyber-physical visualisation tool proposed by Penna et al. (2014) could be utilised for the latter purpose. The augmented reality can also be utilized in conjunction with Emaintenance and developed architecture for machine breakdown (Benbelkacem et al. 2009).

- *Visualisation*

Visualisation systems such as the one intended for building maintenance described in Khosrowshahi et al. (2014) helps the user to quickly identify problem areas and assess the state of the machine as they transform big data sets into easy comprehensible visualisations. Different decision support and expert systems for assessing the health of assets and propose appropriate maintenance actions have existed for quite a long time, but the applicability has often been connected to management level or centralised use.

- *Knowledge sharing and networking and Assistant systems*

Knowledge sharing and networking let all people involved in maintenance to share experiences and knowledge, and assistant systems allows easy interpretation of vast amount of data for the direct use, for instance helping the maintenance technicians in their daily work. Knowledge sharing using e.g. blogs, wikis and web portals is one of the development areas for maintenance as indicated in Kans (2013).

3 System's Complexities in Swedish Railway Transportation

Systems' thinking is a way to understand a complex phenomenon by defining the system characteristics, its boundaries and components, and by describing the interactions between the components in the system. The systems thinking has its origins in the general systems theory developed in the 40s and forward as a reaction to the emerging need for new approaches to problem solving in the modern world (Skyttner 2001). Instead of focusing on separate items or occurrences, these are seen as parts of a bigger whole; the system. Today, the systems approach is applied in virtually every category of science available. The natural science such as biology studies ecosystems, the social science studies human interactions, the engineering science studies mechanical systems and the computer science studies human-computer systems. The systems science and its applications could roughly be divided into two categories: hard systems and soft systems. Hard systems apply mathematical methods and simulations for quantifying the system and the interactions between components in the system. Operational research and management research are examples of hard systems approaches. The soft systems approach is applied for problems that are hard to quantify, such as those involving human interactions and conflicting viewpoints (Checkland and Poulter 2006).

Railway in general is a system with high level of complexity especially with respect to technology and operations. From the technological point of view the railway consists of a number of physical objects, both rolling equipment and fixed, that interact with each other. Operational conditions, usage and weather conditions are examples of variables that affect the technical systems and their performance. The performance of the technical systems in turn affects the operations. The technical objects interacts with human beings, both employees with specific roles and passengers, in the creation of the main service; transportation. In addition, the objects have to be coordinated in time and space with capacity as a delimiting variable. The operations must reach the goals of punctuality, reliability, safety, and health and environment. The planning, coordination and control takes place on the organisational level, where different actors and organisations interact. It is thus obvious that the railway is an excellent object for systems theoretical studies.

The Swedish railway sector has undergone big changes since 1988 when the national railway organisation, SJ, was split into two parts, SJ and Banverket. SJ became responsible for the traffic and Banverket for the fixed assets. In 2001 SJ was converted into a company and in 2011 the traffic was fully deregulated. The amount of train-kilometres has increased steadily, mainly in the passenger side, and is around 120 million annually in Sweden today. Meanwhile, the number of actors in the railway transport industry has increased, from less than ten in the late 80s to more than thousand when all sub-actors are taken into count. More advanced technology in trains as well as in infrastructure and increased speed has also changed the railway transportation industry. The railway transportation is today a highly complex activity with respect to organisation, operations and technology. In this paper we address the Swedish railway transportation from a systems complexity perspective.

3.1 Organisational Complexity

The organisational complexity of the railway has previously been studied mainly using qualitative, or soft, approaches. Busby (2006), Alm et al. (2012) and Gustafson et al. (2013) used a qualitative approach for understanding risk behaviour and to increase safety in railway, while Kyriakidis et al. (2015) used a quantitative approach for understanding risk behaviour of operators. In Nishikawa (2014) the organisational change process in Japanese railway is described from an organisation cultural perspective.

The Swedish railway organisation has since the deregulation in 2006 increased from a handful of actors to hundreds of actors involved in one or several key processes. In 2013 there were 42 main bodies in Swedish rail traffic (Trafikanalys 2014). The railway is on the national basis operated by two state authorities, The Swedish Transport Administration and The Swedish Transport Agency, and regulated by the Regulatory body. 20 regional public transport authorities and 19 regional agencies act on the regional level. In addition, one private company, A-Train AB, is acting as main body, and also as an infrastructure manager. 30 different actors were responsible for the operation of train traffic in 2013. These actors are the ones directly involved in the railway traffic, whereas several other actors are found in supporting and managing positions: train manufacturers, train managers and maintainers, infrastructure maintainers, and property managers, to mention the most important ones. Figure 2 describes the railway value chain according to Alexandersson (SOU 2013).

For each of the four main processes identified (build, manage, maintain and operate) a number of functions are found. These functions support the main activity labelled "Transportation service" in the far right. The functions are planned and coordinated horizontally for reaching this, but a vertical coordination is also required. Coordinated investments are often found on the strategic level, i.e. on the

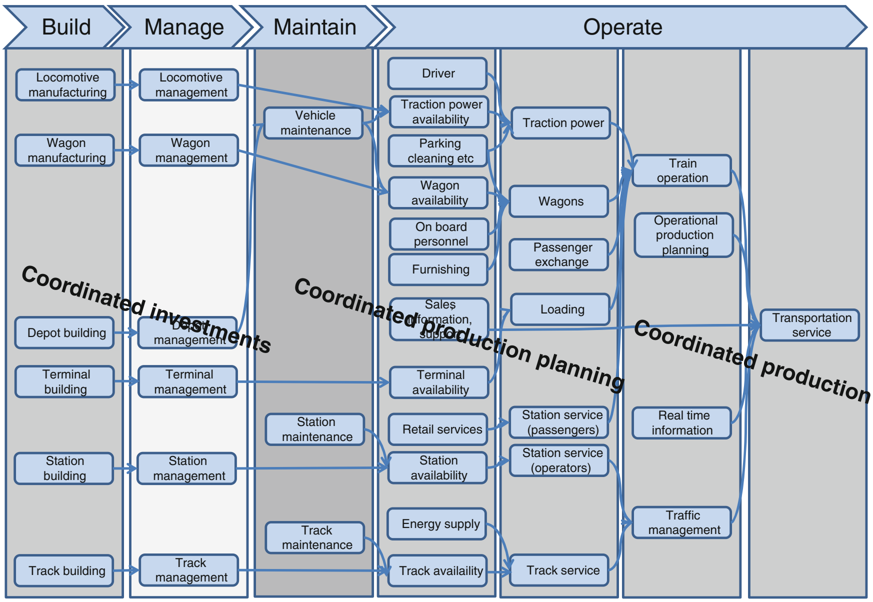

Fig. 2 Main functions of the Swedish railway

long term planning scale, while the coordinated production planning is in the annual to weekly horizon, i.e. on the tactical level. Coordinated production is a daily operational matter. Coordinating all actors and functions within the main processes is a complex problem, both with respect to information flow and decision making. Because of the high amount of actors involved in the timetabling process, there are long lead times in the planning. The timetable process for instance is a yearlong process, from the first application of capacity utilisation in February to April, to the detailed time plan in October, which is translated into the operational timetable that takes effect in December (Trafikverket 2014a).

3.2 Operational Complexity

For addressing the operational complexity in the railway the hard systems approach has been applied in various researches, such as Mussone and Calvo (2013), Bugarinovic and Boskovic (2015) and Ke et al. (2015). These articles propose models for capacity, cost and schedule optimisation based on different operational research methods. The operational complexity occurs during the “operate” phase of the value chain, and especially the early stage of this phase, where assets are made available for the production, is sensitive. The ability to have assets available when needed is moreover directly affected by the efficiency of maintenance, see Fig. 1. The ability to provide assets when needed is a scheduling problem. Many actors have to be coordinated, for instance train owners, operators, infrastructure managers, and regulatory bodies. When put into an extraordinary situation, such as the situation during the winter season 2009/2010 with heavy snowfall causing delays and cancellation of trains, the complexity of the organisation was one of the factors that created additional negative impact (SOU 2010). The seasonal changes are an additional factor of operational complexity, as well.

From 1990 to 2012 there was a 42 % increase in the railway transports in Sweden. Especially the major routes and routes in major cities experience very high capacity utilisation. This creates several operational problems. The most direct is the timetabling of major bottlenecks. The south passage in Stockholm is such a bottleneck; all southbound traffic has to pass this bottleneck, which causes big impact on the punctuality if even the smallest deviation in the timetable occurs (Trafikverket 2014b). The speed is also reduced. The high capacity utilisation moreover affects the possibility to conduct maintenance, which in turn affects the safety. As an example, postponed maintenance caused a derailment of a freight train south of Stockholm the 12th of November 2013 (Aftonbladet 2013). This incident affected the traffic for over one week.

3.3 Technical Complexity

The technical complexity of the railway system has been addressed mainly using the hard systems approach. Ignesti et al. (2012) propose a model for the prediction of wheel and rail wear. In Johansson and Hassel (2010) static and functional properties of interdependent technical railway infrastructure systems are modelled, and the results could be used for vulnerability analysis. A tool for energy and wear simulation and optimisation of train traction and braking systems is proposed by Conti et al. (2015). Ignesti et al. (2012) address one of the complexities in railway, i.e. the interaction between rolling elements and fixed assets. This complexity makes it hard to create reliable wear models. Lack of reliable models for deterioration and for assessing the condition of Swedish railway infrastructure is one of the deficiencies reported in Riksrevisionen (2010). Railway is a large networked system where different fixed and rolling elements thus are interacting. The Swedish railway network is 10,957 km (Trafikanalys 2014) and is a mix of single and double track, older railroads and newer equipped with modern technology. The amount of course equipped with the new traffic management system European Rail Traffic Management System (ERTMS) increased by 35 % to 573 km in 2013. This diversity of technological solutions and age of the infrastructure adds on to the complexity. Today Trafikverket, the infrastructure manager, simply does not know the true condition of the full railroad network. In addition, due to the interactions of technical systems and components, it is hard to assess the true cause of failure (Granström 2008), which in turn affect the detection of the true cause of train delays.

4 The Positive Effects of Maintenance 4.0 on the Railway Transportation System

This section discusses on the effects of maintenance 4.0 on handling the organisational, operational and technical complexities in Swedish railway industries.

4.1 Effects on Operations and Technology

Maintenance 4.0 enables automated, interoperable and inter-connected advanced traffic management systems; scalable and upgradable systems, utilising standardised products and interfaces, enabling easy migration from legacy systems; the wealth of data and information on assets and traffic status; information management systems adding the capability of nowcasting and forecasting of critical asset statuses. Indeed, the positive effects of forecasting asset status do not provide benefits just for maintenance planning but also for traffic management. Maintenance 4.0 also allows

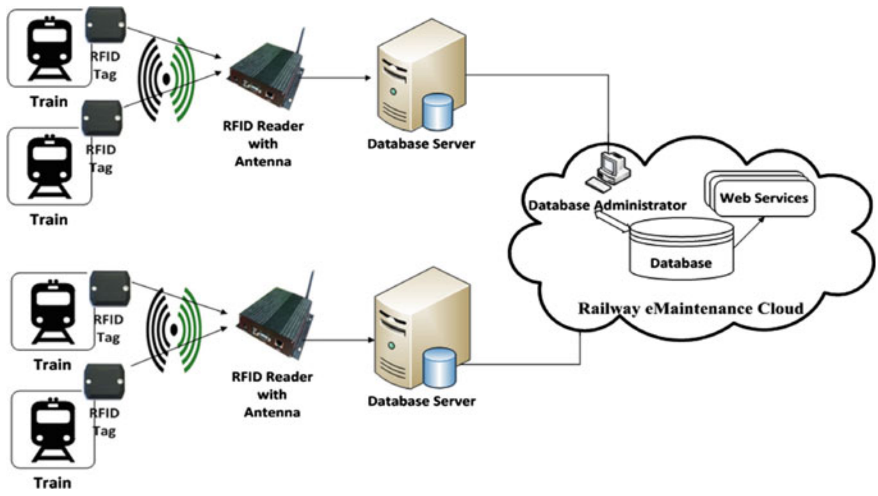

Fig. 3 Data acquisition using RFID technology

for more accurate assessment of the health and status of the vehicle which makes it possible to extend the life length of components and subsystems.

One of the main advantages of Maintenance 4.0 will be the improvement of the traffic operation and management by the means of side benefits also gotten with the deployment of Maintenance 4.0 such as:

- A standardised approach to information management and dispatching system enabling an integrated Traffic Management System (TMS).
- An Information and Communication Technology (ICT) environment supporting all transport operational systems with standardised interfaces and with a plug and play framework for TMS applications.
- An advanced asset information system with the ability to 'nowcast' and forecast network asset statuses with the associated uncertainties from heterogeneous data sources.

RFID technology makes it possible to analyze and visualize data of trains for the cost effective maintenance planning. With the application of this technology, real time information related to location and identity of trains is available to the Emaintenance cloud for operative and proficient maintenance decision making and helps the operator to identify and track the location of the trains. Figure 3 shows the information logistics from the coarser level to more refined level (Kour et al. 2014a).

Maintenance 4.0 also addresses a common Achilles heel in asset management and specifically in transportation: a better assets status forecasting, commonly called prognosis. The estimation of the remaining useful life constitutes the basis

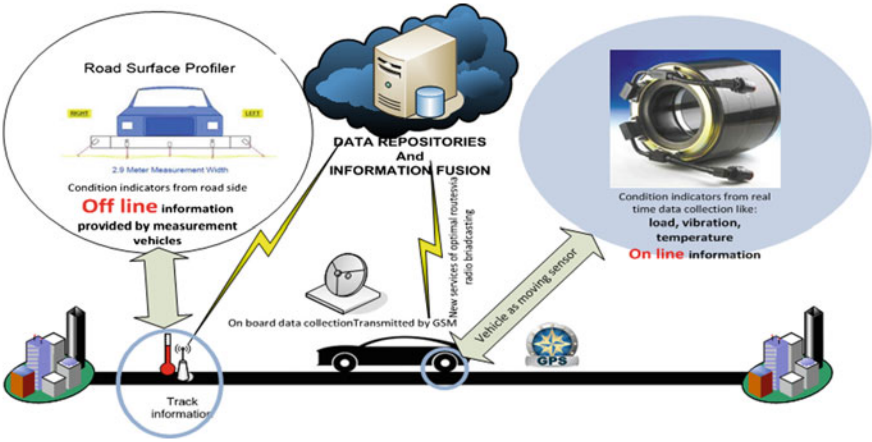

Fig. 4 Business intelligence applied in transportation merging vehicles and infrastructure sources

for any operation or maintenance service in order to check the probability of mission accomplishment by the asset (Galar et al. 2012c). The Fig. 4 shows a common scenario where a vehicle merge its status with the infrastructure condition in order to forecast the asset condition and verify the user scenario selected in the on board computer. (The same scenario is applicable with some modifications for railway transportation.) The BI tools will provide relevant information regarding the probability of getting the desired destination according to the current condition of the car and other information sources like road condition weather etc. Relevant information regarding maintenance planning, spare parts and inspection may be provided as well and sent to the closest workshops.

For these reasons, a transportation system with Maintenance 4.0 should be able to provide advanced automated, interoperable and inter-connected; scalable and upgradable traffic management systems. All these goals will be achieved utilising standardised products and interfaces enables easy migration from legacy systems since Maintenance 4.0 must have a smooth transition from earlier attempts, failed initiatives and proprietary systems. The new traffic service that is based on the prognosis is shown in Fig. 5.

Currently deployed Traffic Management Systems are combinations of various sub-systems with limited integration and non-standardised interfaces and display rules. In this scenario, the dramatic change will come in the way of a seamless, fully-automated TMS enabling integration with railway related services and other modes of transport. However the disparate number and nature of current transportation assets with distributed non-integrated and non-standardised asset registers makes the integration of data sources extremely difficult and therefore the network asset status information cannot be widely understood or exploited to inform TMS decision making (Galar et al. 2012b). Even more challenging is the integration with

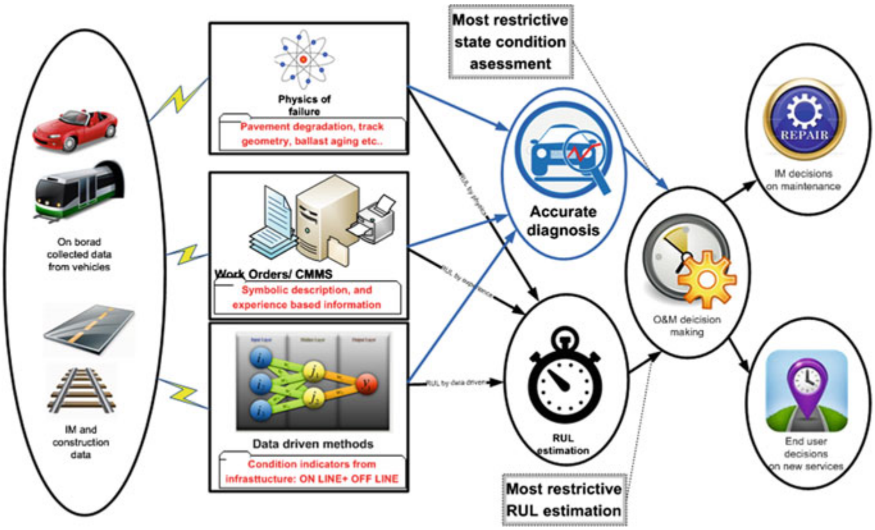

Fig. 5 New traffic services provided by prognosis besides maintenance

other information domains like maintenance related services, energy resources etc., which must be done manually.

In summary operation and maintenance are completely disconnected in terms of incoming data sources and further decision making (Parida et al. 2011). For this purpose, new BI approaches from other sectors, where success is already proven, may provide Maintenance 4.0 as a technology trigger in order to harmonize and create single sources of data with accepted, adopted and exportable taxonomies and ontologies cross over infrastructure managers, contractors and service providers (Thaduri et al. 2014). It is relevant to mention the need of ‘Big data’ approach to diverse sources of information and create new services based on the ontologies exploited and therefore knowledge discovery performed (Baglee et al. 2015). This adoption of BI and Big data may pave the ground for a real Operation and Maintenance policy in transportation bridging the gap between them. By the use of visualisation tools, the interpretation of data is made easy, allowing for better utilisation of the available data for operations and maintenance planning.

In addition to the formal and structured TMS as described above, the introduction of networking and knowledge sharing tools such as blogs, wikis and discussion for a would allow for a more instant and informal knowledge sharing amongst the different maintenance actors. The main benefits are better cooperation and openness between actors and possibility to speed up the troubleshooting process, because the contractor can instantly ask for help from others. Virtual reality applications used for training and expertise guidance will reduce training costs and execution time while reaching better accuracy in the maintenance.

4.2 Organisational Effects

Maintenance 4.0 has a direct positive effect on operations and maintenance as described above. The automated, interoperable and inter-connected advanced traffic management system allows for coordination of actors, information and activities throughout the value chain (see Fig. 2). Planning and production is supported directly by the system, and the information could also be used for investment decisions. This in turn leads to better efficiency in O&M and better ability to meet the formal objectives for the transportation services in Sweden, which are to ensure cost-effective and sustainable supply of transports for citizens and industry (Trafikverket 2014b).

In addition, maintenance 4.0 will contribute to achieve the objectives of the Transport White Paper. In this document EU members (EC European Commission 2011) state that

> Transport is fundamental to our economy and society. Mobility is vital for the internal market and for the quality of life of citizens as they enjoy their freedom to travel. Transport enables economic growth and job creation: it must be sustainable in the light of the new challenges we face. Transport is global, so effective action requires strong international cooperation.

Considering that many European companies are world leaders in infrastructure, logistics, and traffic management systems and manufacturing of transport equipment—but as other world regions are launching huge, ambitious transport modernisation and infrastructure investment programmes, it is crucial that European transport continues to develop and invest to maintain its competitive position. For this purpose a sustainable maintenance of the infrastructure and the vehicles is a "must" as a crucial tool in the European agenda.

Therefore Maintenance 4.0 will provide specific benefits as follows:

- Long-term needs and socio-economic growth: Maintenance 4.0 will develop common methodology for improving infrastructure capacity, safety and environmental impacts.
- Smart materials and processes: SMARTness in transportation is closely related to maintenance methodologies aiming for self-maintenance and self-repair systems in order to maximize capacity and utilization of the assets minimizing shutdowns. Therefore instrumented, interconnected and intelligent assets will be maintained in a very different way from traditional policies.
- System integration, safety and interoperability: New maintenance policies will provide open cross borders with higher interoperability by the means of harmonization in RAMS analysis and calculations, increased safety as a consequence of increased reliability, and finally a common way to integrate systems creating complex assets as system of systems but in such a way that reliability is not affected by the complexity along the international corridors. Last but not least, the potential benefits of Maintenance 4.0 in Energy and sustainability are not disregard. It is already proven that better maintenance reduces energy

consumption and therefor improves the carbon fingerprint of the assets, therefore optimized maintenance methodologies which consider the whole life cycle of the asset in a cradle to grave approach will contribute to the sustainability of the transportation system in a significant way.

5 Conclusions and Future Directions

This paper has described several application areas of Maintenance 4.0 for the railway transport industry, and some of the most important positive effects that could be reached. The authors foresee an increased interest for the concept in the future both from practitioners and researchers in this industrial area and similar ones, such as shipping and road traffic. The development of systems based on Maintenance 4.0 is beneficial especially within operations and maintenance, but it is important, the authors believe, that the concept is implemented not only as a technical solution to technical problems, but as a means to affect the whole system, including the organisation, the economy and the people involved, in a positive way. This can be made by considering the railway transportation industry from a systems perspective, consisting of hard systems and soft systems in interaction.

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Business Models for After Sales Services—Current State and Future Directions

Mirka Kans and Anders Ingwald

Abstract The core strategic decisions describing what, where, how and whom to make business with are defined in the business model. The business models adapted by industry have evolved as a consequence of changes in the business environment, the production processes as well as in technology, and the modern, innovative business models focus on long term relationships, performance-based and value-driven customer offers, and knowledge intensive processes. Other aspects are the increased complexity of the offer itself and a holistic perspective on the full value chain. This paper reviews the literature with respect to business models, business strategy and business innovation for postproduction activities, i.e. operations and maintenance (O&M) services. The purpose is to describe the current state within the area and based on this give directions for future research and development. Four main aspects are found as being important for the successful development of O&M service models: the mix of products and services in customer offers (bundling), relevant setup and metrics for performance-based business models and contracts, Information and Communications Technology (ICT) as an enabler and a prerequisite for business model development, and the need for a holistic view on the value chain by utilising the asset management concept.

1 Introduction

In the last few years business modelling and business model innovation has gained increased attention (Euchner and Ganguly 2014). Encouraged by the recent developments in for instance the mobile phone industry, companies strive to reach advantages by focusing on their business models. The business model is the means

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by which a firm creates and sustains margins or growth, and therefore it is of high strategic priority. The business models adapted by industry have evolved as a consequence of changes in the business environment, the production processes as well as in technology, for instance in form of globalisation, shorter product development and life cycles and a growing competition (Visnjic Kastalli et al. 2013). The modern, innovative business models are knowledge intensive and focus on value-driven customer offers. In this context, the traditional view on operations and maintenance (O&M) services is changing too, from being a necessary cost for the owner of the product to an activity which potentially could lower the total life cycle cost of the product. This, i.e. the use of a life cycle management approach to realize value from assets, is one of the basic foundations of industrial asset management (ISO 55000 2014). How to realise this advantage and how the benefits should be distributed amongst different stakeholders must be agreed upon and regulated by the different actors involved throughout the full product life cycle. One way is through performance-based contacts and long term relationships (Randall et al. 2012). This article will review available literature with respect to business models for postproduction activities, i.e. O&M services, with main focus on maintenance. The purpose is to describe the current state within the area and based on this give directions for future research and development.

2 Business Models and Customer Offers: A Theoretical Definition

Business models describe in what way a company creates, delivers and gain value (Osterwalder and Pigneur 2010). The business model is built up of different parts that together define how business should be conducted, e.g. strategy, customer relations, market segments and value creation mechanisms. In the following, some of the most important aspects are described: value creation processes, business environments and different types of customer offerings.

2.1 Value Creation and the Business Environment

To be able to position oneself on the market it is important to define the company role and connections to other actors in the value creating process (Sako 2012). This could be in form of a value chain, a star, a network or an ecosystem. The traditional view of value creation is in the form of a stream, or a chain, of transactions. Although, the situation is often more complex than so, where outsourcing and n-party collaborations also connect actors to each other in a star-like pattern (Normann 2001). In a value star the offer is in focus, and not the customer. The customer is still the most important actor: the customer's business and needs are prerequisites for other actors' business. A third way to describe the various actors' relationship to each other is in the form of networks (Cousins et al. 2008). The network reflects the complexity as well as the different connections between various actors. Companies often interact in complex and geographically dispersed patterns which shift over time: actors come and go, relationships are broken and new ones are added (Olve et al. 2013). In order to capture the complexity and dynamics of the environment and thereby create business models and pricing models that best supports the company's objectives Moore (1993) suggests that the company could be seen as a business ecosystem, where development takes place together with other actors. In the business ecology, not only the direct actors in the value creating process, such as producers, customers, suppliers, but also other actors or stakeholders such as government agencies, standards organizations, politicians and the general public, are included. Even potential competitors are important to include. In a traditional production-oriented value chain the value process is mostly linear, in which the actors further up the chain refines the entity further down the chain. It is easy to define who is responsible for which part of the value enhancement process. In a service-based economy the actor constellations are more complex and not necessarily linear. The relationship between actors in a service economy is characterized by reciprocity or co-production (Normann and Ramirez 1995).

In complex cooperation projects procurement has traditionally been based on fixed price for defined work according to the requirements. These types of contracts easily lead to lengthy negotiations on everything that is not included in the price, which can lead to delays and a sense of mistrust. To overcome these problems, cooperative business models based on mutual trust and fairness for all parties have been developed (Olsson 2012). These methods are based on the concepts of partnering. Partnering is characterized by common objectives, project management and risk analysis. The project is created and run in partnership with clients, contractors, subcontractors and consultants. It emphasizes continuous monitoring and improvement and there is transparency in all matters that are common to the parties. Transparency is a cornerstone and what differentiates partnering from the traditional contractor projects and especially the use of open books, where all current expenses are disclosed to the client.

2.2 Customer Offers

Two main types of customer offers exist: products and services. A product is a physical entity that can be seen as a valuable resource for the customer, while the service is an intangible offer that is created and delivered simultaneously and in the present. As a business, you can sell a physical product and then hand over responsibility for service, maintenance and disposal to the customer. Another model is to include after-sales activities in the offer, in which the product is sold with services, such as assuring the continuing function of the physical product (Durugbo 2013). This function can be expressed in different ways depending on the type of product, for example, the number of lifts per year, certain availability or a certain number of kilometres. Allmendinger and Lombreglia (2005) describe that products can be sold with built-in intelligence and that all after-sales activities are planned and conducted based on real conditions, i.e. based on field data. There are also business models whose basic idea is to provide after sales service, i.e., a service-oriented business model. Ljungberg and Larsson (2012) argue that the offer always is a combination of physical product and service in different degrees.

A customer offer is characterized by factors of scope, time and bundling (Normann and Ramirez 1995). The customer offer can contain one or more customer value propositions. A car salesman for instance sells a physical product, a car, but usually the seller will offer a variety of support systems in connection with the physical product, such as a financing solution or a service contract. The time dimension describes the length of the relationship between customer and seller, which can be anything from a one-time offer to multi-year relationships. Bundling is a term that describes in what way the offer has been put together, and what the customer therefore must buy. Microsoft Office is an example of a bundled offer, where the customer gets access to all software included (word processing, spreadsheets, presentation software and a notebook) even if he only needs a word processor. The opposite Normann and Ramirez (1995) call an out-bundled offer, where customer has the opportunity to pick up offers from the same or different vendors to create the package that he wants.

3 Study Description

Business development and business strategy is an area with an extensive research base, but the number of articles dealing with business models linked to postproduction activities such as maintenance is relatively small. Searching the databases for maintenance business models or business strategy related to maintenance most of the hits will fall outside the actual focus area. For finding the few interesting articles which are available, a structured literature survey approach has to be applied.

3.1 The Literature Survey

The literature survey was conducted in early 2015 and included seven different databases and publishers. The sources to include were determined in a preliminary search in the search engine “One Search”, which combines several available sources. This tool is too blunt and non-reliable to use for a literature survey, but it gave directions on what type of publications one might find when combining the terms “business model” and “maintenance” or “maintenance management”. The searches resulted in 7481 and 4552 hits respectively, ranging a vast number of sources and subjects. Most common subject areas were maintenance, telecommunications, mathematical models, decision making and industrial management. This indicates that the key terms chosen were suitable for the intended purpose. Most common publishers were Elsevier Science, Taylor & Francis, Wiley-Blackwell, IEEE, Emerald, and Springer Science, and the databases Business Source Premiere, Science Citation Index, Science Direct, Social Sciences Citation Index, and PsycInfo. From this list, the following publishers and databases were selected: Business Source Premiere, Emerald, IEEE, Science Direct, Springer Science, Taylor & Francis and Wiley Science.

Separate searches were thereafter conducted in each data source. The key terms used were "business model" and "maintenance" for all sources except for Business Sources Premiere where the term "maintenance" was combined with following standardised search terms according to the database: "business models, business strategy and innovation" and "business models and strategic management", i.e. two separate searches were made in this source instead of one. The searches were delimitated where possible to only search in the abstract. In Springer Science this type of delimitation was not possible, so a full text search was made. For Science Direct the standardised delimitation "abstract, title, keywords" was used. When possible, the search was also delimited to journals and scientific articles, this to exclude books and book chapters. The search resulted in a total of 755 articles. The selection of relevant articles was made first by reading the metadata and thereafter browsing the full article. If the article was within the area of maintenance management or business modelling, it was selected for more close examination, in total 35 articles. After thorough reading of the articles, 16 articles remained. These articles were all in the intersection of maintenance and business models. The survey design is summarised in Table 1. The dominating source for the 16 remaining articles is Science Direct. The list of relevant articles is found in Table 2, which is found in the next section. The list was extended with one article (Sebastian 2013) published by Hindawi Publishing Corporation. The article was extracted when reading the approximately 100 first results of the preliminary searches in One Search. For the 16 articles, the distribution for publication year is found in Fig. 1. Main part of the articles was of later dates; the oldest published in year 2000 and the newest in 2014. One article was published in a conference proceeding (source IEEE) while the others were journal articles. The articles were published in several different journals representing a wide span of different subject areas, from marketing to reliability engineering. Only one journal was represented twice (Industrial Marketing Management), while the articles were published in different journals. The distribution in publication year as well as journals indicates that the phenomenon of study is rather new as a research subject.

Table 1 Survey design summary

Source	Key terms	Delimitation	Total number of hits	First selection	Second selection
Business Source Premiere	(a) Business models, business strategy and innovation, maintenance (b) Business models and strategic management, maintenance	Abstract	(a) 6 (b) 23	(a) 2 (b) 5	3
Emerald	Business model, maintenance	Abstract	16	1	0
IEEE	Business model, maintenance	abstract	36	2	1
Science Direct	Business model, maintenance	Abstract, title, keywords	144	17	9
Springer Science	Business model, maintenance	None	14	3	2
Taylor & Francis	Business model maintenance	Abstract	467	1	0
Wiley Online	Business model, maintenance	Abstract	49	4	1
Total			755	35	16

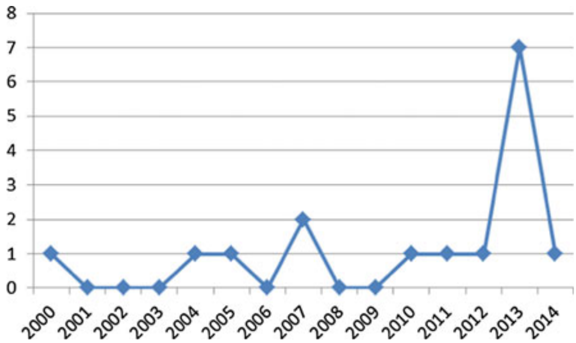
4 Survey Results

The seventeen articles were classified according to the industry or application area of focus and the methodological approach used, see Table 2. The most common methodological approach is the empirical. Ten out of seventeen articles is based on, or include, an empirical investigation, often in form of one or several case studies. Some articles base their results in extensive empirical research, or based on grounded theory. Mathematical modelling is the base for the three of the articles. Conceptual approaches, where the modelling is based either in case studies or literature reviews, or both, are found in four of the articles. It was noted that several articles focus on one or more of following four aspects: extended offerings, performance-based contracting models, ICT as an enabler or and a prerequisite for business model development, and the need for a holistic view on the value chain. The positioning of articles with respect to the aspects is found in Table 2 marked in grey. In the following, the articles are presented and discussed based on these aspects.

Table 2 Survey results summary

Source	Method	Industry / Application	Extended offerings	Performance based model	ICT	Holistic perspective
Choy et al. (2007)	Conceptual	Aviation		X	X	X
Esmaeili et al. (2014)	Mathematical					X
Fabry, Schmitz-Urban (2010)	Conceptual	Traffic systems			X	X
Falls, Tighe (2004)	Empirical /Longitudinal	Road maintenance				X
Famurewa et al. (2013)	Empirical /Conceptual	Railway		X		
Gebauer, Segev (2000)	Literature review	Petroleum			X	
Godoy et al. (2014)	Mathematical	(Mining)				X
Holland et al. (2005)	Empirical	Petroleum			X	X
Kopácsi et al. (2007)	Conceptual	SMEs	X		X	X
Kowalkowski et al. (2013)	Empirical	SMEs	X			
Kujala et al. (2011)	Empirical	Power plants	X			X
Ng et al. (2013)	Empirical /Statistical	Defence		X		
Norden et al. (2013)	Empirical	Maritime		X	X	X
Pascual et al. (2013)	Mathematical					X
Randall et al. (2012)	Empirical	Defence		X		X
Sebastian (2013)	Empirical	Civil infrastructure				X
Visnjic Kastalli, Van Looy (2013)	Empirical	Manufacturing	X			

Fig. 1 Publication year



4.1 Extended Offerings

Research on customer offerings that are a combination of products and services is growing. The terminology is not uniform, and therefore there are many names for the same phenomenon depending on research school and subject area, such as "Product-Service Systems", "servizitation" or "Service infusion in Manufacturing Firms" (Kowalkowski et al. 2013). Already in 2007 Kopácsi et al. developed the concept of "extended products" in the maintenance context. They position maintenance as an overlapping or common factor of the two concepts Product Lifecycle Management (PLM), which focuses on products' information needs throughout the life cycle, and Service Engineering (SE), which aims to improve the design of service processes. The combination of products and services is also addressed in Visnjic Kastalli and Van Looy (2013) under the term "servitization". Their results indicate that sales of products and sales of services complement each other and a positive result is gained when the products are extended with service offerings, while the same trend is not visible to the opposite, i.e., services expanded with products. Labour-intensive offerings, such as maintenance, show the greatest positive effect. Visnjic Kastalli and Van Looy points out, however, that one must view the services as a strategic complement and not an add-on product. In other words: in order to achieve the positive effects the business model must change.

Kowalkowski et al. (2013) study the phenomenon in small and medium-sized enterprises, and concludes that there is no single best practice for these companies. Instead, many different types of business models, from the flow-oriented to network-based, suits depending on the context. Kujala et al. (2011) studies the concept of "servizitation" in the power industry and proposes seven factors affecting the choice of business model: The supplier's or the customer's institutionalised and accustomed business practices, Customer's maintenance organisation, Skill-level of the maintenance organisation, Perceived complexity of technology, The customer's financial resources, The supplier's marketing approach, and The customers core business. The business models included in the study are three forms of project-based value proposition: one where the project is completely separated from the operation and maintenance service, one in which the project and after sales services are coordinated, but still separated, and one where everything is integrated.

4.2 *Performance-Based Contracting*

Outsourcing as a business model is treated in a number of articles, and then usually in the form of performance-based models. Famurewa et al. (2013) study the implementation of performance-based contracting of railway infrastructure. Among other things, a number of outsourcing scenarios are specified where the division of responsibility between the maintenance contractor and the infrastructure manager is described and describe the different types of delivery strategies depending on how the maintenance services and maintenance items are bundled. The main result of the article is a framework for performance-based contracting of railway infrastructure. The framework is a practical four-stage model for the introduction of performance-based contracting. Famurewa et al. also define a number of metrics that can be used for monitoring. Maintenance for the aerospace industry is another complex activity involving a large number of operators and third party logistics services. Choy et al. (2007) propose a performance measurement system that evaluates maintenance supplier performance, identifies bottlenecks and compare with "best-in-class". Potentially, the system could support decisions on supplier mix/service bundling or renegotiation of contracts.

Ng et al. (2013) study the value drivers of performance-based benefit-driven service contracts. Alignment of information and behaviours (e.g. training, relationship building or alteration of mental images), and to have complementary skills prove to be key value drivers. A common understanding of expectations is also important. However, material and equipment alignment, i.e. coordination of material flows between different actors or in processes, has no significant effect on the contract performance. Norden et al. (2013) focus on the condition monitoring technology and maintenance related services utilizing this technology for the maritime industry, but recognise a potential problem in the high investment costs and risks connected to the new technology. To overcome the problem new business models that can support technology introduction are developed. The authors advocate holistic service packages against a fixed, time-based fee. Randall et al. (2012) highlights the difficulty of comparing different business models in maintenance, and especially performance-based models versus traditional models that focus on discrete maintenance. The two approaches differ in terms of economic models, relationship-building, and how knowledge is handled and preserved. A prerequisite for performance-based maintenance services are multi-year fixed price contracts, according to the representatives of the defence industry which were interviewed.

4.3 Information and Communications Technology

Articles discussing ICT cover two main application areas: supply chain management and condition based maintenance. Gebauer and Segev (2000) address IT solutions that support the procurement of maintenance services in the oil industry (e-procurement). As the article is a number of years old the IT solutions are somewhat outdated, but the case descriptions provide an interesting insight into how to reconfigure supplier networks and achieve efficiencies, and how to enable the automation of the procurement process. In the first case, the number of maintenance providers was reduced from over 1000 spread over a large geographical area (USA) to 24 core suppliers, all located in the business area of Alaska. These suppliers accounted for a total of about 250 suppliers and sub-suppliers, but the e-procurement solutions involved only the 24 core suppliers. The concentration led to direct transport cost reductions of approximately 12 %, in addition to the efficiency gains reached in the procurement process. In case number two the number of suppliers was reduced from nearly 60,000 to 38,000. Of these, long-term alliance agreements were settled with 200 core suppliers. At the same time, the purchasing organization was changed and the management of long-term alliance contracts was centralized. Holland et al. (2005) describe how information is shared between the company BP and its suppliers by utilising a common asset management system as information sharing technology platform. The authors argue that using a common software system instead of the general data interchange solutions, such as XML, lead to economic, strategic as well as behavioural benefits. The system allows for instance BP to adapt faster to changes and create a closer collaboration between the suppliers and the company. ICT applications for supply chain coordination are also proposed. In Choy et al. (2007) a performance measurement system for supplier relationship management is described. The conceptual systems design is described in the article and exemplified by a case study, including descriptions of data sources and data processing logic. Fabry and Schmitz-Urban (2010) study maintenance-related activities in a value chain and propose an IT platform for effective spare parts management and the coordination of information throughout the value chain.

Kopácsi et al. (2007) discuss the possibilities to support new maintenance-related business models with advanced IT solutions. Kopácsi et al. introduce the concept of ambient intelligence, i.e. computers integrated into real world objects that are able to communicate with each other, and with human beings through user adaptive intelligent interfaces. An early prototype supporting condition monitoring and condition based maintenance utilising ambient intelligence solutions is presented. In many respects, this article could be classified as one of the first addressing the concept of “Maintenance 4.0”, although the authors themselves do not use the term. Norden et al. (2013) also address the application of new and innovative technologies for maintenance services in the maritime sector, especially condition monitoring technology and its applications. In Norden et al. a technical concept for corrosion monitoring is described based on the OSA-CBM standard, see ISO 13374-1 (2003).

4.4 Holistic Perspective

One could argue that performance-based models by definition are holistic in their nature, because they shift focus from a narrow perspective of O&M activities as add-ons in the systems life cycle to a perspective where O&M is the dominating life cycle phase which is in need of efficient support. In some of the articles on performance-based contracting this is evident. In Norden et al. (2013) the life cycle approach is evident, and one of the objectives in the project ThroughLife is the minimisation of a vessel's life cycle cost. Randall et al. (2012) view knowledge as central to performance-based logistics contracts: Possessing system knowledge (technical), supply chain knowledge (organisational) and innovation knowledge will lead to success in performance-based contracting. The knowledge enables the customers and providers to build a common experience base. The desired situation is described in terms of an ecosystem, which can be interpreted as a systems approach on the subject. Also in Kopácsi et al. (2007) the life cycle approach is evident, even if this article is not dealing with performance-based contracts. The authors argue that the emphasis should be put on the postproduction phases (O&M) for being able to compete successfully and propose extending the products with additional life cycle support. Falls and Tighe (2004) deal with the operation and maintenance of road surfaces. Through four case studies, which analyse real economic data, it is demonstrated that the benefits of a coordinated system for coating maintenance far exceed the costs, and that one can achieve better road standards with the same cost if you work preventively. Although the findings are not directly related to business models the article includes an interesting discussion about the achieved benefits for not just one, but three, different stakeholders: road users, the agency, as well as the public more generally. It also points out the importance of the coordination of road assets information and between different actors through a common pavement management system for improved decision making. Also Holland et al. (2005) propose the use of a single IT system for coordination of supply chain activities. Similarly, information coordination and decision making in aviation logistics is discussed in Choy et al. (2007), where a performance management system is suggested as a part of the solution.

Traditionally the various actors in a value chain try to maximize their own profit. A number of authors have attacked the profit allocation problem and propose profit distribution methods that intend to maximize all participants' profits. Pascual et al. (2013) present a mathematical model for optimizing maintenance contracts in coordinated value chains. The model maximizes both the purchaser and the contractor profit and deals with two problem areas, namely assuming a perfect maintenance and an infinite contract period, which usually is adopted in this type of models. Godoy et al. (2014) deal with optimised spare parts management, and it is demonstrated that the model developed is capable to optimise business performance for the full supply chain, thus both the client and agent are encouraged to improve the maintenance continually. A special type of service contracts is the warranty contract. Esmaeili et al. (2014) use a game theory approach when modelling such contracts between three actors: the manufacturer, the agent and the customer. The optimal price and warranty period for the manufacturer and the optimal maintenance cost for the agent are obtained by maximising their profits. For the customer's part the customer satisfaction is maximized by the risk-based options he is suggested.

A holistic approach on the procurement process is discussed by several authors. Sebastian (2013) proposes new business models for infrastructure projects in the framework of the projects Trans-IND and Pantura. The traditional procurement strategy for infrastructure projects is lowest price bidding, the development process is linear, and design and construction are handled separately. The value chain is thus fragmented, and lacks the life cycle perspective. The solution is to introduce the concept of Asset Management and procurement based on life cycle cost instead of project cost. Value chain integration through integrated procurement processes of the type "design and construct" and developed forms, such as "design, construction, (finance) and maintenance", are also proposed. Fabry and Schmitz-Urban (2010) propose a business model that consists of two main models for acquisition and service provision, and a number of models for the management of information, resources, finance, revenue, supply, distribution, customer and competition.

5 Conclusions

The literature review shows that there is an increasing interest to view the O&M activities from a strategic perspective, but also that the subject area is still rather unexplored and in need of further research. Based on the literature review, four main aspects are proposed as being important for the successful development of O&M service models: the mix of products and services in customer offers (bundling), the need for a holistic view on the value creation process, relevant setup and metrics for performance-based business models and contracts, and Information and Communications Technology (ICT) as an enabler and a prerequisite for business model development. Each aspect was addressed by four or more of the seventeen articles; see the description above and Table 2. Moreover, about half of the articles address more than one aspect, which could imply that the aspects are interlinked. Especially the need for a holistic view on the value creation process by understanding all actors involved, level out the profit generation and benefit creation in the value chain, and applying a life cycle approach on assets is evident.

Business models providing extended offerings (products combined with services) have been proved to have a positive effect on the operations (Visnjic Kastalli and Van Looy 2013). It is profitable to think strategically and in long term for the maintenance service offerings, and especially in form of performance-based models. But to achieve these benefits the view of the business must change, which Kujala et al. (2011) clearly show. Companies can no longer solely focus on *what* they offer, but also have to see to *why* and *what benefits* the offer can bring to others, i.e. position oneself as an actor in a value chain or network, and adopt a holistic approach to not only the company business but on the value of the offer itself in the total value chain. This is quite evident in Kowalkowski et al. (2013), Sebastian (2013) and Famurewa et al. (2013). There is a need to develop theories and methods supporting new, holistic business models for O&M services. Lifecycle approaches, holistic business strategies, value chain integration and coordination as well as asset management are some of the key terms for the future development; see Falls and Tighe (2004), Fabry and Schmitz-Urban (2010), Visnjic Kastalli and Van Looy (2013), Sebastian (2013), and Norden et al. (2013). It seems like the soft aspects of the value chain coordination are more important than the hard aspects (Kujala et al. 2011; Ng et al. 2013).

Another aspect apparent in the literature review is the opportunities ICT provides for driving the change; see Gebauer and Segev (2000), Kopácsi et al. (2007), and Norden et al. (2013). New business models are knowledge and information intensive, and ICT is therefore a prerequisite for the successful implementation. ICT solutions can be seen as an integral part of the new business models, and therefore research on O&M business models should include research on information modelling, knowledge management and software development. There is a great need for developing appropriate ICT solutions that enable new business models, see for instance Choy et al. (2007), Kopácsi et al. (2007), and Fabry and Schmitz-Urban (2010).

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Remote Condition Based Maintenance in Modern Life Cycle Services

Juha Kautto, Christo Roux, Igor Elias and Ari Numminen

Abstract When working globally, remote services, like remote condition monitoring and analysis services, are important because of the need for efficient services practises. Sites can derive advantage from remote control, remote condition monitoring, remote analysis and diagnosis or other remote services. For example in Condition Monitoring benefits from sharing information for the purposes of consultation, troubleshooting, collaboration and reporting are clear when multiple resources with competences in several locations can look same condition data at the same time.

1 Introduction

Plants are facing challenges keeping processes and machinery in good running order with high OEE during whole life cycle with optimum costs. This means that that process and machinery should be up and running when they are needed with the capacity planned. Unplanned shutdowns or production disturbances should not be allowed. Because of the demands for high OEE production availability, capacity and product quality must be high and planned shutdowns short. Machines must be in good condition during operation and restored to condition to meet requirements

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during planned shutdowns. Small stoppages and unplanned shutdowns because of machinery failures should be avoided.

High costs due machinery failures in process facilities are mainly due to cost of lost production together with repair and replacement costs. Optimum production costs are achieved by avoiding process problems and machinery failures causing loss of production and unplanned shutdowns. Proper preventive maintenance and condition monitoring is needed together with optimal operation of processes. In maintenance point of view conditions promoting problems and failures must be avoided.

Despite proper preventive maintenance actions and keeping operating conditions optimal it is a statistical fact that failures occur even though probability of failures can be limited to minimum with preventive actions. Methods and practices to monitor possible failure mechanisms and detect those in early stages are needed. Based on condition monitoring and inspections corrective actions can be planned and executed during operation or in planned shutdowns before major breakdown and possible secondary damages etc.

For that sites can derive advantage from remote control, remote condition monitoring or other remote services offered by technology provider. For example in Condition Monitoring benefits from sharing information for the purposes of consultation, troubleshooting, collaboration and reporting are clear when multiple resources with multiple competences in several locations can look same condition data at the same time.

2 Definitions of Condition Based Maintenance

Condition based maintenance is a type of preventive maintenance which includes a combination of condition monitoring measurements and inspections (Standards EN 2010). Information about machine condition is used to plan maintenance actions in time when the maintenance work is cost-effective and before the equipment loses its optimum performance. Machines are left to service on the condition when they meet desired performance standards (Moubray 2001).

Based on measurements and inspections, analysis and diagnosis is made to define actions to schedule needed maintenance actions to planned shutdowns and to avoid unplanned shutdowns. Condition Based Maintenance is based on indications of asset health as determined from inspections and measurements of different condition parameters and condition indicators (Gulati et al. 2010). Maintenance actions and their timetable are following a forecast based on follow-up of known measurement parameters and/or inspections defined from technical characteristics of machine.

The condition assessment with measurements and inspections is technically feasible, when there is a limit, change or symptom available that indicates a fault and the fault propagates so that its development can be monitored and predicted. Proper analysis and diagnosis of measurement and inspection results is the basis of efficient Condition Based Maintenance.

3 Remote Condition Monitoring

Remote condition monitoring, analysis and diagnosis are important because of the need for efficient Condition Based Maintenance service practices even in remote sites, but sites with own competences or easy accessibility of experts can derive advantage from remote control, remote condition monitoring or other remote services too. Challenges keeping processes and machinery in good running order with high OEE during whole life cycle with optimum costs are the same.

Quite often situation is so that sites own competences are limited. As often technology provider could have information and solutions available that is not common for onsite personnel. Modelling processes, planning and designing process equipments and maintaining those globally in different conditions have created competences and knowledge which gives advantages. These advantages can be utilized in real time by remote services and remote technical support.

Typical remote services delivered include remote monitoring and troubleshooting for equipment and processes. Customer is supported with a remote monitoring or remote analysis of equipment, process and plant. Equipment condition data is analyzed and diagnosed to identify need for maintenance or operational changes, making it possible to prevent deviations even before they occur.

For technology provider information from different sites, processes and equipments supports the development of new methods and parameters for condition monitoring. But not only for condition monitoring and maintenance, when information is available it will help to create technology solutions that supports better the entire life cycles of processes, including their operation too. There are needs for all data available to support analysis, diagnosis, and decision making processes. Today's ability to compute and observe parameters other than what would normally be monitored in a traditional condition monitoring program also new kind of services can be developed.

4 Some Examples of Remote Condition Monitoring and Diagnosis Services

4.1 Short Introduction to Grinding Mills

Grinding mills are large rotating cylindrical steel vessels used to grind ore and minerals into finer particles. There are both trunnion and shell supported mill designs. Trunnion support is the most common way of supporting a mill in a minerals processing application. Shell supported mills are more compact, occupy less floor space and require simpler foundations than comparable trunnion-supported mills (Outotec 2015).

Most mills are driven by pinion and ring gear. These gears are usually with helical type teeth to make them reversible, allowing the use of both flanks

Fig. 1 Typical trunnion supported mill design with motor, gearbox pinion and ring-gear (Outotec 2015)

throughout their operational life. Motors are either high-speed induction type or low-speed synchronous type. The availability and reliability of grinding mills and their drive trains are important. If mill drive train or support bearing fails without any warning or advance indication, then an unscheduled shutdown is unavoidable. Condition monitoring is needed (Outotec 2015).

Sacrificial wear liners are installed in mills and form the working components in breaking ore down to the required size. It is critical that these wear liners do not run to failure and expose the structural members behind them to damage, however it is equally important to extract as much life as possible from the liners before calling a shutdown which is expensive in cost and in downtime. Lining materials include cast steel, cast iron, solid rubber, rubber-steel composites or ceramics (Outotec 2015).

As 70–80 % of all machinery failures are random, time based preventive maintenance practices alone will not be effective way to prevent unplanned shutdowns. Methods and practices to monitor possible failure mechanisms and detect those in early stages are needed. Based on condition monitoring and inspections corrective actions can be planned and executed during operation or in planned shutdowns before major breakdown and possible secondary damages (Fig. 1).

4.2 CASE 1: Remote Condition Monitoring Application for Drive Train

Before suitable methods can be selected or defined to monitor condition of the drive train and plan maintenance and operative actions based on that, there is a need to identify which is critical, which failures can occur and how to predict them.

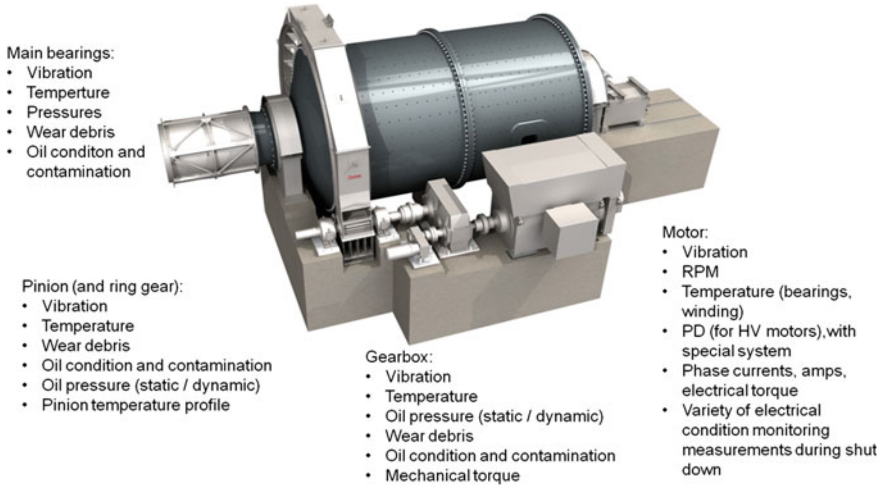

Fig. 2 Grinding mill drive train condition monitoring needs (Outotec 2015)

Early detection of failures gives time to react, plan and execute corrective actions during operation or in planned shutdown before major failure or catastrophic breakdown happens. Following operating conditions and symptoms of failure causes gives possibilities to pay attention to failure promoting tasks and able corrective actions done in best cases even before failure process has actually started.

Typical grinding mill drive train condition monitoring needs to predict possible failures are presented in Fig. 2.

With vibration measurements, oil analysis and temperature measurements around 75 % of possible mechanical failure mechanisms can be covered. In Fig. 3 there is one solution for remote vibration monitoring presented. In this solution vibration data is gathered from customer site remotely by on-line systems. Data is delivered to database where back office experts can have access to data. Data is analysed and diagnosed remotely and reports on assessment delivered for clients.

4.3 CASE 2: Remote Data Analysis for Grinding Mill Liner Condition Monitoring

Laser scanning is a common technology for collecting data on a wide range of objects. In this case laser scanning technology has been developed to capture the entire wear history inside grinding mills using laser scanners for data collection. Laser scanning is an accurate and fast method of collecting liner thickness measurements (Clarke et al. 2014).

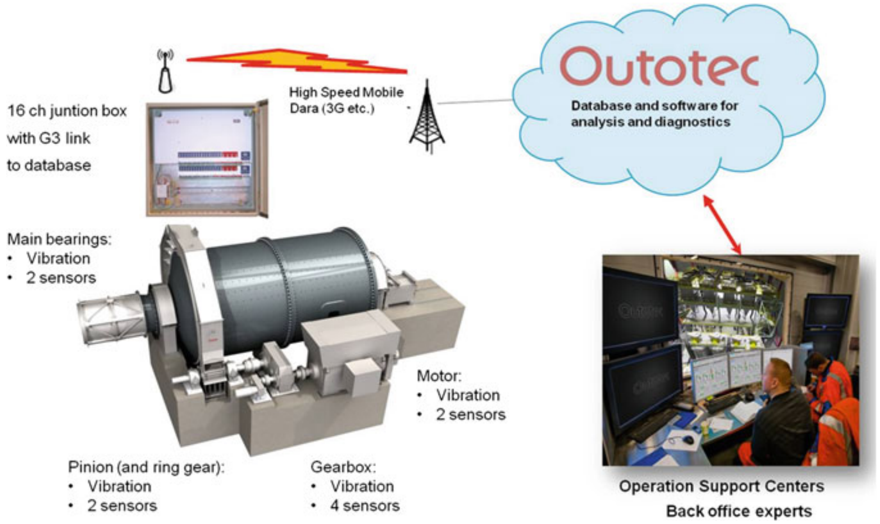

Fig. 3 One solution for grinding mill vibration monitoring where condition monitoring system on site in linked to database where back office experts can have access to data for follow-up, analysis and diagnosis (Outotec 2015)

Fig. 4 Laser scanner in mill

Using laser scanners on site to gather liner condition data is routine task and no special skills and competences are needed to do the scanning (Fig. 4). Processing and interpreting data needs special software and special competences are needed for analysis and diagnosis of the data which makes it ideal for remote service (Clarke et al. 2014).

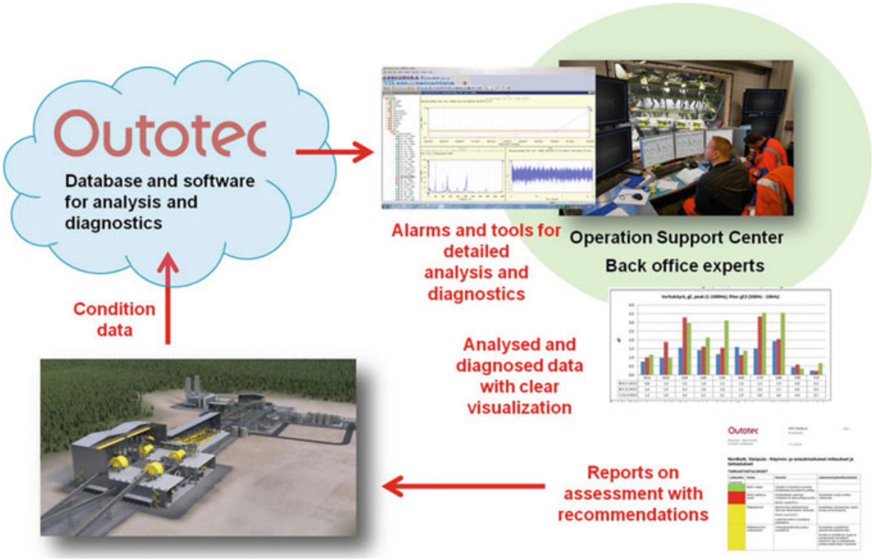

Fig. 5 Basics of remote analysis and diagnosis (Outotec 2015)

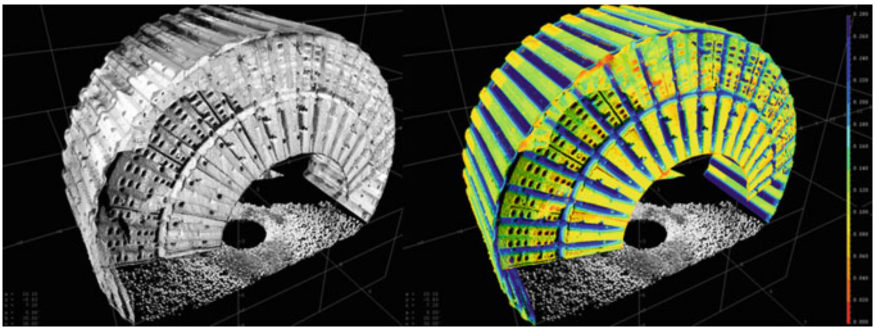

Fig. 6 Mill raw data and processed 3D model (Clarke et al. 2014)

To analyse the data and make diagnosis for required maintenance actions data gathered from scanning on site is delivered to database where back office experts can have access to data (Fig. 5).

Following the scan, the raw data is uploaded and processed to deliver a high definition 3D model (Fig. 6). This is colour-coded according to liner thickness and provides point thickness measurements on all wear surfaces to an accuracy of ±3 mm. The software automatically detects high wear zones and asymmetric wear patterns. Cracked liners, loose plates and broken grates are also detected.

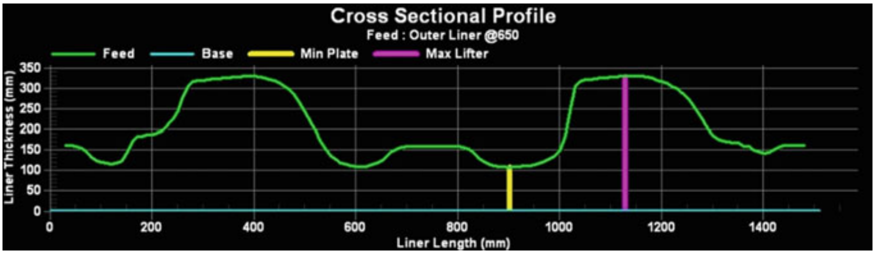

Fig. 7 Cross sectional profile (Clarke et al. 2014)

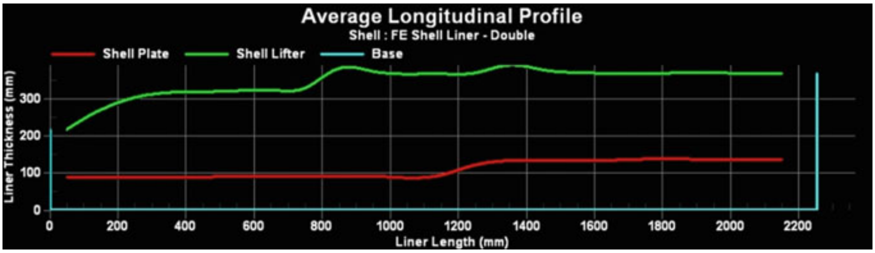

Fig. 8 Longitudinal profiles (Clarke et al. 2014)

From data gathered with laser scanned on site a 3D thickness model, shown on the right of Fig. 6, is generated. Data is processed, analysed and diagnosed remotely and reports on assessment delivered for clients (Clarke et al. 2014).

When special analysis methods and remote competences to analyze the data are used true power of the technology for mill liner condition monitoring and optimisation is realised. Some examples of reports, which are created based on 3D model, are shown in Figs. 7, 8, 9 and 10 (Clarke et al. 2014).
Following automatic detection and flagging of the wear 'hot spots', the software produces precise wear curves and intelligent forecasting based on trend data gathered from over ten million thickness points on the liner. The reporting software also produces cross sectional and longitudinal profile curves and reline efficiencies.

Liner designs can be optimized by providing historical cross-sectional and longitudinal wear plots for each liner type. Optimized liner design can increase throughput tonnage, extend reline schedules and minimize material wastage.

Reline forecasts are determined with advanced tonnage based modelling techniques specifically designed to capture high wear zones within the mill. Reline schedules can be optimized with confidence, the advanced forecasting algorithms capture dynamic wear rates over each liner lifecycle and historical data of several lifecycles can be compared to the current one.

Fig. 9 Wear curve for ball mill liner (Clarke et al. 2014)

Forecasting | Wear | Profiles | Charge | Base Data | Reline Efficiency

Description	Profile (m...	Liner Type	Reline (t)	Reline Date	Failure (t)	Failure Date
Shell						
FE Shell Liner - Single	2150	Plate	5009038	30-Apr-2009	5149859	07-May-2009
FE Shell Liner - Single	2150	Lifter	5699063	31-May-2009	5852401	07-Jun-2009
FE Shell Liner - Double	2150	Plate	5884838	09-Jun-2009	6150233	21-Jun-2009
FE Shell Liner - Double	1950	Lifter	5755183	03-Jun-2009	5947863	12-Jun-2009
DE Shell Liner - Single	50	Plate	5050439	02-May-2009	5188444	08-May-2009
DE Shell Liner - Single	50	Lifter	5495191	22-May-2009	5652015	29-May-2009
DE Shell Liner - Double	50	Plate	5842818	07-Jun-2009	6130328	20-Jun-2009
DE Shell Liner - Double	50	Lifter	5660104	30-May-2009	5863401	08-Jun-2009
Feed						
Inner Liner	1250	Plate	14441544	05-Mar-2010	16982184	17-Jun-2010
Inner Liner	1350	Lifter	10355348	19-Sep-2009	10831718	08-Oct-2009
Outer Liner	1450	Plate	7878224	10-Jun-2009	9148544	01-Aug-2009
Outer Liner	1350	Lifter	9747409	25-Aug-2009	10473306	24-Sep-2009
Discharge						
Inner Liner	1350	Plate	11045416	28-Jan-2010	11735441	01-Mar-2010
Inner Liner	1250	Lifter	9244779	08-Nov-2009	9737654	30-Nov-2009
Outer Grates	310	Plate	12149456	19-Mar-2010	12839481	20-Apr-2010
Outer Grates	50	Lifter	8533725	07-Oct-2009	8947740	26-Oct-2009

Fig. 10 Reline forecasts (Clarke et al. 2014)

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Decision Making Situations Define Data Requirements in Fleet Asset Management

Sini-Kaisu Kinnunen, Salla Marttonen-Arola, Antti Ylä-Kujala, Timo Kärri, Toni Ahonen, Pasi Valkokari and David Baglee

Abstract Large amounts of data are increasingly gathered in order to support decision making processes in asset management. The challenge is how best to utilise the large amounts of fragmented and unorganised data sets to benefit decision making, also at fleet level. It is therefore important to be able to utilize and combine all the relevant data, both technical and economic, to create new business knowledge to support effective decision making especially within diverse situations. It is also important to acknowledge that different types of data are required in different decision making context. A review of the literature has shown that decision making situations are usually categorized according to the decision making levels, namely strategic, tactical and operational. In addition, they can be classified according to the amount of time used in decision making. For example, two situations can be compared: (1) optimization decision where a large amount of time and consideration is used to determine an optimum solution, and (2) decisions that need to be made instantly. Fleet management of industrial assets suffers from a lack of asset

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management strategies in order to ensure the correct data is collected, analysed and used to inform critical business decisions with regard to fleet management. In this paper we categorize the decision making process within certain situation and propose a new framework to identify fleet decision making situations.

1 Introduction

Automated decision making is increasing due to large and often detailed amounts of available data. This is not just an issue within manufacturing organisations; recently this problem has been identified within asset management. New technologies including advanced sensor arrays, advanced analytics and cloud computing enable the development of new approaches to collect, analyse and utilize data to improve decision making within fleet asset management. The term fleet can be described as "a population of similar entities" (Tywoniak et al. 2008). Often the term fleet refers to equipment provider's installed base of units in customer sites around the world, including machinery and equipment, such as cranes, trucks, and paper machines. It is important to identify which use of the term fleet is appropriate for each research. Therefore we suggest that the concept of 'fleet' can be broadened on demand to describe different kind of fleet. In this paper we regard the fleet as "*a population of similar physical assets*" (machinery, equipment, vehicles and spare parts). Fleet may include even thousands of assets and they generate valuable data that could be utilized to fleet management.

Fleet management is an important area of research and several authors including (Mishra et al. 2013; Hounsell et al. 2012) discuss this topic in detail. Furthermore little consideration is given to the whole-life management, and the data required to manage and maintain a fleet of vehicles (Knowles and Baglee 2015). The trend in asset management has changed due to introduction of advanced technologies including eMaintenance and condition based maintenance (CBM), both of which have been discussed in the academic literature. Due to the large amounts of data available it can be argued that the required data has not fully been captured and data from historic systems is often challenging to obtain, therefore the necessary data should be identified and collected in order to be utilized more effectively in the decision making process. More effective use of data in decision making makes possible the management of asset fleets. Fleet asset management has still not been sufficiently researched and increasing understanding of fleet management and different fleet decision making situations is highly important.

The objective of this study is to increase an understanding of fleet asset management, fleet decision making situations and to identify the key data required in order to make accurate decisions. The main research question of this paper is: *What kind of decision making situations are related to enhancing fleet asset management?* This question is supported by two sub questions: (1) how are various fleet decision making situations categorized in literature? (2) what decision making situations are identified by industrial practitioners?

In this paper, we utilize design science approach as we aim at building a theoretical framework for practical managerial purposes. The design science approach aims at developing a construction, a model or a method in order to solve a problem (van Aken 2004). In design science research process, the following steps are included: identification of the problem, development of the solution (design), demonstration of the solution and validation. In this paper, we deal with the first phases of design science process, as we identify the problem and the need for a solution; in addition, we propose a framework based upon a literature review and supportive insights from industry practitioners. Insights from industry practitioners are collected in workshop organized by a research program dealing with the service solutions for fleet management. Insights are gathered from representatives of ten companies. Further testing and development of proposed framework are executed later in future research.

2 Literature Review

Fleet management techniques have been studied in the literature with regards to vehicle fleet management (Mishra et al. 2013; Hounsell et al. 2012) and fleet-wide asset health management (Voisin et al. 2013). The literature has presented a number of different fleet management systems, tools, and models which have been developed for a number of different decision-making situations. For example, Antuñano and Dessureault (2011) have developed a real-time fleet cost tool and Andersen et al. (2009 present an optimization model that improves the integration of vehicle management and service network design. Knowles and Baglee (2015) have proposed an asset management strategy for vehicle fleets based upon the use of pre-installed vehicle telematics systems which offer an opportunity for operators to continuously monitor the performance and effectiveness of their vehicles.

Optimal fleet management requires all relevant fleet data is available between stakeholders in industrial network which may consist of a large number of players, including equipment providers, customers, and service providers. This is now possible with Internet of Things (IoT) enabling advanced technologies, which help to gather and share large amounts of new data more easily between business partners. These new possibilities bring the concept of the 'industrial ecosystem' into discussion. We define the industrial ecosystem as an industrial network combined with IoT, where the ecosystem consists of companies, their assets and data which all are connected by the Internet. Availability of data gathered in ecosystem needs to be uncomplicated in order to get all the relevant data to decision making in order to enhance fleet management. To better understand the problem related to fleet decision making, the current academic literature has been reviewed to gain an insight as to how decision making situations have been categorized and what fleet decision making situations have been already designed, developed and implemented. It can be argued that there is no comprehensive framework which allow categorizing decisions making situations and takes into consideration multiple dimensions at time, such as fleet perspective. One commonly used approach is to divide decision making situations based on the level at which they are made, i.e. operational, tactical, and strategic levels. This will allow the user to separate everyday routine decisions from decisions with longer-term effects on the whole organization. Thus, the division into short and long-term decisions have also been addressed in literature. In addition, decision making situations have been categorized based on the level of uncertainty and risk. Due to the development of a number of innovative technologies the division into human and machine decision making is covered extensively within the literature (Porter and Heppelmann 2014; Davenport and Harris 2005). In asset management, Sun et al. (2008) present the classification of decision making situations using relevant time scale as criteria. They separate decisions with time scale varying from several years to the decisions that need to be done when an event occurs. Consequently, there are several ways and perspectives to observe the categorization of decision making situations but none of them takes into consideration the perspectives of fleet decision making.

Classifying fleet decision making situations is not widely discussed in literature and framework to analyse or structure fleet decision making are at best limited. As Table 1 shows, fleet management is somewhat discussed in latest academic research and there is a need to better understand the subject. When reviewing the literature, it can be noticed that fleet management problems presented in literature can be separated into four groups of decision making situations: reactive, real-time, proactive, and strategic decisions. This categorization is a conclusion from literature concerning asset management decisions and fleet management.

Table 1 Categorizing fleet decision making situations, literature review

Category of decision making situation	Decision making situation
Reactive decisions • Decisions after the event occurs • Detailed technical data and cost analysis usually cannot be conducted	Corrective maintenance, fault diagnosis and corrective actions based on data from multiple similar assets (Sardar et al. 2006)
Real-time decisions • Fast reaction, aiming to act real time • Technical, real-time data	Real-time accident handling (Ngai et al. 2012), real-time bus fleet management (Hounsell et al. 2012), dynamic fleet management problem (Shi et al. 2014)
Proactive decisions • Developing predictions and plans: actions before something happens • History and life-cycle data, including technical and economic data	Fleet-wide diagnostic and prognostic assessment, proactive monitoring (Voisin et al. 2013), optimized resource utilization (Andersen et al. 2009; Mishra et al. 2013), optimizing reliability, availability and maintainability of fleet, fleet cost management (Antuñano and Dessureault 2011)
Strategic decisions • Long-term strategic decisions • Plenty of time and consideration can be used • History and life-cycle data, emphasis on economic data	Replacement investments and strategy (Richardson et al. 2013)

Therefore, we can identify two extremes in the categorization of fleet decision making situations based on the time scale in which the decisions are done. The available time essentially affects to the nature of data and information that can be used in decision making situations. In other words, in reactive decisions which need to be made after an event occurs, detailed technical data and cost analysis usually cannot be conducted (Sun et al. 2008). Due to advanced technologies the trend is moving toward real-time decisions, where the available time is limited but the constantly monitored real-time technical data enable to make decisions even in real time. External forces and uncertainty, for example customer demand (Shi et al. 2014), are typical for real-time decisions but also for proactive decisions. The opposite is strategic decisions where plenty of time can be used and history and life-cycle data, both technical and economic data, are usually needed. Decision making situations can also vary according to the life cycle phase of the assets they are related to. It can also be noticed that maintenance-related decisions, representing the operation and maintenance phase decisions, and replace investment decisions, representing the end-of-life phase decisions, may take place for different levels of the system hierarchy.

3 Fleet Decision Identification Framework

Based on the observations from literature review and supportive insights from industry practitioners, a framework for helping to identify fleet decision making situations is proposed. The framework utilizes the categorisation of fleet decision making situations made based on literature in Table 1. The main observations related to Fleet Decision Identification framework (Fig. 1) are that usage of time varies between different types of decisions, which also affect data requirements. Secondly, there are different fleet decision making situations in every phase of asset life-cycle. Therefore, the framework aims to bring multiple dimension together when categorizing fleet decision making situations. These dimensions are life-cycle perspective, time scale, and asset hierarchy (from unit level to fleet level). Fleet level also include the ecosystem aspect to the decision making as data sources from different parties of ecosystem are needed in fleet based decision making.

In Fig. 1, the first box illustrates decision making situations at unit level trough the life cycle of asset. The second box represents the decision making situations at fleet level where data from the ecosystem and other units can be used. The decision making situations are quite similar both at unit and fleet level, but there is more data available for fleet decision making situations. This is expected to enable more accurate predictions and optimizing models as supporting data is collected from other similar assets and it can be used to make fleet level decisions. Fleet level makes possible, for example, to develop resource and capacity utilization as performance data of all assets in the fleet can be analysed. Consequently, fleet data can be utilized in diverse optimizing decision making situations in order to improve asset management.

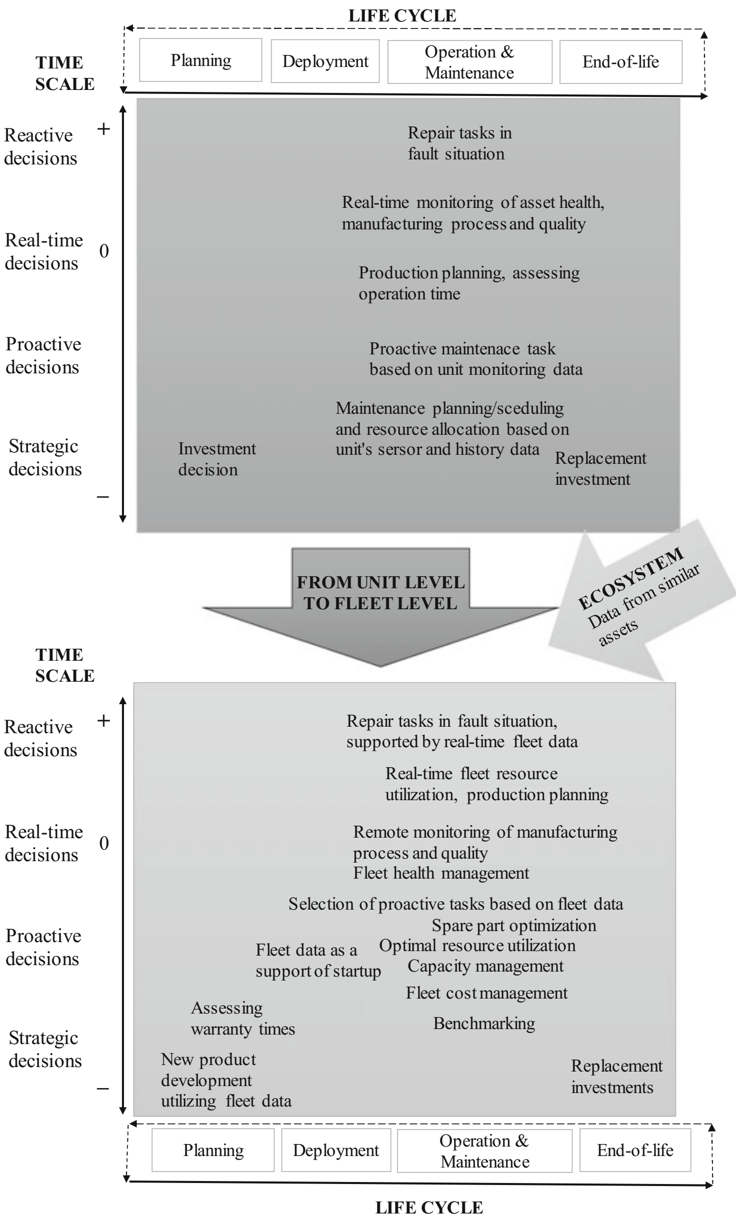

Fig. 1 Fleet decision identification framework

4 Conclusion

Researching fleet management is becoming relevant as business practitioners are facing continuous pressure to manage their assets more efficiently. The results of this research extend current understanding of different fleet decision making situations and work as a basis for better fleet management. The Fleet Decision Identification framework helps researcher and practitioners to identify various fleet decision making situations through the whole life-cycle of assets and therefore helps to understand the significance of ecosystem behind the fleet decisions as the data needs to be gathered from different sources in ecosystem. A benefit is a replacement investment which occurs only once in a unit's life-cycle, but these replacement investment decisions become significant if those decisions can be made perceiving the whole fleet. In addition, increasingly gathered data, technologies, and analytics enable to take advantage of the data in decision making, compared to previously when it was hard to utilize both technical and economic data in decision making. If the amount of automated decisions is pursued to increase, fleet data might enable scale advantage and mass tailoring of fleet services in future. This research acts as a basis for further research which will highlight the problem of how fleet based life-cycle data can be turned into business knowledge in fleet decision making situations. The proposed Fleet Decision Identification framework will be developed further and future research will focus on evaluating information network more precisely in certain fleet decision making context.

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Leveraging the Opportunities of Big Data and the Industrial Internet in Engineering Asset Management Organisations

A. Koronios, J. Gao and A. Pishdad

Abstract The recent breath taking advances in technology have brought us a corresponding exponential growth in the generation and storage of data; so much so that it is unlikely that anyone has not heard of Big Data. Although consumer electronics and internet facilitated social media are the most visible aspects of Big Data, another revolution is also taking place. This is the intelligent interconnection of everything with embedded sensors measuring any parameter that can be conceivably measurable. This is the Age of the Internet of Things (IoT) and the Industrial Internet. These technological advances will have a profound impact on all assets under management. Specifically sensor technologies, advanced controls and automated decision making promise to deliver on the vision of 'no unplanned downtime' of assets and at the same time ensure that reliability, efficiency and cost optimisation are achieved in managing assets. This paper will explore the opportunities and challenges of the Industrial Internet and provide a Framework for achieving the potential benefits of this new technological revolution.

1 Introduction

As our world is getting more intelligent, interconnected and interdependent we are gathering data at dizzying rates. Our ability to collect data grows exponentially each day with more than 90 % of it created in just the last two years through sensors, global positioning systems, retail transactions, scientific experiments and everything in between (Gobble 2013). Virtually all industries, government and research are involved in collecting data, with sensors in particular moving into every area.

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This kind of data is known as Big Data, that is, data that is too large for conventional systems to handle it and therefore new tools need to be created for analysing, storing and sharing it.

This research aims to develop a Framework to guide the leveraging of opportunities of Big Data and IoT advances in engineering asset management (EAM). The proposed Framework aims to provide a holistic view on different capabilities required for big data adoption by addressing four key dimensions, namely organisation, technology, people's competencies, and environment.

2 Big Data in Engineering Asset Management

In general, there are two major types of engineering asset data (configuration data and transaction data). The first type of data (configuration data) is that associated with the physical asset attributes. Included in this data would be data such as acquisition date, acquisition cost, and physical location of the asset. The second type of data (transaction data) is data generated as a result of operation (or use) of the assets. This data can be self-generated (i.e. the asset has embedded sensors that can track when maintenance is necessary and has been completed) or manually generated (i.e. a service technician may perform routine maintenance checks, complete required activities, and record this data in a system separate from the asset itself).

In practice, both the configuration and transaction data can be captured automatically and manually and may involve sensors, field devices, human operators, field technicians and contractors, in a variety of formats, processed in isolation and stored in an array of legacy systems. Data captured and processed by these systems is generally not comprehensive; it is usually process dependent, making it difficult to be re-used for other processes or process innovation. For example, the data captured by the sensor may only be readable in the specially designed monitoring systems, and cannot be exported and used for any other purposes. As a result, over time, a huge volume of data was accumulated in the asset management systems with incoming data from various sources at a rapid speed. Especially, considering the format and nature of the data (numeric, unstructured text—e.g. operator logs, etc.), more and more asset management organisations are facing Big Data challenges.

Big data emerges as a result of continuous interactions of four dimensions, namely data volumes, velocity of data creation, variety of data types, and value of data (the extreme time sensitivity of data diminishing its value if not treated at that moment). Uncovering data patterns in a wide variety of ongoing, fast-flowing streams of data and associating the patterns with the business outcomes, thus, highlights the main goal of big data and analytics (Mohanty et al. 2013). There is a wide agreement in the IS literature that effective big data analytics solutions requires defining coherent robust frameworks, strategies, and methodologies. For example, Fig. 1 shows a multi-step data management framework suggested by Taft

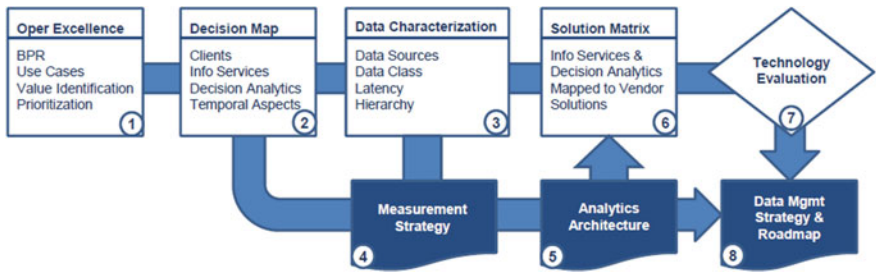

Fig. 1 Data management framework (adopted from Taft and Von Prellwitz 2012)

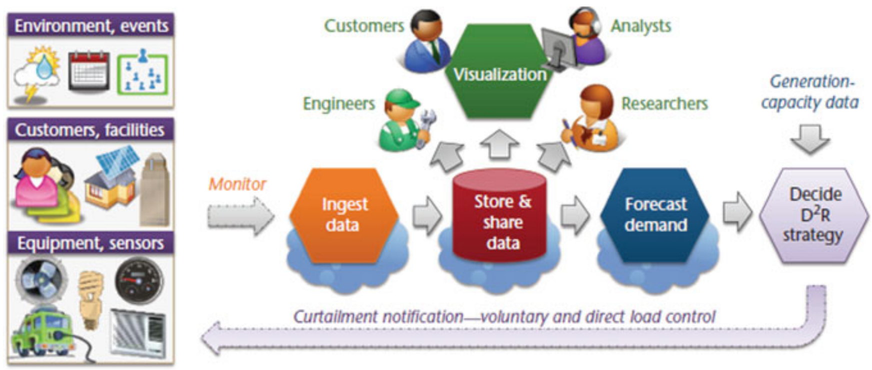

Fig. 2 Cloud-based software platform for big data analytics in smart grids—D^2 R lifecycle (adopted from Simmhan et al. 2013)

and Von Prellwitz (2012) for effective use of data and decision making in the in the utility organisation (connected energy networks). As it is highlighted in this framework, the alignment between technology evaluation processes and business needs is a critical element in achieving business success and value.

As another example, Fig. 2 shows a dynamic demand response (D2 R) Optimisation suggested by Simmhan et al. (2013). This smart grid framework offers near real-time detection, notification and response as well as an instantaneous communication capability between the utility organisation and its customers.

1. **Ingest Data**: This step includes acquiring instantaneous and historical data from smart meters and equipment sensors through the energy control system. In order to support dynamic data acquisition and to be able to adapt to the changing operational needs and data sources, it is essential to have an automated data ingest pipeline

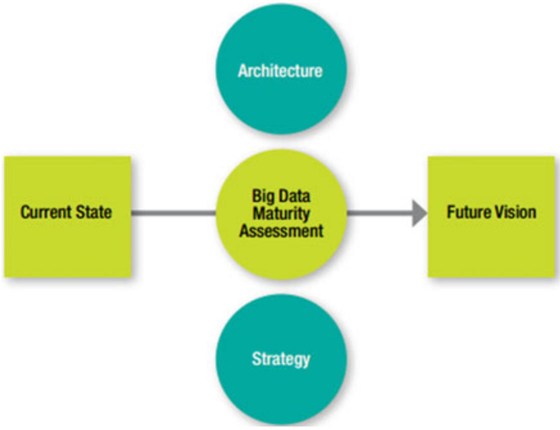

Fig. 3 The microsoft big data profiling model (adopted from Hems et al. 2013)

2. **Store and Share Data**: The acquired data need to be stored and shared with various D^2 R applications for conducting activities such as data mining by researcher and visualising the knowledge on energy profiles by consumers (security issues need to be considered).
3. **Forecast Demand**: Two classes of data forecasting are important, (1) demand forecasting models for predicting energy consumed at different spatial and temporal situations, (2) curtailment forecasting models for predicting potential energy reductions at intervals.
4. **Decide D^2R Strategy**: On the basis of the results of the forecast demanding models, D^2 R strategy selection is performed as an optimisation problem (by using Hadoop MapReduce platform).

Figure 3 also shows the Microsoft big data profiling model for oil & gas companies (Hems et al. 2013). It starts with conducting a maturity assessment to fully realise the existing IT environment (current state). Microsoft suggest that in such maturity assessment, the business and IT leaders need to be asked to answer questions about architecture, advanced analytics, data management and governance, as well as data planning and execution. This assessment includes identifying the business goals and objectives, assessing the current big data capabilities, and specifying next steps on how the company need to proceed. As an output of such assessment, the management receive clear recommendations about various people, process, and technology aspects of their future business intelligence environment.

As an example of general big data and analytics approach, Mohanty et al. (2013) propose a methodology for big data analytics (Fig. 4). This framework is similar to traditional business intelligence and analytics methodologies. The main difference, however, is an iterative frequent nature of the engagement of data analytics designers in executing data analytics steps in order to solve the issues associated with data processing at full scale. In this framework also the knowledge gained during each step is fed into and reflected in the subsequent system analysis and design.

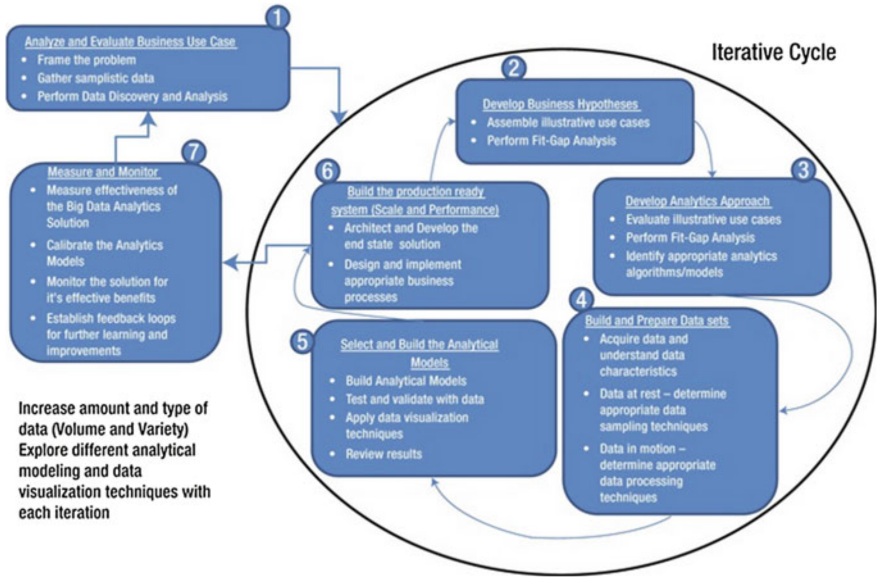

Fig. 4 Big data analytics methodology (adopted from Mohanty et al. 2013)

Finally, Thomas Davenport (a cofounder of International Institute of Analytics) released a "big data readiness assessment survey" as well as an updated version of his early DELTA model for big data analytics in his recent book. They indeed provide useful insights about the critical components of big data analytics which are also used in the early version of BDMM and survey instrument developed for doing this research (Davenport 2014).

3 EAM-Specific Big Data Management Framework

With respects to the existing Big Data management processes, methodologies and framework, given the nature of EAM data, a specific framework was proposed as the literature review result. (Figure 5).

Data quality and governance must be highlighted in the above proposed framework. Organisational alignment between both the business and technology aspects is an important enabler for the success of big data initiatives. It helps in better understanding of the business objectives and technology capabilities which are required for supporting them. As a result, data analysts and designers need to follow an interactive data governance and stewardship process until the agreement upon the business and technical requirements are made (Kiron and Bean 2013; Mohanty et al. 2013). The organisational governance structure as an enabler for managing assets in the age of industrial internet also requires some major changes.

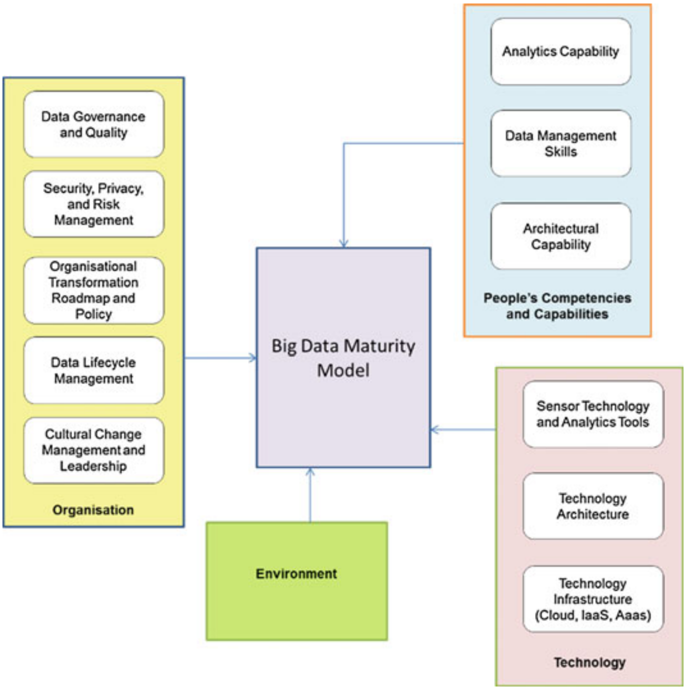

Fig. 5 Proposed framework

For example, the extant literature emphasises the importance of redefining some of the organisational roles and responsibilities such as the disappearance of the role of chief information officer (CIO) and the emergence of the role of chief data officer (CDO) who is responsible for guiding an organisation's information strategy and data governance (Kiron and Bean 2013; Davenport 2014).

Moreover, an effective data governance process such as the one used for enterprise business process management needs to be utilised to reconcile the differences between the various data characteristics and to guide the efforts towards desired directions. The potential data prioritisation and ownership issues associated with governing the big data are required to clearly become highlighted in such governance model (Taft and Von Prellwitz 2012).

Organisations also needs a vision in its Big Data management initiatives as the related projects often resource-intensive and requires ongoing investment. Thus, organisations need to have a detailed execution plan or roadmap for launching big data initiatives in order to increase their chance of producing cost-effective decisions and facilitating efficient resources. In doing so, it is necessary to clearly define and priories the key business drivers (or targets for big data as stated by Davenport 2014) on the basis of the benefits which are expected to be gained by mastering more sophisticated data-driven decisions (Kiron and Bean 2013). This roadmap, however, is not attainable without first establishing strong data management process, practices, and policies wherein the nature of existing architectural and engineering problems are clearly determined before defining a unified data management framework for data analytics. Developing appropriate measurement strategy and solution matrix, therefore, is part of this organisational transformation roadmap. For example, clear identification of sensor system architecture and an observability strategy are part of the process of developing suitable measurement strategy to support asset lifecycle management (Taft and Von Prellwitz 2012).

Finally, as the part of the Big Data roadmap, there is a critical need to establish a Big Data culture in EAM organisations through Change Management and Leadership. In order to realise the greatest benefits from an operation-driven management environment (typical in EAMs) to a more data-driven agenda, a mutual cultural understanding need to be evolved among both the domain/ engineering experts as well as data scientists. One approach towards facilitating this cultural change is increasing people’s awareness of the constraints and assumptions of various organisational domains, for example, the methods used by data scientists or the operational constraints of engineering experts (Shah 2015). At the same time, one of the crucial factors for the efficiency of data analytics in the big data environment is the high willingness of key organisational leaders to sponsor experimental activity with big data (for example, by eliminating the barriers to the implementation of innovative ideas). Senior executives, thus, need to open direct communicating channels with the data scientists and commit to audacious goals, especially in the early stages of introducing big data to the organisations. The dominant organisational culture, thus, need to be in favour of innovation, exploration and experimentation (Davenport 2014).

4 Conclusion

An extensive literature review suggests that there is lack of fully developed and universally accepted maturity model to support organisations in the assessment and improvement of big data capabilities, especially in the context of EAM organisations. The proposed framework is derived from the literature review based on the Big data studies conducted in the relevant domains. It is expected to investigate and fully elaborate each component in the above framework by conducting case studies with various EAM organisations as the second part of this study. It is believed that the final framework will reduce the uncertainties exist in the adoption of big data for EAM organisations by developing a set of managerial guidelines and practical approaches.

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Fleet Service Generation—Challenges in Corporate Asset Management

Helena Kortelainen, Ari Happonen and Sini-Kaisu Kinnunen

Abstract Product manufacturers often have access to information concerning maintenance and operation of their products in customer sites. By analysing data from wider product installation base, manufacturers would be able to have a better understanding of their product's life cycle, than any asset owner. Also this extensive body of information that is available to the manufacturer could help in finding out critical development needs. Thus product manufacturers could support asset owners and end-users by providing knowledge based fleet level services for decision making related e.g. to maintenance and operations tasks. In practise development and provision of knowledge intensive fleet services by product manufacturer is not that straightforward. There are e.g. technical and ownership related barriers on data transfer which may retard development of fleet data based services. In the paper we will discuss from the different point of views current barriers and opportunities of knowledge intensive fleet services supporting end-users' asset management processes focusing on corporate level of companies.

1 Introduction

Global product manufacturing companies have shifted their focus from product delivery to value adding asset life cycle services (e.g. Brady et al. 2005; Ahonen et al. 2010). And now, e.g. rapid development of industrial internet enables an access to information of their products in customer sites. This will change asset management practices in industrial sites and necessitates profound considerations

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on motivations, decision criteria and transparent key performance indicators that support collaborative processes (El-Aruki et al. 2013; Meridium 2007). Competition is steadily hardening, the turbulence of business environment increases, the economic life of assets becomes shorter, the requirements for sustainable and safer production strengthen, and shareholders expect higher profit. As a result, speeding up innovation becomes a critical success factor (Chiesa et al. 2009).

Product manufacturers could support asset owners or operators with knowledge based services by systematically collecting field data from the global installation base. The applicability of the data or the development of services is not straightforward as the installed products differ from each other (e.g. age, type, performance, capacity), with different environments and operational modes. In addition, technical and ownership related barriers might be high, and value sharing for the created solutions is challenging. Consequently, the challenge is to create trust between collaborating parties. One of the main issues is to consider who gathers data, who owns and shares data and to whom, and on which conditions?

This paper is a part of ongoing research which aims to find new ways to gather, analyze and understand, and then utilize information in fleet level operations in a value network and create innovative technological solutions and systems around information. The paper deals with the relationship between fleet service solutions and asset management in the productions system´s use phase. This publication aims to create the basis for further research by reviewing literature.

2 Using Fleet Level Data as a Breeding Ground for Fleet Service Solution Generation

A fleet shall be viewed as a set of systems, sub-systems and components. Common characteristics among units allow the definition of three types of fleet composition: identical, similar and heterogeneous fleets (Medina-Oliva et al. 2014). ‘Fleet management’ also implies that asset owner, fleet operator, maintenance organisation or product manufacturer has an interest for such considerations and that fleet management could bring economic benefits. With current technology manufacturers can collect data, and even control globally distributed installed base of machines and other items as a fleet. Earlier studies, e.g. Tywoniak et al. (2008), Ahonen et al. (2010) describe fleet level asset management as an important research topic, where the further area of research should include issues such as: How to define gains and responsibilities among the actors for a joint gains situation? What business models could provide joint gain situations?

If product manufacturers gain access to information concerning maintenance and operation of their products in customer sites they may develop better understanding of product’s life cycle and its critical points than what asset owners can, with just an access to the information concerning their own sites. Fleet’s units must share some characteristics that enable to group them together according to a considered purpose. These common characteristics may be technical, operational or contextual (Monnin et al. 2011). Using large scale data derived from the whole fleet, and collaborating with the customers, manufactures could develop new radical innovations. Product manufacturers have both business interest and technical possibilities to use fleet data to generate extended service solutions that meet asset owner's or operator's ever-changing asset management needs.

3 Product and Service Life Cycle and Benefits Valuation

In product or service life cycle, most essential things are usually the decision-making situations like business model design, key partner selection, pricing, purchasing and network decisions, product design related issues and also all topics related on product and production maintenance. In the end, a system is always subjected to both internal and external inputs and dynamics that change e.g. options available for between different actors. Some examples of changes in the business and operational environment along the life cycle are shown in Fig. 1.

The understanding of the value creation and distribution of value among the various network members and across the whole life cycle will require overall view of the whole network or fleet. The challenge is that different players in the value chain value different things. E.g. Ramsay (2005) stated that even the definition of value may vary a lot between different companies or people. In addition, part of this complexity in product and service life cycle arises from the fact that the elements diverge in different life-cycle stages. All of this relates quite a well on value definition of Zeithaml (1988), stating that value for customers is generally a definition or a trade-off between sacrifices and benefits.

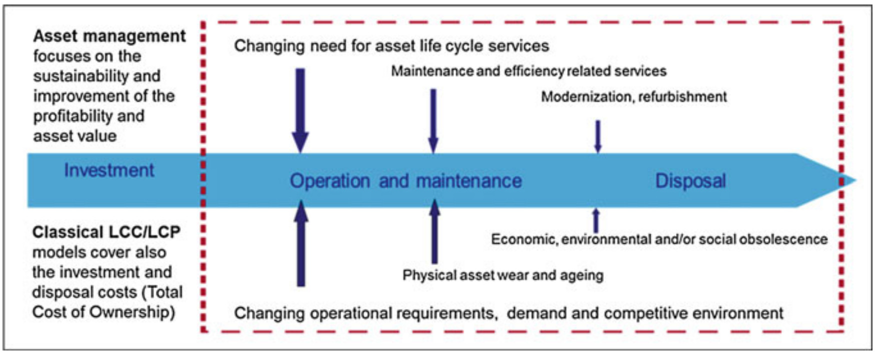

Fig. 1 Dynamics of asset management (modified from Komonen et al. 2006)

3.1 Asset Life Cycle Management

In the recent international standard (ISO 55000) 'asset management' refers to the coordinated activities of an organisation to realize value from its (physical) assets and achieve its business objectives. Even when there are many ways to define what asset management means (e.g. Mitchell 2002) the varying definitions connect asset management to the cycle in which assets are used in order to supply a service or create a product in a sustainable manner.

For organisations, running their operations with high asset utilisation levels, e.g. mining and process industries the availability performance of the production system is an operational success factor. In these sectors assets are expensive and complex and assets have a major impact on enterprise level performance. Even maintenance is crucial part of asset management multiple studies show that customer all too often evaluate the maintenance services just from the cost point of view (e.g. Idhammar 2009). Cost savings are an important driver for outsourcing maintenance activities but additional drivers include the purchase of expertise and increased quality, and companies also pursue to focus on strategic asset management thorough outsourcing (Al-Turki 2011).

3.2 Collaborative Processes for Fleet and Asset Management

In practice, it still seems that in real business context most planning in every business operations are made by inter organisation operational people not in collaboration and by networking with other companies. Also co-operation with service providers and customers is still rather uncommon (Sinkkonen et al. 2014), especially in industrial maintenance context.

In fleet level services collaboration of the product manufacturer with just few of the customers does not allow real full blow usage of the innovation potential hidden in the fleet level data. An active engaging of network partners will be needed for innovations to occur (Miles 2000) at fleet level since by collaborating widely experiences, know-how and knowledge of various stakeholders can be used and combined (Ahonen et al. 2010). Combining knowledge allows collaborating parties to achieve levels of knowledge and to create outcomes, which individual by themselves are not capable of (Wiseman and McKeown 2010).

In fleet level asset management, traditional pair like collaboration management style does not cut it. Additional level of transparency will be required, and companies have to start to operate together, they have to be cost-aware in fleet level, they need clear contracts and risk sharing models, and most importantly key performance measurement and well-defined models for profit sharing (Fig. 2). And all of this has to be done at least in fleet network level; these will need active

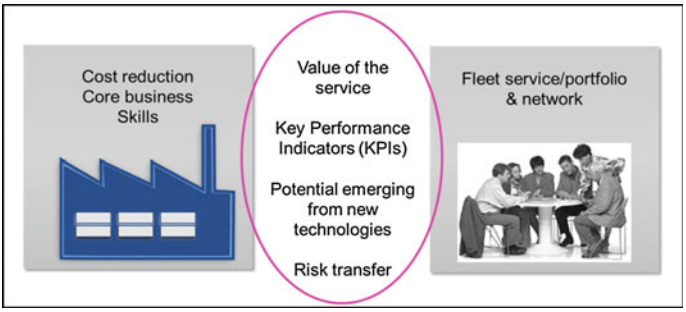

Fig. 2 Generalised visualization of asset management from asset owner's and service provider's perspective

management, to achieve the possible benefits. For the benefits, open communication and gain sharing between the partners is needed for win-win situations (Reinartz and Ulaga 2008).

4 Fleet Service and Asset Management Decision Making

What makes asset management so interesting in the context of fleet level services are the ways asset management activities and product life cycle services connect into each other. Asset management activities include organisational level planning of operations, maintenance actions and decision-making of capital investments. These integrate decision making into asset life cycles, as overall goal for enterprises is generally minimization of total cost of ownership. One part of this integration is the key decisions of making investments in new technology and in new assets, as the cost of maintenance and/or machine productivity cannot be compared anymore to the productivity and ease of maintenance of the new assets, even when the investment costs are taken into account.

In the O&M stage the management utilizes key performance indicators to monitor and control the effective use of assets. Typical indicators are OEE, availability performance and maintenance costs (EFMNS 2012). These KPI's are typically implemented at quite high level of the equipment hierarchy. Also product manufacturing companies collect product performance related data, especially during the warranty period. After that, companies may collect reclamations, maintenance service events, failure data and spare parts consumption information (Valkokari et al. 2012). Therefore mutually beneficial, collaborative shared KPIs are needed.

In several industries product life cycles are long and the product manufacturer's installed base is often heterogeneous. This limits the applicability of the fleet data, and often only the recent product generation include advanced data collection features. Additionally, the customers operate in different business environment and

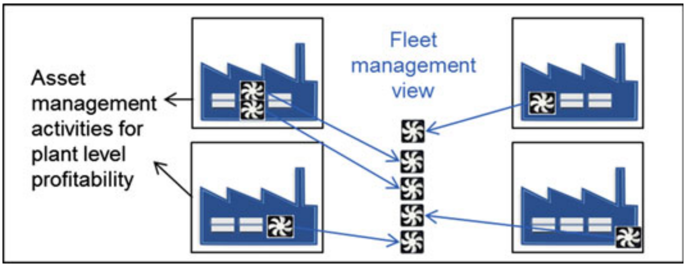

Fig. 3 Fleet asset management illustration

operational conditions. The fleet based service development should be based on a systemic view of the customer's value creation process. If the product use period extends over decades the services have to be developed all the time to meet the changing needs of dynamic business and operational environments.

As illustrated in Fig. 3, the product manufacturing companies and asset owners/operators still have different needs and driving forces, and the incentives for collaboration are lacking. Thus in order to develop breeding ground for fleet services solutions for data ownership, incentives and rewards are needed. Rapid development of industrial internet opens totally new perspectives for collaborative models and possibilities also for new actors that refine data to the business knowledge and offer services in the field of asset or fleet management.

5 Discussion, Conclusions and Future Research

For the asset management and fleet level services, it was found out, that the current practices in industry are still concentrating in collaboration of two players or pairs in information exchange. As the connection to the customer's key performance indicators is not established is the valuation of life cycle services not possible to define. Current technologies could open product manufacturer access to the data for their equipment all around the world. The idea of using shared KPI measures and delivering value added fleet services to the customers illustrates only the first step of fleet level asset management possibilities. Even technical elements for fleet services are available the methods to extract useful information from the data, and models the value generation from the asset and fleet management perspectives require validated approaches. These questions are in the core of our current research activities.

Data collection and analysis at fleet or network level opens also new business opportunities. In this context 3rd party players can be a source of game changers, and some examples on the B2C market already exist. Emerging platforms that collect huge amounts of machine related data and offer data-based services may start to threaten the existence of more traditional concepts. Further research is needed to create more profound understanding and models for data ownership, value creation and transformation in networks and service concepts based on fleet level data, and in the same time keep the emphasis on total cost of ownership. As a result of this, game theoretical approaches or serious gaming should be studied in actual practical context. In addition, the research could build up disruptive scenarios on changes in business environment and their impacts on fleet level data and open data, fleet level service responsibilities and liabilities.

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Life Cycle Cost Calculations Supporting Service Offering; Case Study of Air Conditioning Systems

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Abstract The benefits of services, in terms of life cycle cost, can be challenging to prove to a customer making service purchase decisions. To support the buyers' decision-making, the service provider can highlight all the benefits achieved by services and compare those to the service costs. In this paper, we will describe a practical case study the aim of which was to develop a method and a tool for estimating life cycle costs with or without service. The case company is Chiller Ltd. which is the largest manufacturer of air conditioning equipment in Finland.

1 Introduction

Acquisition costs, operation costs and indirect costs related to the usage of equipment such as air conditioning systems are all significant parts of life cycle costs. Acquisition costs are, however, the only ones that are clearly visible and accurately predictable at the moment of making purchase decisions. For this reason, when making investment decisions, decision-makers commonly concentrate mainly on the acquisition cost of a system. As the lifetime of the system could be up to several decades, the usage/operating costs (such as the cost of energy and maintenance) could, however, be several times higher than the acquisition price. Life cycle cost (LCC) includes all the relevant costs from acquisition to end of service

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when considering the asset owner's point of view. Thus, the aim of the LCC calculation is to optimize the total costs of asset ownership (Woodward 1997).

The challenge is that customers do not typically have estimates about expected life cycle costs. The main reason is that product or service providers are not able to provide that kind of information even if customers are interested in them. In this paper, we describe the process of developing an LCC calculation method and tool by which the case company can calculate the expected life cycle cost of their products with different technical options or service solutions.

2 Case Description

Chiller Oy is the largest manufacturer of air-conditioning equipment in Finland. Chiller produces e.g. Chillquick™ cold water stations that can be delivered with ServiceNext™ remote access service (Fig. 1). The cold water station is chosen according to the user requirements e.g. cooling demands. ServiceNext™ makes it possible to remotely monitor and access the cold water station control system. By using the remote access, Chiller experts can ascertain the status and history of the cold water station, change parameters and resolve failure situations quickly.

By using the remote access with ServiceNext™, Chiller can react rapidly to some abnormalities in the cold water station performance. In many cases, the users of a system have not even noticed that the cold water station needs its parameters adjusting or maintenance work. Without the adjustments made by the Chiller experts, the system could work with poor efficiency for months, wasting energy and money even if the equipment is under building management system (BMS). This is because the BMS does not have adequate knowledge of refrigeration processes and

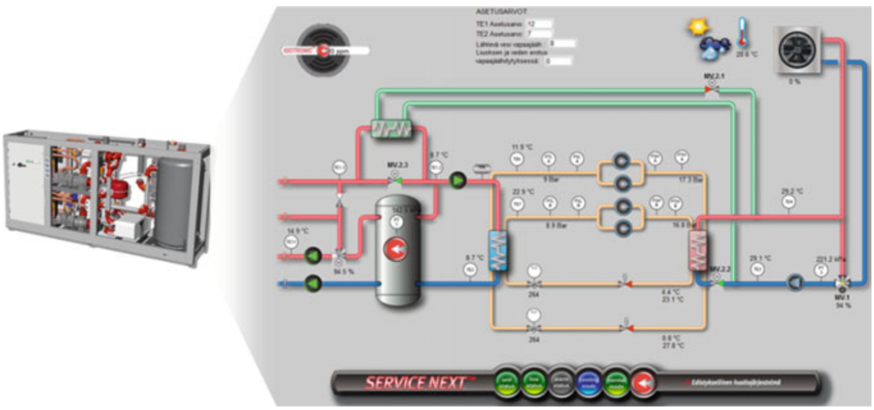

Fig. 1 Example of a cold water station and its remote control system

solutions may vary. The remote control also makes the on-site maintenance more effective, as the maintenance personnel can check the status of a system before entering the actual site and prepare based on that information.

3 Research Hypothesis and Methodology

The main research hypothesis in this study is that 'A provider of product-service solutions can support its customer's decisions to purchase services by providing the customer with detailed life cycle cost information.' The hypothesis is interesting because of the well-known fact that monetary values are the main purchase criteria. The purchase price is always available which makes comparisons easy to conduct. Another reason comes from networks where contractors are not the end-users and thus are not so interested in use time costs.

The questions related to the research hypothesis concern how a solution provider can in practise support their customers' decision-making and how much information about life cycle costs and achieved benefits affects purchase decisions. Life cycle cost consists of several factors, and all of those are typically better known by a product or service provider than a customer. Thus, information about life cycle cost should be provided by the vendor side.

We tested the hypothesis in real cases where a salesman from the case company presented their products and services to a potential customer as in a normal sale situation. During these meetings, the effects of different solutions on life cycle cost were discussed. At the end of the meeting, the researcher conducted the interview with pre-defined questions in order to collect feedback from the customer.

When considering purchases or investments, it is usually the applied life cycle profit approach which considers both costs and benefits. Anyway, in this case the life cycle cost (LCC) calculation method was applied to show the differences of alternatives to be compared. This selection was made, because the benefit achieved by a better air-conditioning solution is a reduction in life cycle cost and not, for example, increase in production. Thus, the calculation of the costs only is applicable in this case.

4 LCC Calculation

Life cycle cost calculation methods have been developing for decades and are quite well established. Korpi and Ala-Risku (2008) stated that companies still do not widely and systematically utilise life cycle cost calculations. According to writers' experiences with industrial companies, there is an increasing interest in applying life cycle cost calculations, but in practise calculation developments are considered too laborious.

The life cycle cost calculation was conducted according to the guidelines given in the dependability management standard (IEC 60300-3-3). The standard method was applied to assure a systematic approach and comprehensive LCC analysis. The next paragraphs describe briefly how the realization was done in this case.

4.1 Cost Breakdown Structure

The cost breakdown structure is a hierarchical representation of costs related to the case in question. It divides a rather abstract life cycle cost value into more concrete and thus more easily estimated cost elements. The hierarchical way to define cost structure promotes recognition of all relevant cost elements. In addition to supporting the estimation of quantitative values, a cost breakdown structure increases the transparency of elements related to whole life cycle cost which are not always obvious to customers or service providers. Distribution of costs is also relevant information for decision-making, because the importance of cost categories might vary.

In the case of an air-conditioning system, the cost breakdown system consists of five main cost categories: purchase price, cost of maintenance, cost of electricity, cost of unavailability and cost of a back-up cooling system (Table 1). The first three cost categories are relevant in all cases, but the cost of unavailability or a back-up system is optional. Not all customers have a back-up cooling system. The cost of unavailability is in this case also optional, because its monetary value might be questionable in some cases. For example, in hotels an inoperative cooling system is uncomfortable and might cause claims but does not really have a monetary effect.

4.2 Estimation of Quantitative Values for Cost Elements

When the cost breakdown structure was defined, the estimation of numerical values was the next step. This step is crucial for the reliability of the results. As far as reliable estimates for cost elements are not available, estimates of life cycle costs are not useful in decision-making.

As shown in the previous chapter, the life cycle cost consists of several different kinds of cost elements which need to be quantified. Different cost quantification methods exist; for example, Niazi et al. (2006) have presented a classification of product cost estimation methods. In order to be able to estimate life cycle cost, we applied different methods depending on available data and the cost type. Cooling systems and service have been in the market for some time, so statistical data was available. The data includes mainly maintenance-related values, but so far the data is quite limited, so in this phase we had first estimates which need to be updated when more data is available. In order to quantify cost factors, we applied four different methods:

Table 1 Cost breakdown structure for the case

Purchase price [€]
Price of the main module [€]
Price of the additional modules [€]
Maintenance [€/year]
Preventive maintenance [€/year]
Work cost [€/task]
Work time [h/prev. maintenance task]
Work cost [€/h]
Travel cost [€/task]
Travel distance [km/task]
Kilometre allowance [€/km]
Spare parts [€/task]
Number of preventive maintenance tasks [number/year]
Corrective maintenance
Work cost
Travel cost
Spare parts
Number of corrective maintenance tasks [number/year]
Price of remote control service [€/year]
Electricity [€/year]
Electricity consumption [kWh/year]
Several case-specific parameters
Price of electricity [€/kWh]
Unavailability [€/year]
Price of unavailability hour [€/h]
Number of unavailability hours [h/year]
Back-up system [€/year]
Price of back-up cooling [€/kWh]
Need of back-up cooling [kWh/year]
Unavailability time [h/year]
Average need of cooling energy [kWh/h]

1. Using constant values previously defined by the case company or other stakeholder, e.g. price of maintenance hours or price of electricity
2. Calculating parameter values based on the technical details of the system, e.g. energy consumption
3. Estimation of parameter values based on the available statistics, e.g. number of maintenance tasks
4. Expert judgements for values without any other data source, e.g. price of unavailability hour

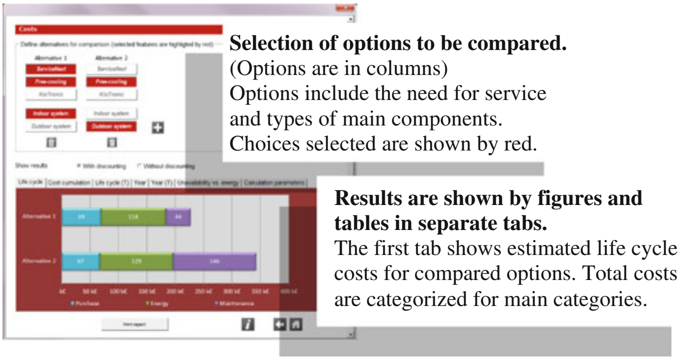

Fig. 2 Interface for options selection and result visualization

4.3 LCC Calculation Tool

In basic LCC, calculations are simple and do not necessarily need any specific calculation tool. However, in this case the idea was that a comparison of alternatives could be made in meetings together with customers and at the same time there would be a discussion of the effect of service and technical choices on life cycle cost. In order to promote fluent progress in the meeting, a tool was created which allows interactive LCC calculations with customers (Fig. 2).

5 User Experiencies

Towards the end of the development process, the tool was tested in sales meetings at Chiller. There were two test events with structured interviews by researchers. They were both actual sales events, where the main point was to promote Chiller equipment to the customer. At the meetings, sales and product development people from Chiller, engineers and designers from the customer company and one researcher from VTT were present. In addition to these structured test situations the tool has been presented to other customers at ordinary sales events without researchers.

5.1 Summary of User Feedback

The results of the testing events can be divided into (1) exploitation possibilities and potential of the tool, (2) development ideas, and (3) other comments. The results are presented below.

1. **Comments of the exploitation possibilities and potential of the tool**

The general feedback has been very positive. The LCC topic was considered to be novel and very useful in opening the eyes of the customer to be able to think about the whole life cycle of the product. The tool was considered to provide information which was clearly visualized to support decision-making. Customers also pointed out that this kind of information increases an understanding of proper usage and benefits for professional adjustment and service of the chilling equipment.

Customers' trust in the results might be an issue in this kind of calculation when not all calculation parameters are presented and customers cannot have the deep competence necessary to assess the reliability of all parameters. For example one company saw the background information as transparent enough, but the other one would have liked to know more about it.

2. **Development ideas of the tool**

In interviews, some ideas for further development were given, but no major changes were required. The main development proposals concerned data utilization, for example how to justify the background data, add competitor's data and give more flexibility to change calculation parameters according to the case.

3. **Other relevant feedback**

It was considered that in this industrial branch it is very rare to have this kind of tool. Some few companies do have them, but they are laborious to use. So, it seems that providing LCC information can provide a competitive edge at least for a while. But, on the other hand, customers are not asking for this information very much yet, and some are not even interested, depending on their role in the supply chain. However, it is an emerging issue, and the interest is growing strongly. For some customers, the LCC information does already have an effect on their decision-making. Some customers of the engineering companies even require LCC analysis today.

6 Conclusions

Several experts from Chiller Ltd. were involved in the LCC method and tool development process. During the process, the overall understanding of the cost structure of Chiller products improved as the experts shared their knowledge with each other. Also, the relations between different technical properties of products and their effects on LCC costs became clearer while the LCC calculation method was developed during the case study.

The case study showed clearly that the indirect costs such as the cost of unavailability must be taken into account when calculating the profitability of services. In this case, the direct cost savings achieved by services seem to be only a few percent of the total life cycle cost of the system. However, a cold water station can play an essential part in a larger production system, and interruptions of cold water availability can cause major effects on the production line, e.g. product quality problems occur and the production process slows down. If the cost of lost production is taken into account, the effect of services on the LCC costs is probably a lot more significant.

The LCC method and tool developed were tested in cooperation with Chiller's customers. The information LCC calculations provide was considered useful by the customers. They also pointed out that the LCC calculations are becoming more and more significant in decision-making. With the LCC tool, it was possible to see how different product options and ServiceNext™ affected the costs in the long run. Basically, the LCC tool is like a black box; the basics of the calculations are not visible all the time, which makes the tool quick and easy to use. On the other hand, this might raise some questions about the reliability of the results. To avoid this, the explanations of calculation principles are integrated into the LCC tool, and if required they can be presented to the customer as well as the calculation formulas.

The LCC tool was developed by MS Excel, which limits the usage and challenges maintenance of the tool. In the future, the tool could be converted to an online version which works connected to the database. This makes it easier to update the tool and store the customer-specific information more securely. Further research must also be carried out concerning the measurement of the intangible effects the Chiller products may have, e.g. how the lack of cooling affects the customer satisfaction in a hotel, and how it might be measured and added as a part of cost structure in LCC calculations.

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Challenges and Opportunities in Capturing Design Knowledge

Timo Lehtonen, Nillo Halonen, Jarkko Pakkanen, Tero Juuti and Petri Huhtala

Abstract This paper studies engineering asset management from the viewpoint of human capital and design knowledge. Design reasoning pattern (DRP) models are valuable for capturing and managing design knowledge. DRP models aim to explain how designing of a product should be done in a rational way in a specific case. Also the models support recognising of design sequences which aim to describe for example what should be defined first. Our empirical findings reveal several challenges and also some misbeliefs related to making of these models. In this paper, we have recognised six main challenges which relate to generality, validity, ambiguity, contradictions, logic and complexity of DRP models. These challenges are discussed, and different solutions and ways to deal with and benefit from these challenges are suggested. As a conclusion, we state that DRP models enable benefits for managing and steering design activity.

1 Introduction

Amadi-Echendu et al. (2010) define engineering asset management (EAM) as the total management of physical assets and that engineering assets have dimensions related to their economic value. This paper studies EAM from a human

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capital perspective. We claim that design knowledge is one important element of human capital. Making the design knowledge explicit is the starting point in making the design knowledge more manageable. Knowledge differs from information. McMahon et al. (2004) explain that knowledge is about beliefs and commitment and is typically associated with actions such as, business processes. They also add that knowledge is harder to transfer, receive or quantify than information that can be pointed to, found, lost, written down and compared. Therefore, capturing design knowledge can be considered as a challenging task.

Design reasoning patterns (DRP) are the core elements of design knowledge. Designing can be based on both reasoning and coincidences of acts. Reasoning means *thinking about something in a logical, sensible way* (Oxford dictionary). As researchers of design science, our emphasis is that the amount of reasoning should be higher than the amount of randomness. Rittel (1987) has summarised that design reasoning explains how designing happens based on thought acts. Consequently, designing should proceed according to certain principles and also routines. In many situations humans base their behaviour on mental models that support decision making, and the patterns of behaviour can be observed when studying both individuals and groups. This behaviour happens because human brains aim to create routines. Oxford dictionary describes pattern in a following way: "*A regular and intelligible form or sequence discernible in the way in which something happens or is done*". Design pattern thinking has its backgrounds in the first generation publications of design science, such as, Alexander et al.'s (1977) presentation of a pattern language for architecture and urban designing. The introduction of this method was not a breakthrough and similar approaches have been presented also later. One of the most significant concepts is the Design Patterns approach by Gamma et al. (1994) which includes a solution library for tasks that are repeated often in software engineering. This kind of thinking can be adapted also to manufacturing industry and to EAM. Of these two approaches, Alexander's is closer to our research context because his definitions of the patterns were considering also why the product (such as a construction) is as it is. He also suggested that different constructions shared also similar design patterns. Compared to statistical process control (SPC) (Woodall 2000), DRP approach supports process modelling and this way can serve as a starting point for understanding variation sources.

Based on the described definitions of reasoning and patterns in designing, we argue that it is possible to define DRP models which describe how designing of a physical product should be done in a sensible way in a specific case. Furthermore, we claim that it is possible for a DRP model to recognise logical sequences about designing (what should be defined first). Thus, this kind of DRP model aims to describe what design aspects are dominant in each case. The description supports the analysis of why the design is as it is and enables the reuse of DRPs for example in product development. When defining DRP models based on a team work, the aim towards a shared understanding is important. In this paper, shared understanding means that a group of people has a momentary agreement on and a mutual view amongst the relevant design activities, answering questions what, how and why the design is done in such a way. Based on our empirical findings, one of the challenges with shared understanding is that it can vanish because of the participants' mood changes or their knowledge increases or just because of the possibility that the created shared understanding is incorrect regarding the environmental variables. DRP modelling framework includes uncertainties because it is very difficult, if not even impossible, for an individual to use or copy a reasoning chains that someone else has created. DRP models may not present the absolute shared understanding but they work as a media to support communication and create means for getting closer to shared understanding. These uncertainties have to be accepted if more explicit "white box" model of human capital related to designing is pursued, instead of traditional "black box" way to designing.

As an outline for this paper, the focus is on discussing the challenges and possibilities in modelling DRPs in company specific cases, rather than explaining in details how DRP models are defined. Also, the focus is on discussing the value of DRP models. One generic aim of DRP models is that the models should only describe significant aspects relative to value creation of designing. Thus, a DRP model can be one enabler for managing the value stream because the model should explain core human capital aspects about how designing should be done in each company-specific case. DRP modelling can be an eye-opener if some areas or aspects in designing are difficult to present explicitly. This means that there can be need for increasing understanding and know-how in some design areas.

2 Challenges Related to Modelling of Design Reasoning Patterns

This section introduces the main challenges related to modelling of DRP's based on inductive reasoning and approximations of the actual design process. These models as conceptual graphs are able to present a design decision path of a specific product life cycle. Based on our empirical findings, the problem is that this kind of model creation is typically considered as of no remarkable value. We recognise six main challenges:

1. It is difficult to make a generic DRP model because the models are product or product family specific. Design decision path is product specific and generalising of this path to cover all or large group of similar products is considered to be challenging or even impossible.
2. Validity of DRP models is related to the understanding of the modellers. DRP model describes primarily the interpretation of the modellers about the product design decision path. Design decisions are thought decisions made by the designers. Thus, this kind of description is not an exact mathematical or natural scientific model but more like image of the design reasoning patterns by the modellers.
3. DRP models always contain some degree of ambiguity because of previous reason (2) and semantic modelling approach.

4. DRP models often include contradictions. In addition to this, logical loops might bring challenges for analysing the models. Therefore, these models are not graphs which could be managed with mathematical tools.
5. DRP models include logical loops and, therefore, the models lack unambiguous causality. The models cannot be used for defining or presenting the sequence of the engineering tasks to support the project management.
6. DRP models are large and appear to be complex. A model describing a typical multidisciplinary technical product can be so complex that it is difficult to understand.

In the next section, solutions and suggestions for these six unwanted DRP modelling related properties are studied. In addition to the methodological suggestions for solving these challenges, experiences around this topic from the industry and the academia are presented.

3 Design Reasoning Pattern (DRP) Method as a Solution for the Challenges

This chapter presents how the Design Reasoning Pattern (DRP) method aims to solve the challenges described in the previous chapter in order to enable beneficial tool for the product information modelling. First, the six challenges related to the DRP models (see Sect. 2) are reformulated to arguments. Subsequently, these arguments are answered by using counter-arguments. These counter-arguments aim to explain why the challenges do not prevent the modelling of the design reasoning patterns. Counter-arguments are supported by case examples.

Argument 1: Because it is not possible to make beneficial and generic DRP models, it is not reasonable to make DRP models at all.

Counter-argument 1: Generic models are interesting for researchers and teachers. However, the situation is different in the manufacturing industry. Generic models of the products form a simplistic view on the real design process. Instead of the general models, creating product and company specific models is worthwhile and value-adding.

Case A: A glass tempering machine manufacturer used a lot of time for adjusting the machines by doing test runs. Systematic quality control methods could not decrease the process variation but revealed that the variance comes from an unidentified source. Approximately 1750 man-hours were used for different attempts to solve the problem and doing test runs. A DRP model was created to describe the machine and the process. This model guided strongly executing the test runs. After 70 h of modelling and testing, the source of the problem was understood. It was found out that the source was outside the previously studied parameters. Creating the DRP model facilitated the analysis by pointing out that the source of the problem cannot exist in the studied process. Eventually, the problem was found from another product and process. In this case, it can be stated that the use of DRP modelling was 25 times more profitable than the previous attempts to solve the problem. The model described a single machine and a single case but the value of the model was estimated to be of total one man-year right from the start. Finding of the source of the problem and solving it lead eventually to applying for a method patent.

Argument 2: DRP models are not precise descriptions of the products but descriptions about the understanding and impression of how to develop the products by people and therefore, they are not more valuable than opinions.

Counter-argument 2: When experts, who know best the product, participate to the creation of a DRP model, their interpretation represents the best understanding the company could have about the product. Therefore, it is very probable that the resulting model is valid and a close approximation to a mathematical model, unless there is a lack of product development knowledge or modelling exceptions during the modelling process. Even though there exist similar constraints in DRP models as in the conceptual graphs as a media trying to picture real world situations, these models enable to extend and break the participants existing mental models.

Case A: In the company the participants in the modelling process commented that their understanding had improved regarding a subject that they were already familiar with. These participants considered themselves as experts in the field. The DRP model enabled them to form a constructivistic model to visualise their own understanding. Generally in the industry, there was a strong bias towards a belief that it was not possible to manage these unidentified uncertainties in the glass tempering process. The DRP model created a tool to examine the uncertainties and break existing mental models, or more precisely, opened mental blocks and enabled the participants to create shared understanding.

Argument 3: DRP models include uncertainties.

Counter-argument 3: A DRP model is a hypothesis of the participants' best understanding of the situation. For this reason, it must be accepted that there exist uncertainties because of the nature of inductive reasoning. However, there exist new meanings for uncertainties identified in DRP models, which are valuable.

Case B: Air handling equipment manufacturer used a DRP model to plan an integrated product and production development project. Uncertainties about the model were a valuable source of information to identify know-how requirements for the project. For example, the modelling of the production layout design reasoning patterns revealed that there was lack of knowledge in how to consider material flow, production volumes and storage levels in full detail in order to reach quality targets. The participants did not possess such knowledge or routines of how to create such outcomes. As a result, an expert was hired to contribute to the design process prior to the scheduled time frame.

Case C: In a maritime transportation equipment manufacturer, uncertainties during the modelling of DRPs revealed the differences in viewpoints between the participants on what kind of process is required to design their specific product right from the start. DRP modelling enabled the creation of an accommodation, momentary agreement that certain steps in the design process should be executed in a specific order. Still, it was identified that in the final version of the DRP model there were uncertainties in some parts of the model due to the lack of details to reveal the true logical reasoning behind specific elements.

Arguments 4 and 5: A DRP model is logically contradicted and not a graph in a mathematical context. Therefore, the DRP models cannot be used as a basis for a project plan, including the schedule and the order of implementation. Furthermore, the existence of the loops makes the model unusable.

Counter-arguments 4 and 5: The above mentioned properties are preventing the processing of the DRP models by using algorithms but these properties are not preventing procedural treatment of the models to be more like the graphs like. In fact, the contradictions are powerful boundary objects to reach shared understanding in a design team. The research group responsible for this paper has developed a tool and a work process known as disposition modelling (DiMo) (Halonen et al. 2012). As a starting point, this DiMo tool accepts that the DRP model includes contradictions but the aim is to revise the model by removing conflicts and loops. The approach is similar to the tools used in Design Structure Matrices (DSM) (Steward 1981).

Case D: A manufacturer of large process machines had a goal to design a "good enough" product that would have the lowest possible cost price with such product properties that would fulfill the minimum requirements. A DRP model was made of the products design process. The model presented the relations between the design decisions and their effect to costs and the minimum requirements. The model facilitated recognising that the suggested product proposal was not the optimal for the design goal. This saved the project from three months delay and approximately 550,000 euros direct labour cost. The cost of the DRP modelling was approximately 100,000 euros. In the case study, specific contradictions and loops in the model were natural elements of the model to examine the optimisation possibilities, whereas most of the contradictions were purely irrelevant and not in interest.

Argument 6: DRP models will become too large and uncontrollable.

Counter-argument 6: Currently, there are several ways to manage models regardless of their size and quality. When using inheritance mechanisms in object oriented modelling (OOM), the DRP model can be divided into logical sections (generic elements) which are managed separately. With OOM principles, separate DRP models can be combined to create a larger model without losing information. This kind of combined DRP model can include contradictions but there are solution to manage these issues, as described in counter-arguments 4 and 5. Furthermore, because of the nature of patterns, and loops, there exists natural repetition inside the models that enables new means to manage big models.

Case E: In a company producing forest machinery, a solution similar to OOM was created to manage large DRP models. Their product was distributed to logical generic elements, i.e. modules. DRP models were made specifically for each generic element. The idea was that in the future, during the planning phase of a product development project, the relevant DRP models of generic elements are chosen. Using OOM, a complete DRP model is structured and contradictions are identified. This complete model is designed to be used as a platform for the planning process of the project.

4 Conclusions

Understanding of why an asset or a product is as it is, offers remarkable opportunities for management. For example, if a component needs to be changed, availability of the reasoning knowledge for a certain kind of component selection helps in finding a suitable replacement component. We believe that in the future, design reasoning pattern (DRP) models that make the sequence of design decisions explicit on a company level, will become more frequent. Our cases discussed in Sect. 3 support the statement that making company specific DRP models is valuable in many ways. If the experts, that know the products best, have contributed to the modelling process, then DRP models can be considered as the best design process knowledge available. These models will always contain uncertainty, but if they are treated as hypothesis, this is acceptable. With the well-chosen tools and methods the approximation model of the DRP can be reprocessed towards mathematical and natural scientific models. By following specific rules in the modelling, the models can be defined as graphs and processed, for example, using similar principles as with design structure matrices. This processing helps in removing the loops and the contradictions in the DRP model and enables using of the DRP models also as a base for project planning. DRP models can be large and challenging to manage. By using object oriented modelling approaches and disposition modelling tools, large models can be divided into smaller, manageable entities.

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Reliability Modelling for Electricity Transmission Networks Using Maintenance Records

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Abstract Maintenance decisions for transmission network assets (TNAs) require accurate reliability prediction. However, there are a large number of operating, design and environmental variables that potentially influence their reliability. This paper presents a new reliability prediction method for TNAs. Failure times were identified by extracting significant unplanned maintenance events for critical failure modes. A regression tree-based grouping analysis was utilized to analyse the influences by variety of factors on future unplanned maintenance. These results were then used to build the reliability prediction model allowing a decision maker to have an estimate of future unplanned maintenance requirements. A case study using real industry data was conducted to test the proposed reliability prediction model. The results demonstrate the feasibility of using this approach for TNA maintenance decision support.

Keywords Reliability · Maintenance decision support · Regression tree

1 Introduction

Electricity transmission networks are a crucial part of the national infrastructure. Failure of transmission network assets (TNAs) can lead to significant consequences including: megawatt losses, regulatory penalties, and safety hazards. Despite their criticality, making informed replacement decisions prior to failure remains challenging, primarily due to the difficulty in assessing and predicting the dynamic condition of transmission network assets.

Decision-making can be supported by accurate reliability modelling for complex repairable systems which can assess and predict the future condition of TNAs. Reliability analysis and predictions can give decision makers nuanced information

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such as identification of likely network hot spots (i.e. areas that require more maintenance attention) and enable "what if" analysis.

However, reliability analysis and prediction is complicated by the fact that TNAs are linear assets (as opposed to discrete assets) which require specific modelling approaches for reliability and risk assessment. Additionally, the reliability prediction model needs to be based on actual data since the failure risk will not be uniform across the transmission network. There are many factors may influence the risk of failure. Structure characteristics (e.g. conductor type), voltage, load, and the operating environment (mechanical loading, wind, temperature, pollutants and humidity) are but a few examples of potential variables that can alter a section's risk profile, and these factors need to be accounted for in order to predict risks accurately.

This situation is further complicated by the fact that unambiguous failures are extremely rare. The majority of reliability analysis of TNAs treated outages as failure (Billinton and Kumar 1981; Amjady and Ehsan 1999; Yong and Singh 2010; Vaiman et al. 2012; Albert and Hallowell 2013). However, in many cases, outages are transient and the network is restored to service within a small time interval (often less than 1 min). Also, avoiding long term outages are not the sole performance goal of network management. Safety and regulatory compliance are also important goals that are not captured by defining outage as failure. Therefore, outage data is of limited utility in providing significant maintenance events and costs for evaluating potential maintenance policies. Providing a workable definition of "failure" for TNAs represents a significant contribution of this work.

This paper details a new reliability prediction model for TNAs. Instead of using outage data, failure times are identified by extracting significant unplanned maintenance events for critical failure modes. A regression tree based grouping analysis was integrated with a reliability prediction model to analyse the influences by the variety of factors on future unplanned maintenance. A case study was conducted using real industry data to test the proposed reliability prediction model. The results demonstrate the feasibility the proposed approach for TNAs maintenance decision support.

2 Methodology

The decision support framework proposed in this study can be seen in Fig. 1. The key contribution of this work is the definition and prediction of *maintenance triggering events* (MTEs), which we define as:

An event record (work order/notification) that requires immediate maintenance action due to network performance, safety, or regulatory compliance.

Essentially, an MTE defines an event that drives maintenance costs and risk and can be thought of as "failure" in a general sense. In this work, we use maintenance notifications and work orders to identify MTEs from historical records. However, these data contain *all* types of maintenance actions, including inspection and

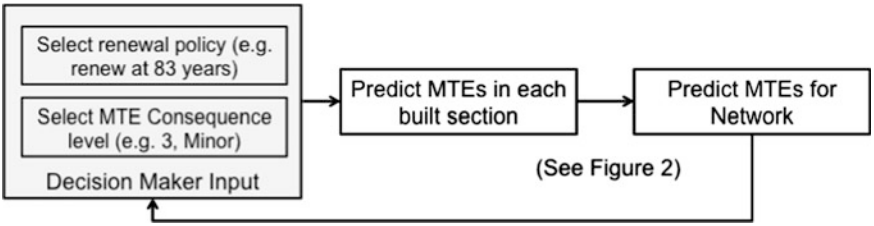

Fig. 1 Decision support framework for transmission network assets

replacement, for every structure, equipment, or part for any reason. Since only some of these notifications trigger significant events, expert knowledge was employed to identify which of these events require immediate action. Despite the large number of notification and work orders, only a small subset of them constituted MTEs and experts were easily able to identify the relatively small number of notification types and priorities that would require immediate action.

The remainder of this section details the construction of the reliability model for the prediction of MTEs, an overview of which can be seen in Fig. 2. MTEs were identified from a sample of transmission network data. Subsequently, for each MTE the structures are "grouped" together according to the variables that influence the MTE statistics (e.g. coastline distance for corrosion MTEs) and a hazard model is fitted to the empirical hazard calculated from the data (Sects. 2.1 and 2.2). The prediction of the expected number of MTEs is then conducted within each group and amalgamated into a total network MTE prediction (Sect. 2.3). Importantly, the amalgamation can be skipped and future "hotspots" can be predicted. Finally, the prediction of the effects of different maintenance actions is addressed by prediction the MTEs after maintenance action or by applying a maintenance policy for the prediction horizon (Sect. 2.4).

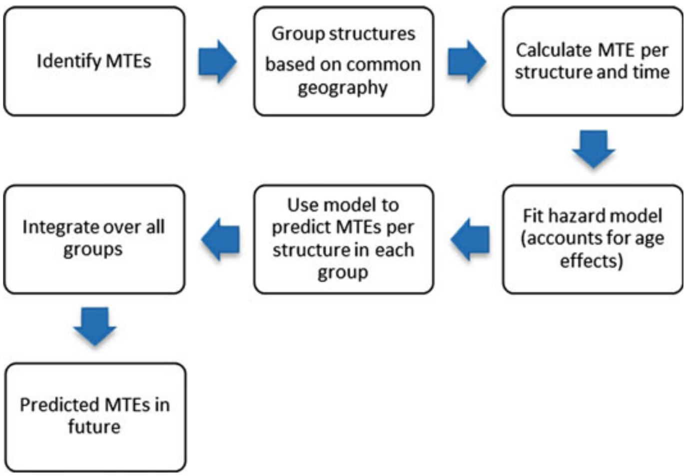

Fig. 2 Overview of the MTE prediction methodology

2.1 MTE (Hazard) Rate Modelling

A discrete hazard-based modelling method was developed by Sun et al. (2008) for linear assets, where it was assumed that the lifetimes of assets followed a piecewise hazard function, which is given by

$$h(t) = \begin{cases} \lambda, & 0 \le t < \xi \\ \lambda + \frac{\beta(t-\xi)^{\beta-1}}{\alpha^{\beta}}, & t \ge \xi, \quad \alpha > 0, \quad \beta > 1 \end{cases} \tag{1}$$

where λ is a constant failure rate, ξ indicates the wear-out point, $\xi = 1, 2, \ldots, \alpha$ and β are the scale and shape parameters of the Weibull distribution, respectively.

We propose the use of (1) to model the *MTE rate*, which is defined as the number of specific failure mode MTEs in time period *t* per network structure, which is essentially a distributed hazard rate. Therefore, we set $MTE\ Rate = h(t)$. To estimate the model in Eq. (1), Non-linear regression is utilised to estimate the parameters λ, α and β and ξ using the empirical MTE. The Empirical MTE Rate is defined as the number MTEs per structure, per unit time which is obtained from the notification and work order data.

2.2 Grouping

The network contains a number of built sections. These built sections and their constituent segments (structures, conductors, insulators, etc.) can follow different degradation processes (i.e. have different parameters in in their hazard models). While analysis is ideally conducted for an individual structure, the number of MTEs for an individual structure is normally insufficient for any meaningful statistical analysis. To compromise between data availability and specificity, lines with the same or similar characteristics are grouped to form an analysis population. In this study, a non-parametric decision tree technique, Classification and regression trees (CART) is used to split data into homogeneous groups by examining all independent variables. The selection of significant variables was conducted using expert advice and trial and error.

2.3 Prediction of Future Maintenance Triggering Events

Under the assumption of minimal repair, which is appropriate when one repairs a small part of a large system, the expected number of MTEs of type *p* for each Structure *i* for the time (age) interval [0, *t*] is given by:

$$H_{i,p,g}(t) = \begin{cases} \lambda t, & 0 < t < \xi \\ \lambda t + \frac{1}{\alpha^{\beta}} \cdot \left[(t - \xi)^{\beta} \right], & t \geq \xi, \quad \alpha > 0, \quad \beta > 1 \end{cases} \tag{2}$$

and the expected number of MTEs for each structure i in group g, over the age interval $[t, t + \Delta t]$ is given by the difference between $H_{i,p,g}(t)$ and $H_{i,p,g}(t + \Delta t)$,

$$MTE^{s}_{i,p,g}(t, t + \Delta t) = H_{i,p,g}(t + \Delta t) - H_{i,p,g}(t) \tag{3}$$

where structure i is located in group g. The expected number of MTEs for each built section $j \in g$ over the time interval $[t, t + \Delta t]$, $\widehat{MTE}^{BS}_{j,p,g}(t, t + \Delta t)$, is given by

$$\widehat{MTE}^{BS}_{j,p,g}(t, t + \Delta t) = \sum_{i \in j} MTE^{S}_{i,p,g}(t, t + \Delta t) \tag{4}$$

where $i \in j$ (in a slight abuse of notation) indicates the structure i belongs to section j. The expected number of MTEs for each network section $j \in g$ between dates T_1 and T_2 can be computed as

$$MTE^{BS}_{j,p,g}(T_1, T_2) = \widehat{MTE}^{BS}_{j,p,g}\left(T_1 - build\ date_j, T_2 - build\_date_j\right) \tag{5}$$

where *build date*$_j$ indicates the build date of built section j. The total expected number of MTEs between dates T_1 and T_2 is given by

$$MTE_p(T_1, T_2) = \sum_{g} \sum_{j \in g} MTE^{BS}_{j,p,g}(T_1, T_2) \tag{6}$$

where $j \in g$ (slightly abusing notation again) indicates the built section j belongs to group g.

2.4 Evaluation of Replacement Policies

To use the MTE predictions for decision support (as proposed in Fig. 1), we propose presenting the decision maker with an expected number of MTEs for two types of replacement policies: Age-based and threshold-based. In age-based replacement, a built section is replaced when it reaches a certain age during the planning horizon T. Different cut-off ages can be specified for each different group g. In a threshold-based replacement policy, a built section will be replaced when its predicted number of MTEs reaches a certain value (*threshold*). For instance, if *threshold* $= 20$, the predicted numbers of corrosion MTEs of three built sections are greater than 20 in 2015, then these built sections will be replaced at 2015 based on the threshold-based replacement policy.

3 Case Study

The proposed reliability prediction model was applied to the prediction of corrosion maintenance events for an electricity transmission network in Australia. Using the available data and expert analysis, significant corrosion maintenance notifications were identified for further analysis. It was found that the distance from the coast has a strong influence on the corrosion MTE rate. The MTE rate decreases as the costal distance increase until approximately 100 km inland. Through data grouping analysis (Sect. 2.2), the transmission line system is classified into three groups, $\text{AveCoastDis} \leq 6\,\text{km}$, $6\ \text{km} < \text{AveCoastDis} \leq 55.48\,\text{km}$, and $\text{AveCoastDis} > 55.48\,\text{km}$.

Figures 3, 4 and 5 show the empirical and fitted corrosion MTE rate as a function of age for the three groups. It can be clearly seen that TNAs closer to the coast have higher corrosion MTE rates. Using the methodology in Sect. 2.3, we can prediction the number of corrosion MTEs in each calendar year, based on the (clearly non-uniform) age of the different assets. Figure 6 displays the expected number of

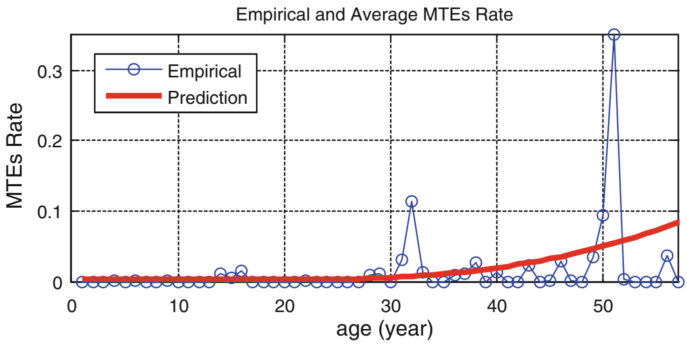

Fig. 3 Prediction of significant corrosion MTE rate for $AveCoastDis \leq 6\,\text{km}$

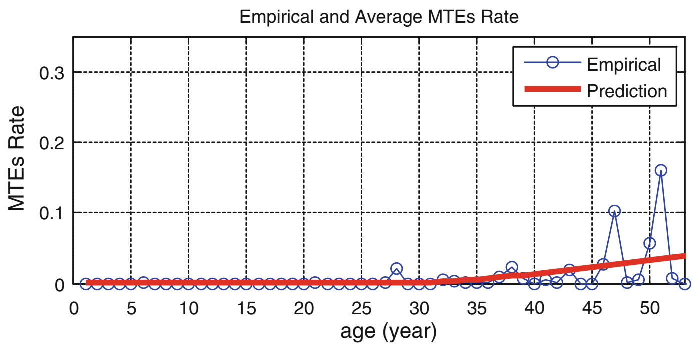

Fig. 4 Prediction of significant corrosion MTE rate for $6\,\text{km} < AveCoastDis \leq 55\,\text{km}$

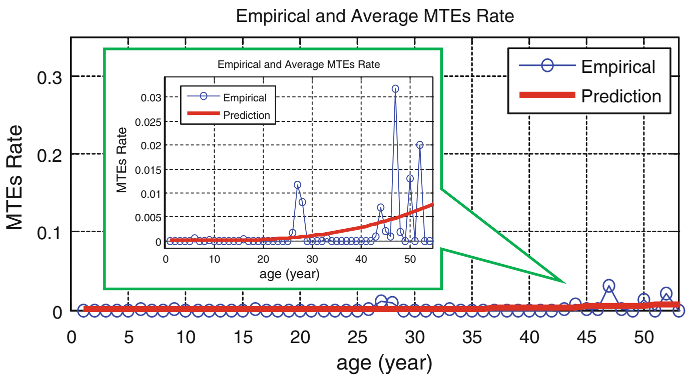

Fig. 5 Prediction of Corrosion (Level 3 and 4) MTE for $AveCoastDis > 55\,\text{km}$

corrosion MTEs (computed using Eq. (6). Prior to calendar year 0, the MTE number are known and displayed as bars, but after year 0, the MTE values represent predictions. The information can be disaggregated to display a geographical distribution of the MTEs (as shown in the bottom two plots in Fig. 6).

3.1 Prediction of Notifications Under Repair Policies

In this section, the MTE prediction methodology is used to evaluate the effectiveness of different repair policies. The prediction of the effects based on age-based maintenance policies for the predicted MTEs is demonstrated in this section. The threshold for replacement age can be different for each group and the policy demonstrated is as follows: Group (1): AveCoastDis $\leq 6\,\text{km}$, replace when age > 60 years; Group (2): $6\,\text{km} < AveCoastDis \leq 55\,\text{km}$, replace when age > 65 years; Group (3): AveCoastDis > 55 km, replace when age > 65 year. Figure 7 shows prediction of average number of significant corrosion MTEs for each calendar year under the different policies.

Instead of replacing on age, one can utilise the prediction of the expected number of MTEs, i.e. if the expected number of MTEs for a built section exceeds a threshold, the built section will be replaced. For corrosion MTEs, the results of this policy for two different thresholds can be seen in Fig. 8 ($threshold = 10$). We see that the threshold-based policy has a similar number of MTEs, but far fewer replacements over the time horizon.

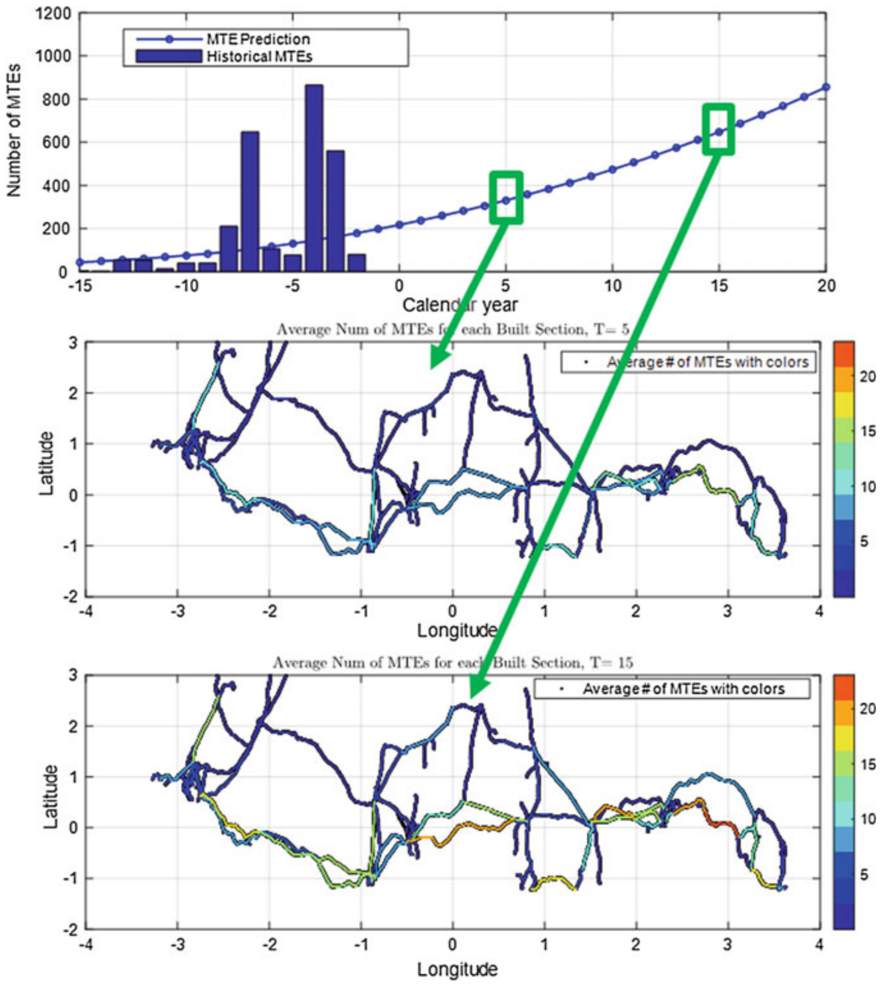

Fig. 6 Prediction of Average Number of significant corrosion MTEs with calendar year (*top*), the prediction of significant corrosion MTEs for each TNA section at T = 5 years (*middle*) and T = 15 years (*bottom*)

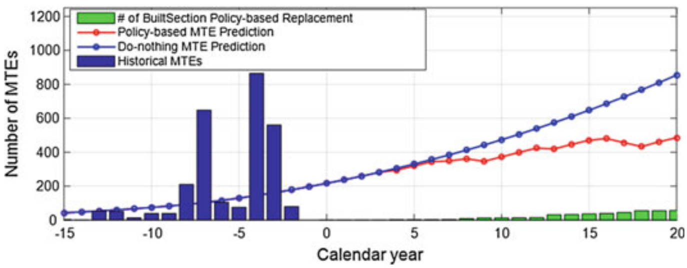

Fig. 7 Prediction of Average Number of Corrosion MTEs (Level 3 and 4) with calendar year using age-based replacement policy

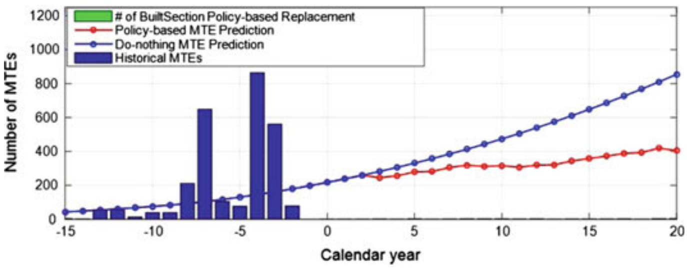

Fig. 8 Corrosion MTEs prediction using the threshold-based replacement policy (*threshold* = 10)

4 Conclusion

Electricity transmission networks are long-life, reliable and linear assets, which require innovative reliability modelling approaches to support maintenance decisions. This paper details a methodology that extracting significant unplanned maintenance events for critical failure modes, termed Maintenance Triggering Event (MTE), and introduces a new reliability prediction model for their prediction. A regression tree based grouping analysis is integrated with the reliability model to analyse the influences by variety of factors on future unplanned maintenance, where it was found that age and geography have significant effects on particular corrosion MTEs. These results were then used to build the reliability prediction model allowing a decision maker to have an estimate of future unplanned maintenance requirements.

Though only corrosion maintenance event prediction was demonstrated here, this model is also capable to predict future unplanned maintenance requirements for other failure modes. Two different replacement policies have been integrated with the model and it was demonstrated how maintenance actions can be evaluated in the framework. A case study was conducted using real industry data to test the proposed reliability prediction model. The results demonstrate the feasibility and benefits of using this approach for TNA maintenance decision support.

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Enhancing Information About Sustainability Features for Sustainable Housing Delivery

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Abstract Sustainability practices in government regulations and within the society influence the delivery of sustainable housing. The actual delivery rate of Australian sustainable housing is not as high as other countries. There is an absence of engagement by stakeholders in adopting sustainable housing practices. This may be due, in the current Australian property market, to confusion as to what sustainability features should be considered, given the large range of environmental, economic and social sustainability options possible. One of the main problems appears to be that information demanders, especially real estate agents, valuers, insurance agents and mortgage lenders do not include sustainability perspectives in their advice or in their decision processes. Information distribution in the Australian property market is flawed, resulting in a lack of return-on-investment value of 'green' features implemented by some stakeholders. This paper reviewed the global sustainable development concept and Australian sustainable assessment methods. This review identified the possibility of a research project which aimed at identifying and integrating different perceptions and priority needs of the information demanders, for developing a model for the potential implementation of sustainability features distribution in the property industry. This research will reduce confusion on the sustainability-related information which can influence the decision making of stakeholders in the supply and demand of sustainable housing.

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1 Introduction

Different approaches have been taken with the aim towards a clear definition of sustainability. The Brundtland Report, which defined sustainable development in terms of fulfilling quality of life and future generations' needs, established the linking between environment and development, in the present and in the future (WCED 1897). Sustainable development was successfully shifted to a global binder through the establishment of Agenda 21 in 1992. This calls for the greater request of sustainable development in property industry (Bryant and Eves 2012).

Whilst the property industry has taken a somewhat positive response to sustainable development, there remains significant confusion in the sector possibly due to the enormous amount of sustainability-related information available and the different sustainability challenges facing specific geographic, economic and cultural regions. There is no effective information distribution among stakeholders, especially developers, investors, and occupiers. Responsibility for sustainability appears to be passed between stakeholders, as a result of a lack of financial justification on the market value of sustainable housing (Warren-Myers 2012). This problem could be addressed by acknowledging the key role of information demanders such as valuers in communicating sustainability features whereby all stakeholders could see the benefits of sustainability (Lorenz 2008). Effective communication is required among the stakeholders in order to achieve this.

This need for effective communication can be illustrated by comparing the approaches, needs and motivations of different stakeholders in their approaches to sustainable development. A research and technical approach to this problem is the development of international standards relating to sustainability and buildings. ISO 21929-1 defines a framework for the improvement of buildings' sustainability indicators to assist the minimum functionality and performance of buildings with minimum environmental impact while improving economic and social aspects at local and global levels (ISO 2011). Individual buildings are believed to impact on seven core protection areas of sustainable development: cultural heritage, economic capital, economic prosperity, ecosystem, natural resources, health and well-being and social equity. The purpose is the protection of the areas of sustainability development, and the scope is the building life cycle.

A regulatory approach, in this case the National Construction Code (NCC) of Australia, provides a minimum amenity, safety, health and sustainability standard in the design and construction phases of new buildings. The purpose is to prescribe minimum acceptable performance standards in a limited number of criteria and the scope is the design and construction of the building (ABCB 2010).

A market approach is represented by LJ Hooker, one of Australia's largest real estate franchises. LJ Hooker developed an appraisal checklist (The 17 Things™) and a training program for real estate agents by collaborating with building and assessment industries (Hooker 2014). The purpose is to identify and communicate the sustainability potential of individual dwellings for buyers and sellers, and the scope is existing (new and old) dwellings at a particular point in time.

These three approaches, each with different motivations, purpose and scope, are shown in Table 1, revealing two key messages. Firstly, five of the ISO core indicators are addressed to some extent by the Australian NCC and seven by the market's checklist. Six of the core indicators are not addressed by either regulation or the market in Australia. Secondly, the market's checklist approach is descriptive (does the property have this feature of not), with no quantitative or qualitative information as to the extent of the sustainability outcomes. The Australian NCC tends to be qualitative (with no measures of outcomes), whilst the ISO implies that core indicators are quantitative, qualitative and descriptive (though not all indicators can be quantifiably measured).

However, these approaches are not well-delivered to enhance sustainable development. Decision-making to support sustainable housing development requires new approaches to information distribution that are able to provide different perspectives in a more holistic manner (Lorenz and Lützkendorf 2011). This requires the application of a suitable model for identifying the commonly agreed sustainability information by different stakeholders and an information distribution method that is able to guide stakeholders through their decision-making processes. As such a model for standardising and distributing the required information does not exist, this paper will focus on introducing proposed research to address this

Table 1 Comparison of technical, regulatory and market approaches to building sustainability indicators

Technical approach (ISO 21929-1)	Regulatory approach (Australian NCC)	Market approach (LJ Hooker, Australia)
Emissions to air (global warming potential and ozone depletion potential)	Minimum energy efficiency requirements for building envelope	Energy rating; energy efficient heating and cooling devices; lighting and hot water system
Amount of non-renewable resources consumption	Requirements to use energy more efficiently	Solar photovoltaic system; energy efficient
Amount of fresh water consumption	Water efficiency and rainwater (some regions)	Low water garden; water efficient appliances; rainwatertank
Amount of generated waste	–	–
Change of land use	–	–
Access to services	–	Living locally
Accessibility	–	–
Indoor condition (thermal, acoustic conditions)	Ventilation; minimum daylight factor	Orientation, cross ventilation, insulation, shading/sun control
Adaptability	–	–
Life cycle costs	–	Energy efficient
Maintainability	–	–
Safety	Structural stability	–
Serviceability	–	Zoning
Aesthetic quality	–	–

issue. The lack of an agreed model in helping decision-making processes limits the potential for effective implementation of sustainable housing.

2 Value of Sustainable Housing

Various studies have been carried out to examine the financial benefits of sustainability-related information to stakeholders for achieving sustainable housing development. Internationally, a study to analyse the impact of energy efficiency on residential sales and rental prices in European countries revealed that the majority of countries showed a positive relationship between energy efficiency and house price (Mudgal et al. 2013). For example, one letter of energy efficiency improvement in Austria was estimated to result in an 8 % increment in sales price. In one Australian market, a one star level of improvement in a house's energy performance equated to a 3 % market value improvement as shown on the Energy Efficiency Rating (EER) on detached house prices in the Australian Capital Territory (ACT) (DEWHA 2008). The positive relationship (Table 2) between sustainability-related information (in this case energy efficiency) and house price provides an incentives for stakeholders to invest in sustainable (energy efficient) housing.

However, there are restrictions on the positive financial benefits and efforts taken by the property industry in showing the value of sustainability-related information on house price. Lee and Wang (2010) argued that whilst an EER was compulsory in the ACT market, there was a poor compliance rate (37.54 %) in the property market (the EER was not included in property advertisements) and that compliance was greater for higher star rated houses when regulation for those ratings was increased from 3 to 5 stars in 2006. This latter issue may explain the reluctance of some sectors to embrace regulatory and market moves to communicate sustainability features, as such moves will natural 'disadvantage' poor quality buildings with no or few sustainability features.

The property industry and its clients are inclined to focus on the short-term benefits rather than to the long-term savings (Robinson 2005), in contrast to the life-cycle approach of ISO 21929-1. One could argue that the main challenge for the application of sustainable development is the benefit-cost relationship. Real estate agents, insurers, valuers and mortgage lenders rarely provide advice about

Table 2 Percentage increase in house price for 1 step improvement in energy efficiency

Country	Increment in sales price (%)	Increment in rental price (%)
Australia	3	–
Austria	8	4.4
Belgium	4.3	3.2
Ireland	2.8	1.4

Source DEWHA (2008), Mudgal et al. (2013)

sustainability features to their clients due to insufficient property information. There is still a gap between the sustainable development emphasis and the sustainability-related information deliverance. Policies or government regulations are conceivably required for setting the minimum standards for housing design.

3 Drivers and Challenges for the Implementation of Sustainable Housing in Australia

As shown previously (Table 1), technical, regulatory and market approaches to promote the delivery of sustainable housing result in different documentation, descriptions and guidelines. Compared to other developed nations, Australia was very late in regulating energy efficiency in the built environment. The Australian NCC introduced minimum standards for building energy efficiency for detached housing in 2003, requiring a three star energy rating according to the Nationwide House Energy Rating Scheme (NatHERS). The minimum standards were extended in 2010 (to 6 stars, out of a 10 star band) (ABCB 2010). A 9–10 star rating in Australia would be somewhat equivalent to the Passiv Haus standard.

However, a national review of energy efficiency in the residential sector commissioned by the Australian Government, revealed some issues of non-compliance with the regulated energy performance requirements and lack of best practice in the Australian housing industry. Responsibility for poor industry performance was not attributed to any particular sector, but to the multiple failures in all sectors, contributing to a culture of poor performance (State of South Australia 2014).

The efforts of enhancing the delivery of sustainable housing are not well integrated into the property market, as the industry tends to view such regulator measures as a burden (State of South Australia 2014). The information about sustainability features did not pass down efficiently to the information demander. This leads to the difficulties in including sustainability features into their practice. In this respect, the housing industry should have proper information distribution.

4 Potential Research Opportunity

Much research has been carried out in terms of evaluating the impact of different sustainability assessments and policies. However, these policies, such as the NCC, have limitations in their implementation and information distribution: they do not clearly show how they could be transformed into practical decision making during housing transactions. There is little research focusing on the property transaction level, and distributing the information to the information demanders. The situation worsens as different stakeholders have different perceptions on the information to be included in making their decision.

In between sustainability development policy and sustainability assessment, there is a perception-reality gap and mismatch, specifically on the information delivery and integration of this information to the information demanders. To provide a holistic chain of actions and decisions towards sustainable housing implementation, there is a need in finding effective ways to enhance sustainability-related information delivery during property transaction, along with the assessment methods and policy. It is important to determine which information is important to the information demanders in their decision making processes as this will influence market supply and demand of sustainable housing.

Research being undertaken in Queensland University of Technology (QUT) is attempting to rectify some of the discussed problems. This research aims to identify and integrate the different perceptions and priority needs of the information demanders, and identify the barriers that result on the gap between sustainability-related information and its actual delivery at the property transaction phase.

This QUT research employs a mixed method approach, with both quantitative and qualitative data (Fig. 1). Quantitative data will be collected through questionnaire and real estate databases. Qualitative data will be collected through questionnaire and interviews among real estate agents, valuers, mortgage lenders and insurance agents. A case study will be recruited. These data will provide stakeholders' opinions in property industry that shall reinforce the basis for establishing decision-making and information distribution model for sustainable housing.

While still at the early stage of development, initial analysis on the real estate databases on 10,000 housing data has revealed that only basic property information, such as number of bedrooms and bathrooms, are covered. Property characteristics that impact on the sustainability performance of houses, such as thermal performance of the building envelope, size of solar power systems, and ceiling height (important for tropical climates), are not included in the database. These characteristics need to be analysed by interviewing stakeholders on the strategies for better information distribution and challenges for collecting this information.

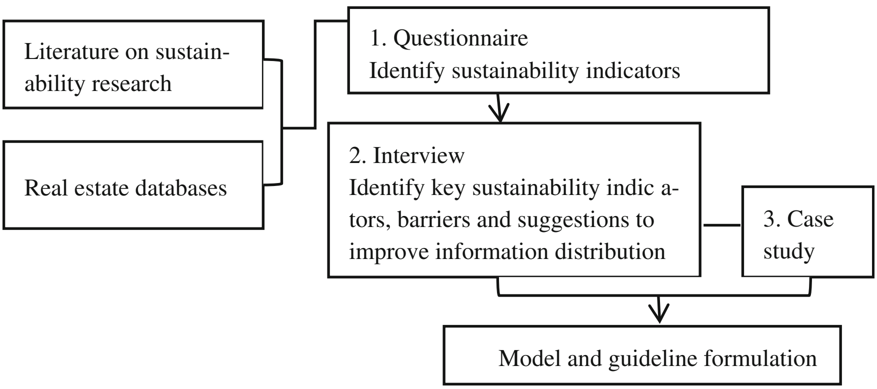

Fig. 1 Research methodology

By investigating the different views shared, simplifying technical property jargon and identifying common information, fragmentation on the sustainable-related information distribution will be reduced. This will enable collaboration and communication among information demanders in including consistent sustainability-related information in their decision making steps throughout housing lifespan.

Work to date has identified over 55 sustainability-related pieces of information (e.g. ceiling height, location of ceiling fans, insulation) that could be beneficial. Questionnaire survey and interviews will refine these criteria (in terms of building descriptions that could potentially be used to adequately communicate with other stakeholders) and/or include some important criteria from different stakeholders' perspective, which will then be tested through one sustainable housing project.

5 Conclusion

Research initiatives have covered different type of policies and sustainability assessments on housing and pointed towards paying special attention on housing for developing a sustainable future. They have not covered the aspects of enhancing the sustainability-related information and distributing information to the information demanders, who have direct contact to the buyers. This paper outlines the possibility of researching into the information distribution and the need to fill in the gaps between recognised importance of sustainability and the eventual realisation delivered at the property transaction. As there may have different property transactions throughout the lifespan of a property, this project aims to integrate different perceptions of property information demanders for developing a model of better information distribution for sustainable housing delivery.

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Development and Implementation of a Maturity Model for Professionalising Maintenance Management

Ravish P.Y. Mehairjan, Martin van Hattem, Dhiradj Djairam and Johan J. Smit

Abstract An overall corporate strategy was the further improvement and professionalization of the maintenance management organisation at the third largest Dutch electricity and gas distribution network operator in the Netherlands. This contribution discusses the development and implementation of a *Maintenance Management Maturity Model* (M^4). Principally, the M^4 is developed for measuring and monitoring the integral corporate vision of a set of multidimensional domains which are necessary for maintenance management professionalization. Maturity levels as measured in 2012 and 2014 are given for gas and electricity network assets. This contribution describes the development and practical application of a maintenance management maturity model, which is found to be a structured guide for implementing new maintenance related activities, evaluating existing activities and directing continuous improvement activities. By looking back into these maturity levels, the maintenance organisation can clearly make insightful which domains have improved or not.

1 Introduction

Historically, the power sector, such as gas and electricity network companies, would consider maintenance management as a merely technical isolated function. After the restructuring and deregulation of the power sector, network companies were not able to sustain and justify maintenance management strategies solely based on technical considerations. Nowadays, more than ever, regulators and stakeholders expect from utilities to consider mixed strategies for maintenance management in which technical, financial, social and other corporate requirements are matched from a holistic business point of view. Many difficulties arise because

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of the mix between different specialities, systems, processes, corporate values and cultures. Consequently, it is necessary to have the ability to clarify whether the maintenance management organisation and its fundamental processes, systems, policies, etc. are adequate and able to improve on continual basis. In general, the mandate for continuous improvement is part of the overall asset management objective supported by the *BSI: PAS55* specification and *ISO55000* standard. An organisation-wide approach for professionalising maintenance management and taking into account a myriad of considerations such as policies, criteria, information requirements, data systems, techniques and tools have been discussed in Mehairjan et al. (2012, 2015). Besides an organisation-wide maintenance management approach, in practice, one issue often remains unresolved, which is the ability to translate each one of the multidimensional considerations that contribute to the overall maintenance management professionalization into a predetermined uniform level. These levels describe the departing point and can be measured throughout the development path leading to maintenance improvement. To assist in addressing this issue, maturity models can be developed and implemented (van der Lei et al. 2011; Pintelon and Vanpuyvelde 2006; Chemweno et al. 2013). Broadly speaking, maturity models can be seen as a set of structured guidelines that describe how different domains within an organisation are able to contribute to a set of predetermined overall outcomes (Volker et al. 2013; Fraser 2002). An extensive history on capability maturity models and literature benchmarks can be found in Chemweno et al. (2013).

This article is organised as follows, we first introduce in Sect. 2 the developed *Maintenance Management Maturity Model* (M^4) and describe the different maturity levels and asset groups associated with this model. In Sect. 3, we then present the implementation procedure along with the results of the 2012 and 2014 assessments. By means of an internal questionnaire, the development path from 2012 to 2014 is analysed and in Sect. 4, we present the results and give some remarks regarding the way forward.

2 Developed Maintenance Management Maturity Model (M^4)

2.1 Maintenance Organisation Dimensions & Maturity Levels

In the organisation-wide maintenance management improvement approach which is described in Mehairjan et al. (2012), five organisational dimensions are recognized. These dimensions are:

– Organisation and Processes
– Policy and Criteria
– Information and Systems

- Data quality
- Performance and Portfolio

These are important dimensions that refer to areas that need to be emphasized on for the further professionalization of maintenance management (Fraser 2002). The utility argued that these dimensions and their improvement is a process which does not occur overnight. To assist in understanding to what extent the improvement of these dimensions are implemented in the maintenance organisation and how they contribute and evolve, a maturity model was developed. A simplified representation of this development process is shown in Fig. 1. The process of developing a maturity model for maintenance management purposes was initiated by means of an extensive strategic stakeholders brainstorming session. In this session strategic asset management stakeholders from various department that influence maintenance management were involved. This key group identified and agreed upon a number of organisation-wide dimensions that influence the performance and further professionalization of maintenance management. Critical dimensions were then grouped into 5 domains which turned out to be the essential building blocks to develop a maturity model. Afterwards, in the development phase of the model, the characteristics and levels of the model were agreed upon. These process phases required strong commitment from all the involved parties and were achieved by extensive discussions.

The maintenance management maturity model design process consists of the following components:

- Dimension selection
- Number of levels and description of characteristics of each levels
- Description of elements of each dimension
- Description of elements and activities of each level
- Maturity level measurement process and evaluation
- Asset categories to include in the model

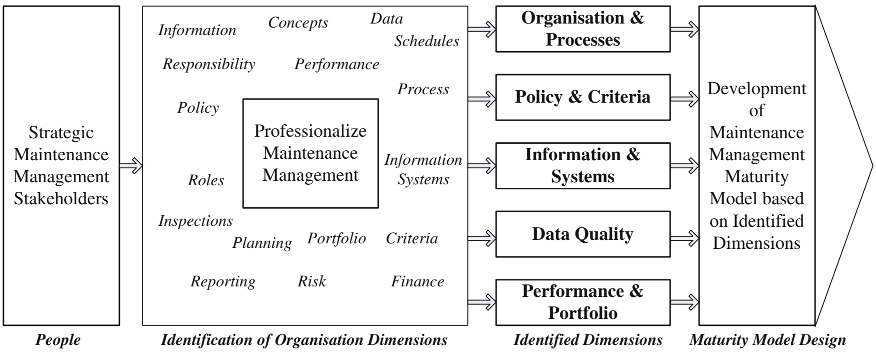

Fig. 1 Simplified representation of the development process of the maintenance management maturity model design

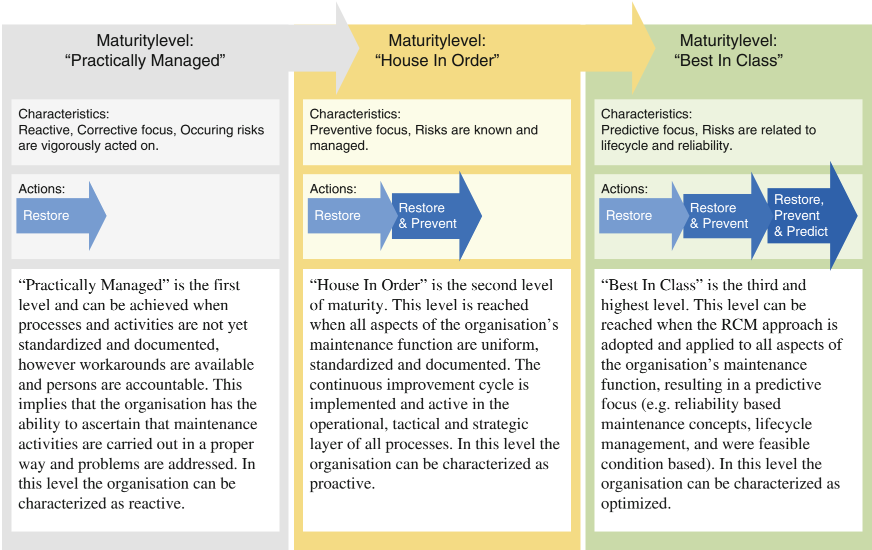

Fig. 2 Brief explanation of the three maturity levels to assess the maintenance management organisation together with the characteristics of each level and which type of actions the utility can be related to

To be able to decide which necessary measures, activities, projects or changes should be carried out in order to achieve a desired level of maturity, it is necessary to define unambiguous levels. In this model, the following maturity levels are defined:

- "Not much in place" (Ad hoc)
- "Practically Managed" (Reactive/corrective focus. Occurring risks are vigorously acted on)
- "House in Order" (Preventive focus. Risks are known and managed)
- "Best in Class" (Predictive focus. Risks are related to lifecycle and reliability)

The last three levels are shown in more detail in Fig. 2. In Fig. 2 the levels along with key action descriptions and characteristics of each level is briefly described.

2.2 *Different Asset Groups*

The use of the maturity model was also intended to provide an ideal standard for gas and electricity assets and their maintenance activities. In doing so, a uniform maintenance approach for the whole of the population is created, whereas in the traditional approach, different asset groups are often perceived in organisational "silos". In the developed M^4 approach, the following asset groups and sub-groups

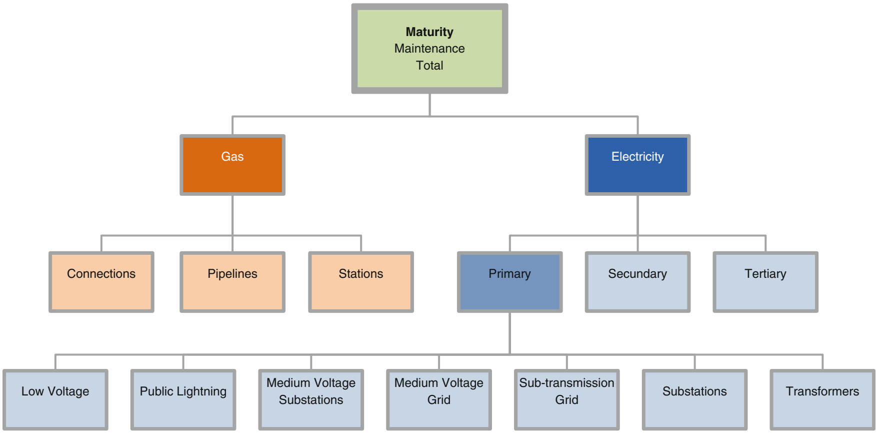

Fig. 3 Different asset groups which are assessed by means of the developed maintenance management maturity model

for electricity and gas distribution networks are considered. This breakdown is depicted in Fig. 3.

In the M^4 approach, each of the asset groups shown in Fig. 3 are assessed on the multiple organisation domains that are mentioned in Sect. 2.1. Added to this, the assessment of the maturity levels are not only performed on asset group (gas or electricity asset) and sub-group (such as cables, substations, gas pipes, etc.) level, but also on secondary and tertiary assets such as protection devices, signalling, communication, fences and buildings near substations. Besides the fact that different asset groups are now seen from uniform perspectives when related to their maintenance activities, more importantly, this approach establishes a holistic view on maintenance activities and the responsibilities of maintenance management. The M^4 approach was actually set up for this purpose, namely to be able to compare different organisational domains that are related to different asset groups and levels of asset groups with each other.

3 Implementation of the M^4

3.1 Methodology and Procedure

The method that is adopted for carrying out the assessment of the maturity levels is based on internal interviews of the personnel that are predominantly responsible for a given asset group regarding all strategic and tactical maintenance management planning and activities. Following from the organisation-wide approach (Mehairjan et al. 2012) these roles are known as *asset captains*. Each responsible *asset captain* is given a set of predetermined statements that are related to questions regarding each organisational domain. The questions and statements comprise a structured collection of characteristics that are related to a specific maturity level i.e. "*Not much in place*", "*Practically Managed*", "*House in Order*", "*Best in Class*". Thus it becomes possible to achieve an uniform and objective maturity level and to evaluate the extent to which an specific asset group has been developed and improved for a respective organisational domain.

Due to internal company specific confidentialities and agreements, we cannot disclose the complete detailed questions and statements of the M^4 approach, however in Table 1 a summary of the number of questions per domain and the overall characteristics of these questions are provided.

The assessment procedure starts with measuring the maturity level. This measurement is based on a series of predetermined questions and answers in the form of propositions, and is performed by each person which is responsible for a specific asset group together with the people responsible for the different dimensions. The questions consist of a structured set of topics that describe the maturity characteristics of an organizational dimension. By doing this in a combined setting with multiple responsible people it is strived to achieve and ensure uniformity and objectivity as substantially as possible throughout the assessments. The procedure that is followed is given in the flowchart shown in Fig. 4.

3.2 Maturity Levels—2012 Versus 2014 Results

The organisation-wide maintenance management improvement was initiated in 2011 and the M^4 was developed along with this as has been published in Mehairjan et al. (2012). In 2012, a first maturity measurement was performed, which also forms the reference measurement against which maintenance professionalization activities and improvements can be benchmarked on their effectiveness. Additionally, this reference measurement was used to document and make insightful what the maintenance management's maturity levels were for each domain at that moment and to set a goal towards which level the organisation would mature. The goals that was set in 2012 was to completely grow towards "*House in Order*" for all asset groups and relevant organisational domains. In order to achieve this goal, a number of specific projects, actions, skills and processes were planned and given priority. In the end of the year 2014, the maturity levels were assessed again in order to evaluate the levels at that given time and more specifically to evaluate whether the goal set in 2012 was achieved or not. In Figs. 5, 6 and 7, the results of the maturity checks of 2012 and 2014 are presented. Although the M^4 is assessed for all assets as shown in Fig. 3, we limit the results of the maturity results here to the total overall scores, total scores for electricity assets and total scores of gas assets as shown in Figs. 5, 6 and 7.

Table 1 Summary of the total number and characteristics of the questions per organisational domain that are adopted in the M^4 approach

Domain	# of questions	Characteristics
Organisation and processes	8	Guaranteeing continuous improvement processes with roles of designated (inter-) departments that are documented – Are processes described, documented and uniform – Are roles uniform, organized, followed – Knowledge and training
Policy and criteria	10	This domain is concerned with the fact that policies and criteria are documented, recorded and implemented. Appropriate strategic policies are translated to criteria on that basis of which maintenance planning can be performed – Are policies documented and followed – Are criteria's adapted and updated on time – Are manufacturer, product and maintenance specifications available and used
Information and systems	12	This domain is related to the information requirements and information systems used for maintenance management for each asset group and whether required information is available and recorded in the systems – Are assets registered, available in systems, and structured – How is information gathered – Inspection and failure reports available and used – Is the information supporting lifecycle management capabilities – Is analysis and reporting possible, automated and uniform – Are systems asset centric, uniform, coupled and available
Data quality	6	This domain is related to the degree to which data is suitable for the purpose for which it is used on strategic, tactical and operational level of the maintenance processes – Insights in the quality of data such as, timely, completeness, correctness – Are data quality measurements performed and how are they done – Are criteria for data quality assessment available – How are data quality issues dealt with
Performance and portfolio	13	This domain is responsible for transparent financial and portfolio planning business rules, suitable for the operational environment, leading to a uniform way to categorize maintenance activities – How are maintenance and inspection actions scheduled and reported – Are KPI's followed and available – Maintenance planning and actions and effect of maintenance – Financial planning and administration

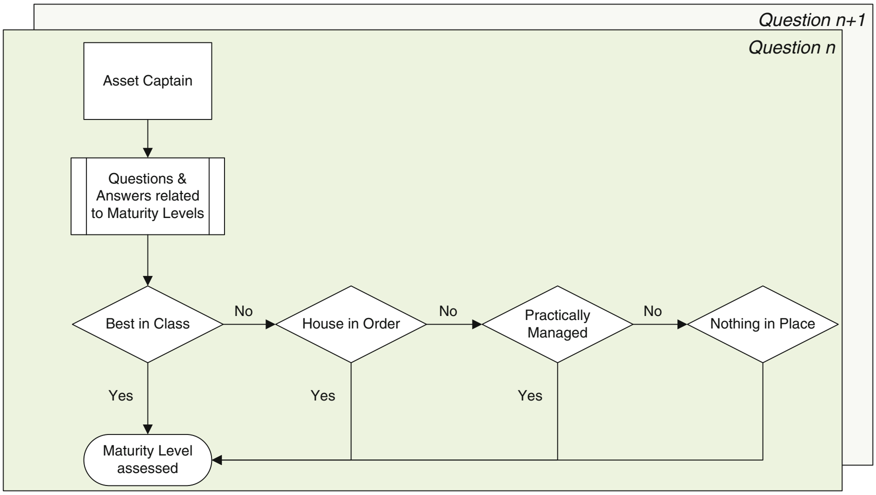

Fig. 4 Flowchart of the procedure that is followed during the assessment of the questions when establishing the maturity levels

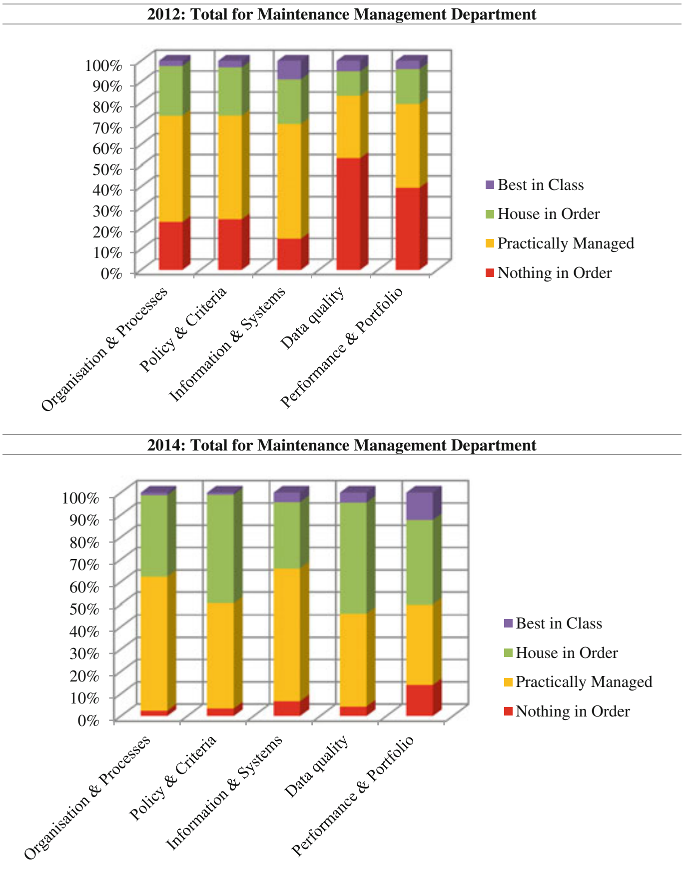

Fig. 5 Summary of the total results of the maturity levels for 2012 and 2014

Fig. 6 Summary of the total results of the maturity levels for 2012 and 2014 for electricity assets

4 Maintenance Management Professionalization Growth & Way Forward

4.1 Growth

With the goal to understand the underlying aspects that had contributed positively or slowed down certain maturity growth, an internal questionnaire amongst the *asset captains* was organised. Amongst others, one part of this questionnaire focussed on what the respective *asset captains* consider as important for growing towards *“House in Order”*, while another part focussed on what it would, according to them, take to achieve the most advanced maturity level *“Best in Class”*. Here a summarized overview of the main findings is given.

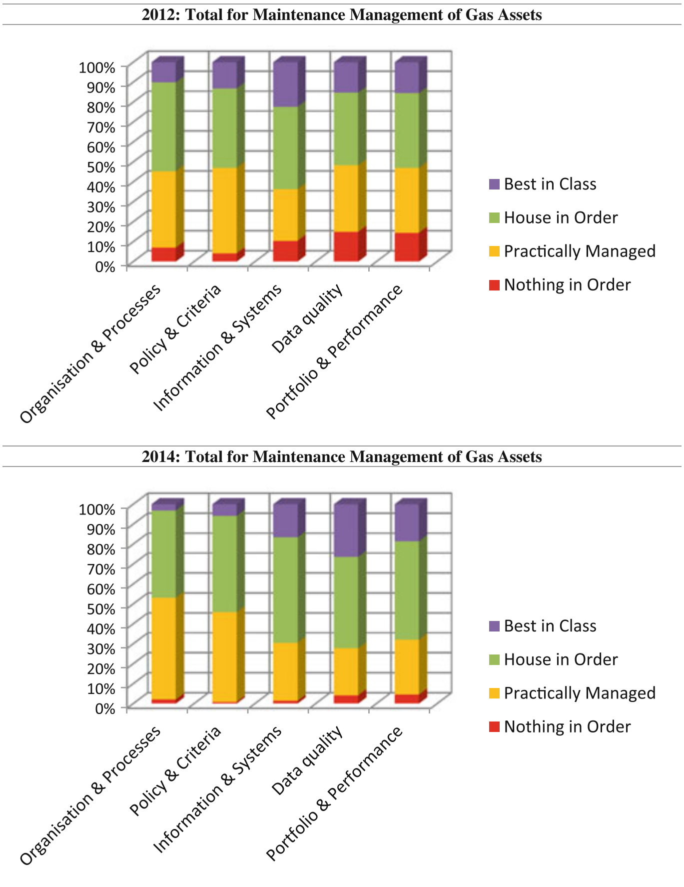

Fig. 7 Summary of the total results of the maturity levels for 2012 and 2014 for gas assets

4.2 Benchmark of M^4 with Available Literature

In Pintelon and Vanpuyvelde (2006) and Chemweno et al. (2013) an extensive overview of different benchmarked maturity models is provided. The authors in these references distinguish the maturity models based on the application domain they are developed and applied for. These range from generic to specialized domains such as IT support management. From this overview it is found that a number of maturity models are developed which are directed to maintenance management. In Table 2 the reported maintenance maturity models together with the developed with M^4 is given (Tables 3 and 4).

Table 2 List of summarized results from the internal questionnaire related to 'What is at least needed to grow towards the maturity level "House in Order"'

What is required to grow towards "House in Order"	
Domain	Summary
Organisation and processes	Formalisation, approval and stability of all maintenance roles and processes (in- and outside the asset management department)
Policy and criteria	Produce and formalize all the policy, criteria and product specifications. Improvement of the failure data recording process for assets. Drafting and carrying out health assessments for gas network assets, such as is the case for electricity networks assets
Information and systems	Finalizing the project entailing the complete *Computerized Maintenance Management System (CMMS).* Implement a number of specific *Geographical Information System (GIS)* changes and updates. Moreover, the link between static asset data systems and dynamic failure and inspection data systems is required
Data quality	Monitoring data quality in a formal and structured way in order to prevent data pollution and discrepancies
Performance and portfolio	Implement measures to be able to demonstrate the effectiveness of maintenance on the following years planning and budgets. Establishing means to ensure that maintenance management plans are guiding decisions and not solely based on budgets

Table 3 List of summarized results from the internal questionnaire related to 'What is at least needed to grow towards the maturity level "Best in Class"'

What is required to grow towards "Best in Class"	
Domain	Summary
Organisation and processes	Long term strategy for maintenance management and using risk management as guiding principle. Internal and external auditing. Creating and securing a line-of-sight throughout the whole company regarding maintenance management
Policy and criteria	Formalize all the policy, criteria and product specifications. Securing the continuous improvement cycle. Improving and developing lifecycle asset maintenance management models *(RAMS)* and risk-based maintenance management models
Information and systems	Establishing component level in-depth analytical methods supported by information and systems. Integrating *CMMS, ERP, GIS* and other specific information systems with each in a common data architecture
Data quality	Securing the current data quality levels. Enriching operational data quality levels. Creating an awareness on the operational levels (in the field) for recording field data with precision and useful quality
Performance and portfolio	Linking financial planning with asset planning in order to provide lifecycle modelling by means of analysing the risk reduction for every spend budget. Development and implementation of maintenance *Key Performance Indicators (KPIs)* most favourable based on *RAMS* philosophy

Table 4 Overview of maintenance maturity models specifying development phases, dimensions and assessments items

Literature review of maintenance maturity models together with M^4			
Reference name	Levels	Dimensions	Assessment items
(Oliveira et al. 2012) Maintenance management based on organizational maturity level	Survey based	5	Propose 15 assessment areas
(Campbell and Reyes-Picknell 2006) Maintenance maturity grid	6	10	Generalized assessments criteria
(Galar et al. 2011) Integrated maintenance scorecard	4	4	Based on 4 perspectives defined from the balanced scorecard
(Mehairjan et al. 2015) ***Maintenance management maturity model (M^4)***	***4***	***5***	***Based on 49 proposed question assessments***

4.3 Way Forward

The maturity level assessment that was performed in 2014 and the results from this are also used to set new goals. As this assessment was the first after the reference assessment (2012), it was also found that some initial goals were probably on the ambitious side. This experience and knowledge is used to adopt a set of new goals. The use of the maturity model has shown to provide advantages in the process of setting goals, because it is able to provide a common language and it assists in sparking discussions on where the organisation stands now. Moreover, it proved means to grasp better how certain developments within the organisation that are not directly related to maintenance management might influence the achievement of goals that are set and thus the maturity levels.

On one hand, the maturity model serves as an indicator of the departing point for the further development of each organisation's domain for maintenance. On the other hand, it will form the basis to compare the maturity for different asset groups with each other throughout the development path and provides the scope within which specific actions plans have contributed.

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A Case Study on Replacement Decision Making

Christinah Mohloki, J.E. Amadi-Echendu and Luis Barberá-Martínez

Abstract Reliable supply of electricity is a challenge in some developing countries. The impact on economic and socio-political developments imposes enormous pressure on electricity utilities to decide on which equipment to re-furbish or replace in case the aged/old equipment cannot meet the grid. The pressure sometimes results in ad hoc incoherent, and inconsistent decisions to replace equipment. This paper is based on a case study and highlight gaps in decisions regarding equipment replacements.

1 Introduction

According to Antoine and Ruiz-Escribano (2002), the essence of asset management is to make decisions that lead towards optimum balance between financial performance, operational performance, and risk exposure. Specifically, in electricity utilities, capital investment planning must take into consideration the replacement of degrading assets to ensure a reliable, safe, and sustainable supply of power. Equipment degradation that leads to unscheduled outage of power supply may result in penalties as imposed by the utility regulator. Sun et al. (2012) point out that maintenance interventions must be appropriate to maintain the operational reliability of equipment in electrical installations.

Electricity supply depends on transmission network to load centres and distribution network to end-users. The transmission system needs to be well-maintained to deliver a reliable supply of electricity, and it also need to be strengthened to meet

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changing customer needs. The transmission network is the primary network of interest which covers electrical networks with voltages ranging from 220 to 765 kV and the substations where these networks terminate. Electrical companies often faced with pressure to decide on which equipment to refurbish or replace in case the aged/old equipment cannot meet the grid. This paper aims to highlight the deserted aspect of equipment replacement decision. Thus the emphasis of the asset management practices is on the rules of decision making. This makes asset management the glue that holds together various functional departments, and ensures optimal decision making for the organisation.

This paper attempts to answer questions like; ‘when in the switchgear’s life is the optimal time’, and ‘is the optimal decision to replace or refurbish?’ The objective is to highlight gaps in equipment replacement decision making. Section 2 includes a brief literature review while Sect. 3 discusses the research method applied. The case study environment is described in Sect. 4, and the practical relevance of the study is summarized in Sect. 5.

2 Literature Review

According to Campbell et al. (2011), maintenance and assets managers must address four decision areas to optimize their organization’s human and physical resources as illustrated in Fig. 1.

Literature review has revealed that the assets replacement decisions are driven by the actual performance and the condition of assets (Rosqvist 2009; Yatsenko and Hritonenko 2015; Richardson et al. 2013; Crespo and Gupta 2006; Swanson 2003; Waeyenbergh and Pintelon 2002). Moreover, the optimal replacement of productive assets under changing operating and maintenance costs caused by technological advances is a problem of enormous theoretical complexity and practical importance (Hartman and Tan 2014).

Traditional methods for analysing equipment replacement decisions involve an estimation of the net present value (NPV) of all life cycle costs (LCCs) associated with a possibly infinite sequence of equipment life cycles. Given these cost estimates it is then possible to investigate how the timing of replacement decisions will affect the NPV. Examples of such replacement analysis include Galisky et al. (2008), Yatsenko and Hritonenko (2011), and Chien (2010). In the simplest case the costs associated with operating and maintaining equipment are assumed to be deterministic (Zambujal-Oliveira and Duque 2011), however, in reality there are significant uncertainties associated with LCCs, including changes in technology, varied utilisation and operating conditions, economic factors, and changes in maintenance practices. This is considered a major limitation in using a deterministic model, and has lead to significant interest in models which incorporate uncertainty. The key role of uncertainty in a replacement decision derives from the fact that with time, new information comes to hand which may influence the decision. Any approach which fails to represent the value/impact of new information on present decisions,

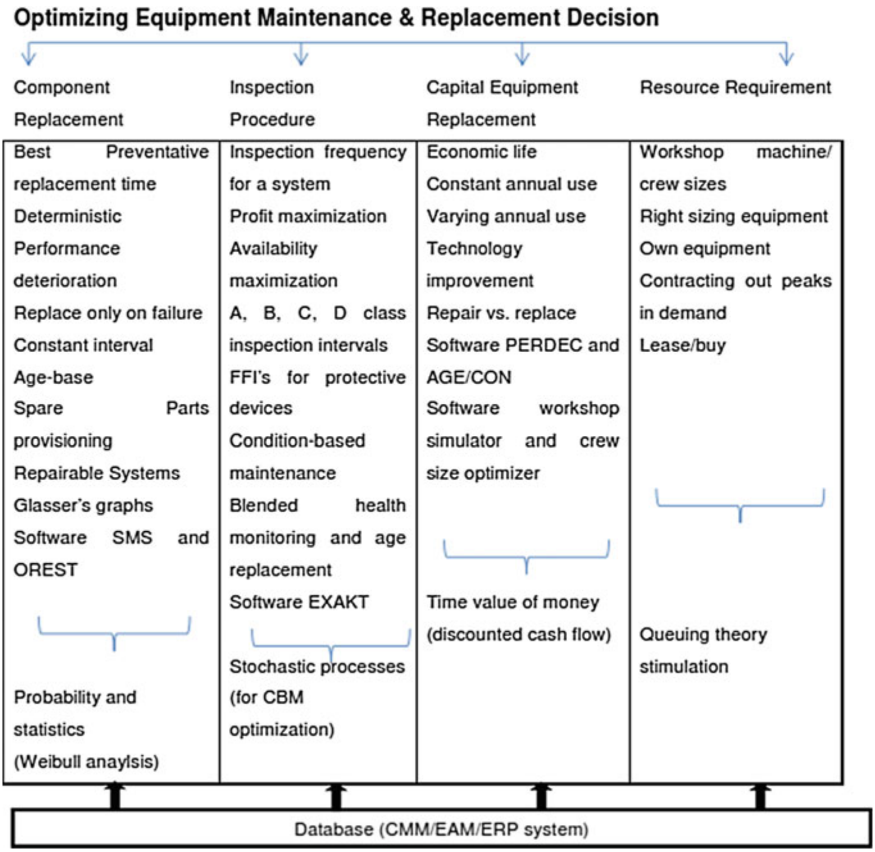

Fig. 1 Maintenance and replacement decision (Campbell et al. 2011)

necessarily fails to represent the role of uncertainty in the replacement decision, and neglects the value of the option to adapt the timing of the replacement decision. Managers must analyse all relevant information to assess the profitability of equipment (performance and condition of each asset, asset life-cycle costs and the real impact of asset failure), give sound investment decisions and consider possible cost saving (Nguyen et al. 2013).

3 Research Method

The research method involved collating available data and information on switchgear installed in the transmission network. This was followed by structured interviews with personnel to validate the data and tease out other pertinent factors influencing decisions to replace or refurbish substation equipment. The data and information collection included:

- Collation of failure rate, age, commissioning and decommissioning dates
- Grouping the consequence of failure based on data collected
- Structured interviews
- Analyses of both quantitative and qualitative data and information.

4 Case Study

A mixed approach was followed, that is, qualitative narratives were used to explain initial quantitative results (Creswell et al. 2003). This involved linking history of replacement decisions to historical data on switchgear.

The data collected covered circuit breakers installed in the entire transmission network, new circuit breakers commissioned, circuit breakers decommissioned and the circuit breaker failure rates. The same applied for isolators installed in the entire transmission network, new isolators commissioned, isolators decommissioned, and the isolator failure rates. Figure 2 shows a graphical summary of data relating to circuit breakers (CB).

In Fig. 2, all data represented is per year. The right-hand side scale of the graph represents the circuit breaker installed in the entire transmission network. The left-hand side scales represent the new circuit breaker commissioned, circuit breaker decommissioned in the network and the circuit breaker failure rate in the

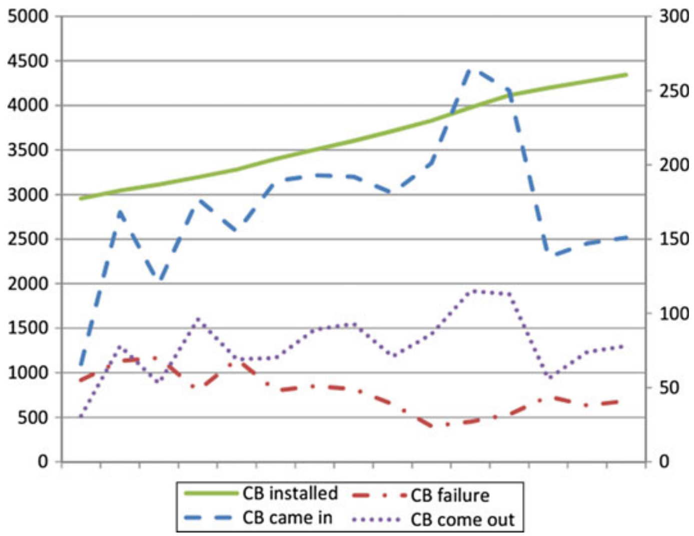

Fig. 2 Circuit breaker data

transmission network. The circuit breaker failure information was based on the period ranging from January 1999 to December 2013, a 15 year period. During this period there were a total of 703 failures which amounted to 1.29 % of the installed base. Categorising each failure into a component group assisted in identifying which part of the circuit breaker has failed.

In Fig. 3, the right-hand side scale of the graph represents isolators installed in the entire transmission network, the new isolator commissioned and the isolator decommissioned in the network. The left-hand side scales represent the isolator failure rate in the transmission network. The failure information corresponds to January 2001 to December 2013, a 13 year period. During this period there were a total of 119 failures which amounted to 0.09 % of the installed base.

As illustrated in the Fig. 3, the product manufacturing companies and asset owners/operators still have different needs and driving forces, and the incentives for collaboration are lacking. Thus in order to develop breeding ground for fleet services solutions for data ownership, incentives and rewards are needed. Rapid development of industrial internet opens totally new perspectives for collaborative models and possibilities also for new actors that refine data to the business knowledge and offer services in the field of asset or fleet management.

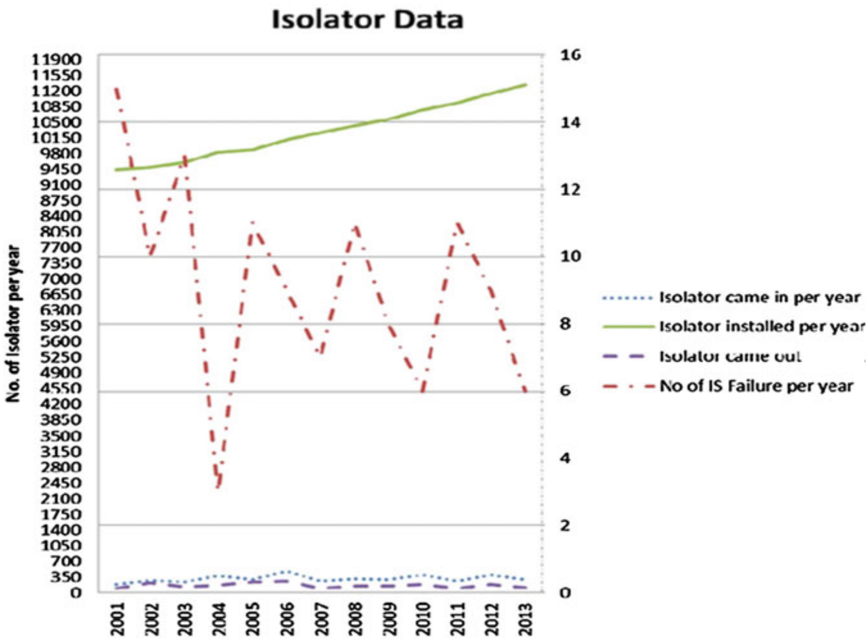

Fig. 3 Graph represents the relation between the isolator in-service, commissioned, failure rate and decommissioned

It is important to note that isolator failures present high risk to the continuity of supply, especially where there is no redundancy on feeders. Unlike circuit breakers, isolators are not bypass friendly and this translates into having to switch off otherwise healthy circuits with a resultant loss of supply. The investigation revealed that customer applications requests are given priority over planned activities which created major cost/time impact on the projects. From qualitative data, it is apparent that age plays a vital role regarding replacement of equipment. All the respondents mentioned that age is important when making decision on asset replacement. According to respondents, age and performance of assets are most contributing factors regarding replacement decisions.

5 Summary

It would appear from both quantitative and qualitative data that the case study company may not be adhering to a systematic approach to making decisions to replace circuit breakers and isolators. The lack of corroboration between historical data and respondent narratives suggest that replacement decisions were not consistent between 1999 and 2013. It is puzzling as to why detailed assessments were not carried to establish the condition of the substations. Instead, the historical data and responses strongly suggest that the decisions to replace switchgear were made on adhoc basis. This brief paper illustrates the suboptimal nature of equipment replacement decisions, and how this can be exacerbated by inconsistent data and information.

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Influence of Human Resources on Implementation of Guidelines for Engineering Asset Management: A Case Study

Cillia R. Molomo-Mphephu and J.E. Amadi-Echendu

Abstract With increasing recognition of the multidisciplinary nature of managing assets, many organisations that depend on engineered artifacts like infrastructure, equipment, machinery, and plant are curious to benchmark performance against an international standard like ISO 55000. In this regard, engineering asset management (EAM) performance depends on how well employees execute their duties as they implement policy guidelines for managing such engineered assets. This paper describes a firm level study of the influence of human resources on the implementation of asset management policies. Employees' attitude, cognition and mental preferences are proposed as useful constructs for evaluating human dimensions in engineering asset management (EAM).

Keywords EAM policies and standards · Human aspects in EAM · EAM implementation

1 Introduction

With increasing recognition of the multidisciplinary nature of managing assets, the associated challenges have taken on new significance especially for many organizations that depend on engineered artifacts like infrastructure, equipment, machinery, and plant to do business. Extrapolating from the ISO 55000 series of standards, the capability view of asset management implies that it includes *processes*, *competences*, *resources*, *technologie*s and *systems* that enable an entity to make decisions in order to derive optimum benefit and economic value from an

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organisation's assets. Even the simplification emphasized in ISO 55000 in terms of costs, risks and performance may not be realized without involvement of human resources. Gaither and Frazier (2001), and Kriege and Vlok (2015) reiterate that human resources are primordial to the management of engineered assets.

Many of the applicable guidelines, legislation and norms indicate that asset management processes may be sequenced into the life cycle stages of acquisition, operations and maintenance, and disposal as depicted in Fig. 1.

As depicted in Fig. 1, planning is imperative during each stage of the life cycle, thus, best practice demands that asset management must, at least, feature the following plans:

- Capital plan—to align engineering and financing realities;
- Acquisition plan—to identify non-asset alternatives and/or requirements for outsourcing, partnerships, and servitisation arrangements;
- Operations and maintenance plans—to deploy complimentary resources, especially human resources, for sustainable utilisation of established assets;
- Disposal plans—to conform to, and comply with requirements for environmental, ecological, financial, and technological sustainability

The fundamental challenges in asset management revolve around how to arrange the processes (i.e., organizational structures) so that the complimentary *competences*, financial and human *resources*, *technologies* and *systems* are efficiently and effectively deployed in order to "maximise the service delivery potential and benefits accruing" from established assets, whilst concurrently minimising the

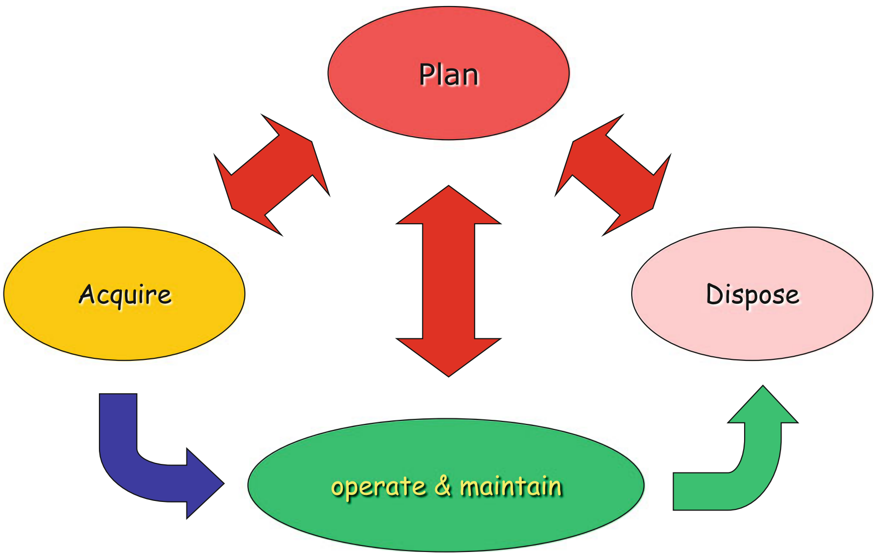

Fig. 1 Life-cycle stages of an engineered asset (*Source* Treasury Guideline, South Africa)

costs, mitigating risks and vulnerabilities associated with assets over the life cycle stages. Implicit in these challenges are sustainability imperatives such as:

i. *Reduce*—(e.g., asset energy efficiency, investment options, economic costs);
ii. *Reuse*—(e.g., asset life extension, upgrades), and
iii. *Recycle*—(alternative uses of asset after end of current life).

This paper briefly describes a study on the impact of human resources on implementation of guidelines for the management of engineered assets. As at the time of the study, the case study organization was carrying out projects to rehabilitate immovable plant and associated infrastructure that it uses to maintain and repair a fleet of movable assets. The study applied the concepts of organizational unlearning and learning to examine employees' attitudes, cognitive and mental preferences with regard to the implementation of ISO 55000 standards.

2 ISO 55000 and Organisational Unlearning

The ISO 55000 standards indicate that value, alignment, leadership, and assurance are fundamental tenets for asset management. Assets provide the means for the realization of value, and this requires leadership, and alignment of organizational structures and processes to assure that business benefits are achievable (Haider 2012). Amadi-Echendu (2010) makes the point that these tenets "demand a shift in thinking styles, cognitive and mental processing modes, attitudes and behaviourial preferences" of humans entrusted with the responsibility to manage engineered assets. Kriege and Vlok (2015) argue that organizational culture, motivation and leadership, learning and development, knowledge management, and change management are human resource dimensions that pertain to the ISO 55000 principles.

To adopt and adapt to ISO 55000, these tenets not only require an organization to learn new ways of doing things but also, they impose upon the employees to unlearn existing ways that may no longer be effective. The reasoning here is that the multidisciplinary nature of engineering asset management accentuates rapid transformations in knowledge, that is "knowledge grows, and simultaneously it becomes obsolete as reality changes", therefore, knowledge that is rapidly becoming outdated should be unlearned (cf: Becker 2005). In principle, individual employees and the organization should respectively unlearn knowledge that has become outdated, whilst concurrently learning new ways to handle inevitable change (Akgün et al. 2007). In their review of literature in individual change and transition, Windeknecht and Delahaye (2004) proposed the model illustrated in Fig. 2 "to address the interface between individual and organisational learning and unlearning". This model was applied to examine employees' attitudes, cognitive and mental preferences with regard to the implementation of ISO 55000 standards.

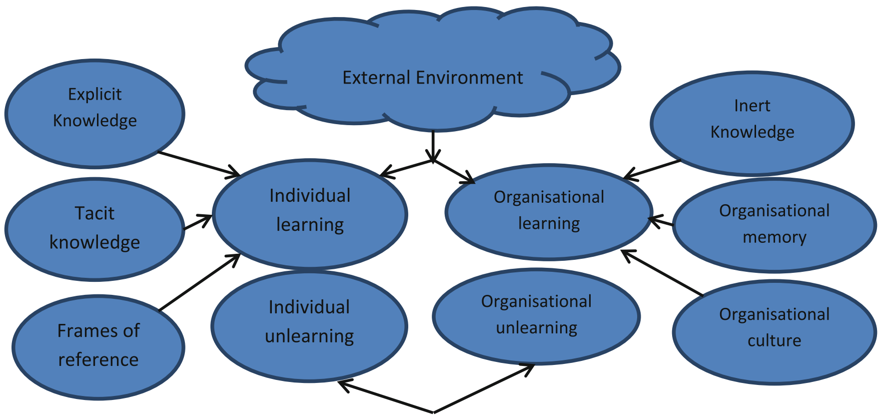

Fig. 2 Individual and Organisational Unlearning (*Source* Windeknecht and Delahaye 2004)

2.1 Employees' Attitudes

It was stated above that engineering assets are there to generate value for the company and its shareholders. It was also mentioned that engineering assets can only generate value when supported by the company's employees. Employees' attitude is therefore put under scrutiny to attempt to understand its impact on value realization by the company through effective implementation of company guidelines. Attitude is defined by Hogg and Vaughan (2005), cited in McLeod (2014) as a relatively enduring organisation of beliefs, feelings, and behavioural tendencies towards socially significant objects, groups, events or symbols. Literature on this topic revealed an interesting correlation between explicit and tacit knowledge, and corresponding impact on attitude. Mezirow (2000) cited in Becker (2005) states that individual frames of reference guide, shape and dictate the everyday attitudes and behaviours of the individual through the deep-seated underlying values and belief systems. Senge (2006) describes frames of reference as mental models and defines them as "deeply ingrained assumptions, generalisations, or even pictures of images that influence how we understand the world and how we take action". Raducanu (2012) surmises that frames of reference are indirectly created from explicit knowledge. They argue that the know-how from explicit knowledge inform socialized knowledge, which in turn informs frame of reference.

Becker (2005) states that "explicit knowledge is knowledge that forms over time as an individual learns more, and is the basis of many decisions made by individuals within organisations". For an individual to learn useful knowledge that will enable good decision-making, Senge (2006) encourages the concept of personal mastery, that is, "a discipline of continually clarifying and deepening our personal vision, of focusing our energies, of developing patience, and of seeing reality objectively".

Tacit knowledge relates to information not easily explained or documented, and is often referred to as know-how (Becker 2005). Polanyi (1966) cited in Raducanu (2012) state that tacit knowledge is also known as personal knowledge, and further mention that it involves intuition, values and viewpoints that individuals gather through years of experience. Windeknecht and Delahaye (2004) emphasize that viewpoint by stating that it is tacit knowledge which often makes the difference between average and an excellent employee based on how they perform their duties.

Assessing the above viewpoints, one may argue that to impact positively on employees' attitude, great effort need to be made in influencing their explicit knowledge in line with what is expected of such employees. This is due to the fact that the above authors argue that explicit knowledge can somehow be explained by the decision that employees take. That means, it can be measured and monitored by how employees' decision-making changes over time. One may further argue that when explicit knowledge is influenced positively, tacit knowledge which cannot be measured easily, will automatically be impacted positively, and therefore positively influencing the frame of reference of employees.

2.2 *Employees' Cognitive Styles and Mental Preferences*

The Free Dictionary (2011) defines cognition as the mental process of knowing, including aspects such as awareness, perception, reasoning, and judgement. The analysis of this topic was however only based on cognitive style which, according to Tsang and Zahra (2008), and Tversky (2014) are concerned with how employees reason, think, and remember. Tversky (2014) refers to cognitive map as "…constructs that can be mentally inspected". He argues that these constructs "are presumed to be learned by gradually acquiring elements of the world, first landmarks, point-like elements, then routes, line-like elements, and finally unifying the landmarks and routes with metric survey information". Senge (2006) describes it as mental models and defines it as "deeply ingrained assumptions, generalizations, or even pictures of images that influence how we understand the world and how we take action."

Analysing the above viewpoints, one may describe frame of reference as a universal viewpoint that individuals create and use to inform the decisions they take. And because this picture is created based on many diverse life constructs, one may further argue that it will impact on any newly acquired knowledge, regardless of the nature of that knowledge. It can therefore be mentioned that for new knowledge to be useful, frame of reference will need to be altered to accommodate it.

2.3 Organizational Factors

At organizational level, knowledge management becomes an essential commodity for the organization to remain competitive. The pace at which the organization absorbs and utilizes new or advanced information will determine how it competes. Organizational memory forms a basis for knowledge management. According to Windeknecht and Delahaye (2004), tacit knowledge, which informs how employees perform their duties, becomes organisational memory at organizational level. Becker (2005) refers to organisational memory as a storage of organisational information and data sources. Cegarra-Navarro et al. (2010) states that organisational memory provides individuals with tacit knowledge such as systemic sets, routines and shared visions. Argyris and Schon (1978) cited in Windeknecht and Delahaye (2004) state that in order for organisational learning to occur, learning agents' discoveries, inventions, and evaluation must be embedded in organisational memory.

The implication is that synergy between organisational memory and tacit knowledge need to be profound for task execution to reflect what is expected. Furthermore, for unlearning to successfully take place, tacit knowledge in individuals will need to be changed through changing or revising organizational memory. It can be argued that leaders influence organizational memory, as it is in the interest of leadership that the organisation acts to realise its objectives.

Organisational culture is yet another factor that influences how employees perform their duties. Martin et al. (2010) define organizational culture as a set of shared, often implicit assumptions, beliefs, values, and sense-making procedures that influences and guides the behaviour and thinking of organizational members, and is in turn continuously enacted and reinforced or changed by the behavior of organizational members". Senge (2006) complements the above view by stating that building a shared vision is important for the team. He describes shared vision as "a practice of unearthing shared pictures of the future that foster genuine commitment and enrolment rather than compliance". The point is that organisational culture needs to capture a shared vision that advances and contributes positively to attainment of the company's objectives. An over-arching message that emerges is that managing organisational culture is a very complex matter that requires careful consideration of all knowledge management constructs.

With regard to implementing the provisions of the ISO 55000 standards, the following arguments may be made:

- That organisational culture is responsible for alignment of employees' cognitive styles. When employees have common purpose, the aligned frame of reference will contribute meaningfully to organisation culture and lead to successful implementation of guidelines;
- That leadership should influence organisational memory towards effective management of engineered assets;
- That employees' appreciation of value will ensure their adoption of constructs that advance realisation of such value through proper asset management;

- Alignment of employees’ cognitive styles and leadership should result in a high performance culture that provides assurance that asset management goal are realised.

3 Data Collection and Analysis

The picture in Fig. 3 is a re-structuring of the model proposed by Windeknecht and Delahaye (2004) to illustrate the linkages between organization unlearning, learning and task execution. This conceptual model was used to generate semi-structured questionnaire for data collection purposes.

The respondents to the semi-structured questionnaire were drawn from the case study organization. The semi-structure questions solicited both qualitative data and quantitative narratives from the respondents. Senior managers were interviewed while supervisory and lower ranking employees completed the questionnaire. The major assumption in this regard was that all the respondents attended fairly to the questions. A summary of the respondent profile is shown in Table 1.

For brevity, the feedback provided by respondent to some of the questions is summarized in Fig. 4. For example, question 1 asked the respondents to comment on the organization’s strategy for managing assets, while question 13 required respondents to comment as to suitability of the organisational structure to implement the tenets implied in ISO 55000. The feedback from the respondents was scored on a 5-point scale in terms of agreement. With reference to Fig. 4, less than fifty-five percent of the initial 422 respondents were convinced that the organization (question 1) had a clear strategy on how to manage engineered assets, and only

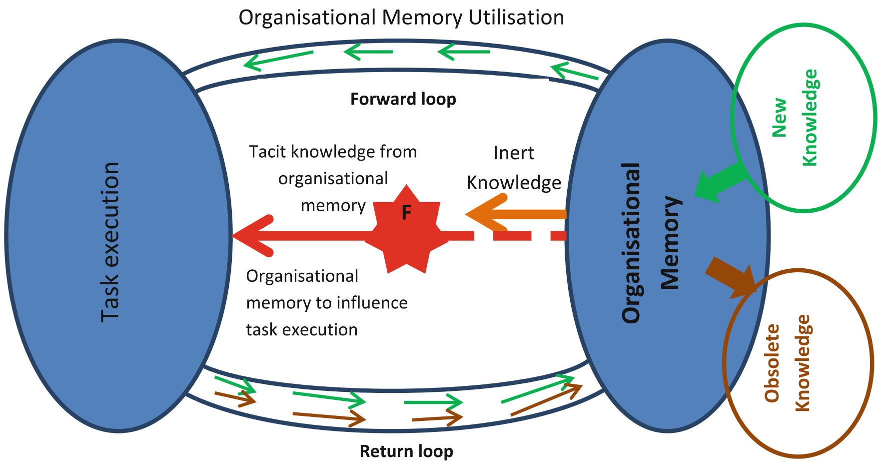

Fig. 3 Linkages between organisational memory and task execution

Table 1 Respondent profile for the case study organisation

Level of sampled participants	Number of participants	Number of responses	% responses	Type of data collected
Top management	10	10	100	Mainly qualitative
Managers	10	7	70	Mainly quantitative
Supervisors	30	22	73	Mainly quantitative
Artisans	145	132	91	Mainly quantitative
Administrative staff	17	15	88	Mainly quantitative

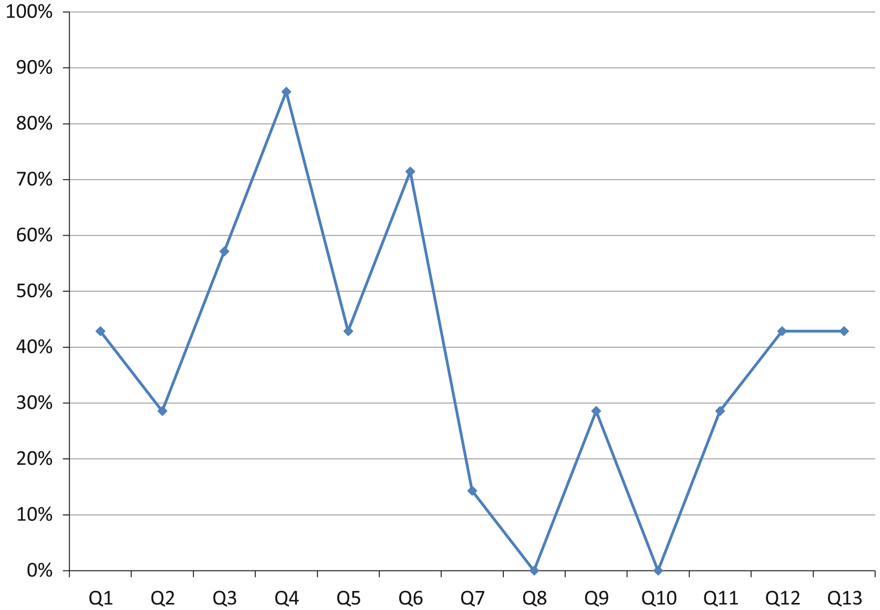

Fig. 4 Respondent feedback

about thirty percent believed that the asset management objectives (question 2) were clear.

Perplexingly, the high percentages for questions 3, 4 and 6 indicate that the respondents felt that the organisation had information systems in place for asset management. Surprisingly, the narratives around communication (question 10) and employee assessments (question 8) revealed that the respondents were completely unconvinced by the processes around such issues. The responses to questions 7, 9, and 11 suggest lack of confidence on how the organisation deals with learning, motivation and employee innovative tendencies. More than fifty-five percent of the respondents also seemed unconvinced that approaches to change management (question 5), culture (question 12), and organizational structure (question 13) were suitable for the implementation of the ISO 55000 tenets.

4 Summary

To validate the respondents' feedback, the evaluations were repeated on four separate occasions with 80 % of the questions on the questionnaire repeated over a period spanning six months, but the sequence of the questions rearranged. The first, second, third and fourth occasions were attended by 132, 136, 128 and 140 employees, with 132, 133, 125 and 135 responses respectively returned. The respondents' attendance suggests no loss of interest and willingness of the employees to collaborate on issues of interest to the organisation. Interestingly, the four occasions suggest that the respondents remembered the questions and this could be interpreted as cognition style that may accentuate the implementation of the ISO 55000 tenets.

The sample data and brief analysis provided here re-emphasise the significance of human attitudes, cognition, and mental preferences on the implementation of new guidelines embodied in the ISO 55000 tenets. In part, the validation process demonstrated organisational memory but, a comment like "it's hard to teach an old dog new tricks" more or less revealed difficulties associated with changing a person's attitude and/or behavior. The suggestion in this paper is that a comprehensive approach to implementation of new tenets may motivate employees to unlearn obsolete knowledge and adapt to newer ways of thing doings.

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Reliability Assessment in Asset Management—An Utility Perspective

S. Rao Palakodeti

Abstract Many utilities are facing a challenge to stay in business as their assets are aging, and many new regulations are being introduced. These utilities are looking for the means to improve the reliability and availability of their assets, while wisely spending their limited resources. Therefore, it is very important for the utilities to understand how their assets will perform in the future, and establish priorities for maintenance and replacements. Many reliability efforts focus on static analyses methods, which result in linear projections of failure probability. A more powerful approach is to characterize each equipment, system and unit using complex statistical modelling and then perform Monte Carlo simulations to provide dynamic reliability and maintainability analyses. There is a vast amount of failure data available for equipment in the form of MTBF and Failure Rate. However, there is insufficient Weibull data to perform the Dynamic Reliability Process for Power Plant equipment. Alstom has started using the data they collected from various equipment to establish a relationship between the MTBF and the Weibull parameters for Power Plant Equipment. This paper describes Alstom's effort in developing this relationship.

1 Introduction

Many utilities are working towards increasing the life of their assets and improving their reliability in order to meet the ever changing market conditions, new government regulations and dwindling resources. They started understanding the importance of reliability assessments in order to make prudent decisions on their resource allocations.

The energy requirement in the United States has stabilized and very few new power plants have been built since 2005 (U.S. Energy Information Administration, Form EIA-860 2014). The US Department of Energy (DOE) predicts an annual

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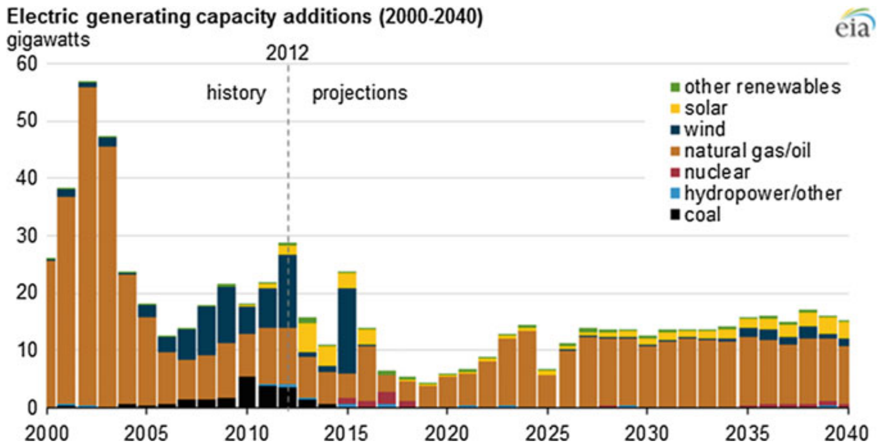

Fig. 1 Electric generating capacity additions in the US 2000–2014 (*Source* U.S. Energy Information Administration, Form EIA-860, and Annual Energy Outlook 2014)

average growth of 16 GW in new generation through 2016 and only a modest growth of 9 GW per year between 2017 and 2022. Because of strict environmental regulations and improved efficiency of the combined cycle plants, an estimated 73 % of the future generating capacity will come from gas fired power plants—mostly from combined cycle plants. This then requires the existing coal fired power plants to operate longer and harder due to cycling. According to the National Association of Regulatory Utility Commissioner report, about 74 % of the power plants in the US are 30 years old and the average is about 40 years. Compared to the US, the plants in rest of the world are relatively young with an average of 21 years (Fig. 1).

Irrespective of where the plants are located, the coal fleet is getting old, and the operators feel running an existing plant is more cost effective than building a new one. That means the plant operators have to manage the assets to improve their availability and reliability (Palakodeti). The plant owners are looking for new methods, tools and technologies to maintain these assets at top performance while mitigating risks at a reasonable cost. The utilities have started performing RAM (Reliability, Availability and Maintainability) analysis to identify opportunities for improvement. However, most of the analyses fall short on predicting the future availability and reliability of the equipment, systems and units. These analyses are typically called ‘Static Analyses’ or ‘Analytical Analyses.’ Alstom developed a unique tool and process which is dynamic in nature to predict future reliability and availability of power plant units. In addition, the process uses Monte Carlo simulation to yield futuristic maintenance costs and optimum time for replacement of equipment, or performing maintenance.

2 Dynamic Reliability Assessment Process

Alstom's Dynamic Reliability Assessment process and tool uses the last five years of CMMS (Computerized Maintenance Management) data which are scrubbed, and then evaluated using a Weibull function. The Weibull output reveals the equipment characteristics. These characteristics together with the maintenance cost data are entered into a Reliability Block Diagram (RBD) and a Monte Carlo simulation is performed to obtain the results. An RBD is a representation of a system or combination of systems connected 'reliability wise' (ReliaSoft Corporation 2008a). The use of RBDs is not new to the industry, but application of the RBDs to power plants and the methodology adopted is unique. The RBDs in the power industry can be as simple as the substation (Konya et al. 2013) shown in Fig. 2 or very complicated for a coal fired unit as shown in Fig. 3.

The process flow of the Dynamic Reliability Process is shown in Fig. 4.

The fundamental data requirements for generating equipment characteristics are cumulative time when the event took place from a starting point in the past and the duration of each event. Usually, the data is collected for the last five years or after a major outage. The assumption is that during a major outage the equipment is either repaired or replaced and it is desirable to capture that information. The information is collected either from the plant's CMMS system or any other records. The required event data has to be scrubbed from a large amount of data the plants normally maintain. Consistency and knowledge of plant operations are required for the analyst to identify and obtain correct and sufficient data. Unlike the Life Data Analysis, which many engineers are familiar with, Recurring Data Analysis (RDA) on repairable items requires only a few years (ex. 5 years) of past data.

One major problem with the plant data is that it is either insufficient or does not exist due to lack of a CMMS system. In those cases Alstom performs a mini FMEA

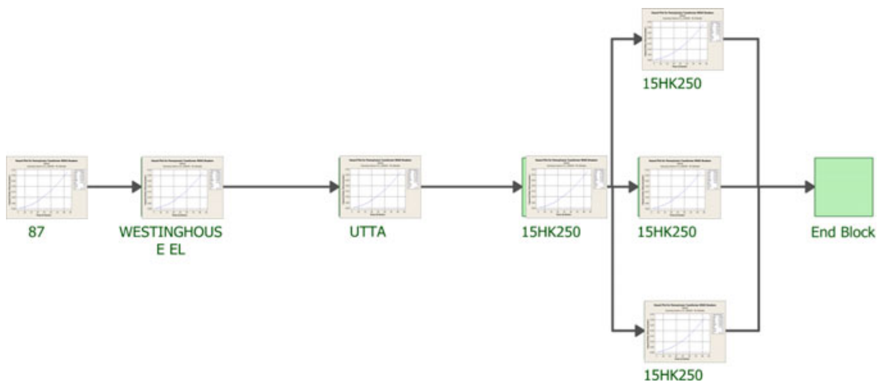

Fig. 2 Simple substation model

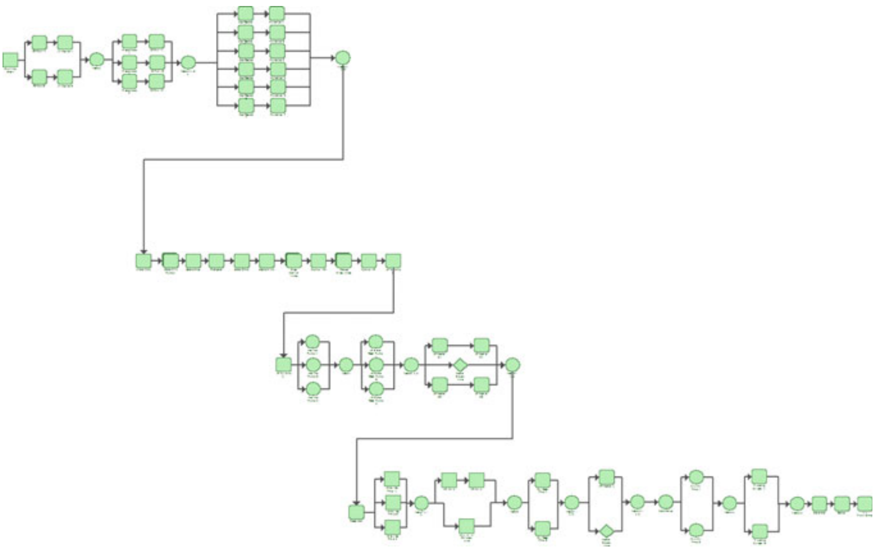

Fig. 3 Complex coal fired unit model

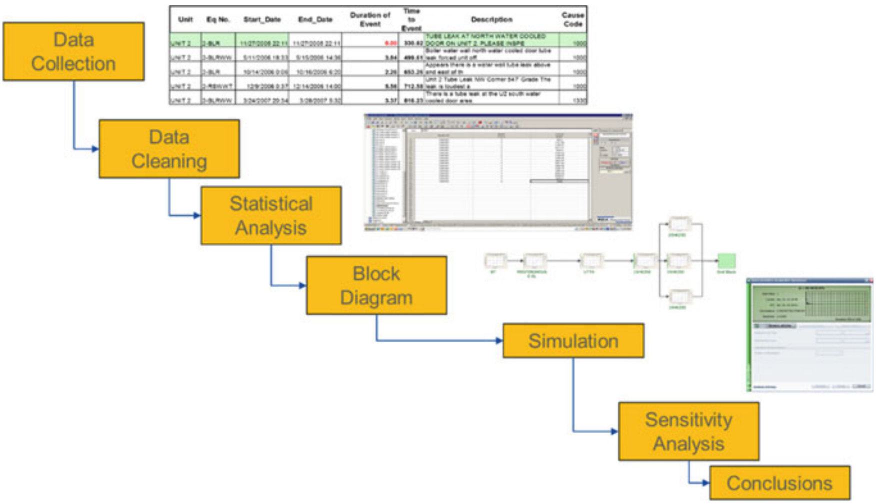

Fig. 4 Dynamic reliability process

(Failure Modes and Effects Analysis) with the System Owners to determine the expected number of failures for the future five years. This information is converted to MTBF (Mean Time Between Failures) and a one parameter exponential distribution is used for the equipment characteristic. Unfortunately this yields a constant

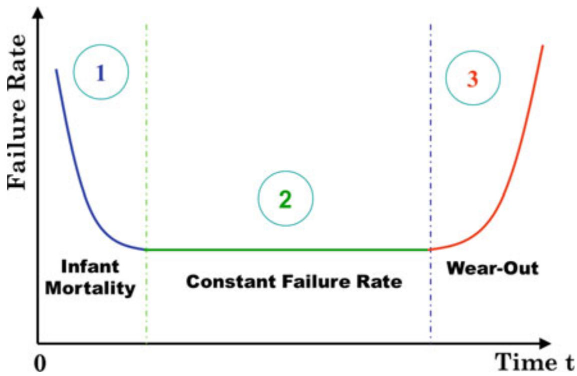

Fig. 5 General component failure curve

failure rate and constant number of failures when a Monte Carlo simulation is performed.

Failure of any component generally falls within a bathtub curve as shown in Fig. 5.

The left side of the curve represents the infant mortality, middle section the random failures and the right side of the bathtub curve represents wear-out, or end of life.

There are two different types of failure analyses performed on any component—(1) Life Data Analysis (LDA) and (2) Recurring Data Analysis (RDA).

Life Data Analysis is performed when the components in a population or a sample have finite life and they are run to failure (ReliaSoft Corporation 2008b). As an example, testing 100 light bulbs until, they fail. In LDA, the data can fit any of the distributions such as Normal, Log Normal, Weibull, Gumble etc. However, Weibull distribution is widely used as it is a general purpose reliability distribution used in many applications such as weather forecasting, time to failure of components etc. A Weibull distribution is defined by β, η and γ which are shape, scale and location parameters, respectively. A two parameter Weibull uses only the shape and scale parameters.

The reliability equation for a two parameter Weibull is given by

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{1}$$

and the cumulative distribution function

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

The goal of any utility operator is to predict the failure rates, costs, availability, number of failures etc. of the components and systems, and a two parameter distribution cannot address these requirements. Power plant equipment and systems

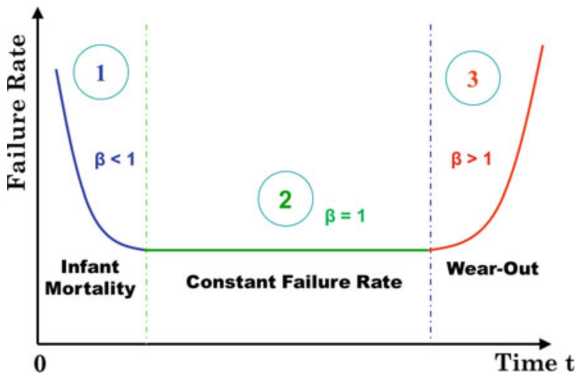

Fig. 6 General component failure curve and β

are complex repairable items and a different process should be used instead of a distribution. The widely used process model is the 'Power Law.'

Dr. Larry H. Crow performed significant work on the Power Law model (Crow 2004). In a renewable system, only the first failure follows a distribution such as Weibull and the subsequent failures are addressed by the Power Law. The Power Law is a very popular model used for repairable items as it generalizes Poisson's process using exponential distribution.

Since the power law uses Weibull distribution for the first failure, the function for rate of reoccurrence or the intensity function can be defined as:

$$\Lambda(t) = \Lambda\beta(t)^{\beta-1} \quad (3)$$

The relationship between the intensity function and the Weibull parameters is given by the equation

$$\Lambda = \left(\frac{1}{\eta}\right)^{\beta} \quad (4)$$

where Λ is the cumulative failure intensity at t = 1. It is also known as the scale factor for Crow-AMSAA model.

The β and η values are significant in understanding the bathtub curve. As shown in Fig. 6, $\beta < 1$ signifies infant mortality, $\beta = 1$ random failures and $\beta > 1$ wear out. However, it is difficult to strictly use these values to determine the three zones because of uncertainties. Some reliability practitioners use a range of $1 < \beta < 3$ as the Constant Failure Rate zone, but Alstom feels that a more conservative range of $1 < \beta < 2$ for this zone is a better approach.

In the Dynamic Reliability Process, LDA is used for determining the probability distribution for the event durations as each shutdown duration is an exclusive onetime event. The data is fitted to the best distribution. On the other hand, in the RDA all failure events fit only one distribution that is the Power Law.

Many static analyses assume the repaired component is as good as new, or it is returned to the original condition. This leads to the saw tooth effect. However, the RDA provides a new measure—Restoration Factor (RF)—in addition to the β and η values. The Restoration Factor is defined as the amount of life the equipment is restored to after the last repair. An RF of 0 means that the condition of the equipment is the same as it was prior to the last repair. Similarly, an RF of 1 implies the equipment is returned to its original condition which normally happens when a component is replaced. However, all repairs are not perfect, and the equipment is restored to a semi-original condition placing the Restoration Factor between 0 and 1. RF plays an important role in determining the future behavior of the equipment when a Monte Carlo simulation is performed.

One of the major problems faced by a RAM practitioner is obtaining correct and useful information. There are many references and sources available for general equipment failure data (Akhmedjanov 2001; Globe 2002). U.S. Energy Information Administration, Form EIA-860 2014 attempts to list some of those sources. However, most of the references provide MTBF or failure rates for either components or equipment. The equipment failure rates (λ) can be computed from its individual components. However, very few resources are available for Weibull parameters (β and η) for either components or equipment. Many manufacturers conduct their own tests and the data is normally not shared with the customers (Barringer 2010; Block 1998). Another problem is the lack of knowledge on how to use the publicly available Weibull data and confusion between the terms Mean Time to Failure (MTTF) and Mean Time Between Failures (MTBF) (Speaks 2010).

Often Engineers use these two terms interchangeably. But the MTTF is the mean time to failure of a non-repairable item, and MTBF is the mean time between failures of repairable items. The Weibull parameters for MTTF can be calculated from the equation

$$\mathrm{MTTF} = \eta\Gamma\left(1 + \frac{1}{\beta}\right) \text{ where } \Gamma \text{ is a gamma function.} \quad (5)$$

For Life Data Analysis, η can be calculated from the above equation if MTTF is known. The MTTF values are generally published and a one parameter Weibull can be performed assuming a value for β based on the Reliability Engineer's perception on where the component is on the bathtub curve. However, caution should be exercised when assuming the β and calculating the MTTF. As can be seen from Fig. 7, the error between MTTF and η increases significantly at lower values of β. Both the values are equal when $\beta = 1$ and start approaching each other as β increases to greater than 1.

A similar relationship was attempted between MTBF and η values. The relationship between MTBF and η for various β values are plotted in Fig. 8. In most cases the MTBF and η were in phase showing that possibly there is some dependency between the three parameters MTBF, η, and β.

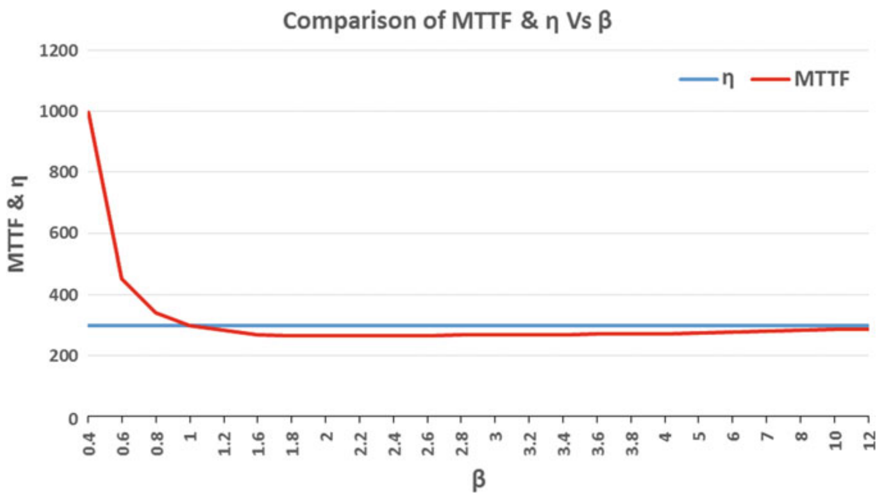

Fig. 7 Relationship between MTTF and η wrt β

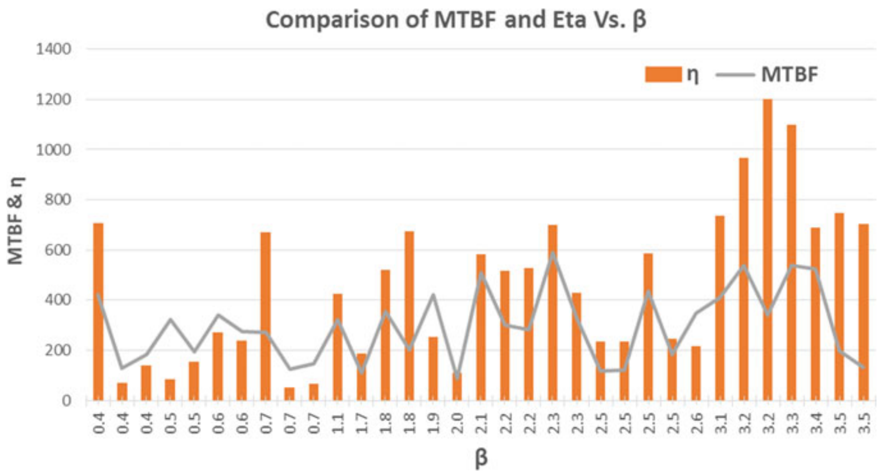

Fig. 8 Relationship between MTBF and η wrt β

3 Results

Twenty two data sets of η and MTBF values were selected out of a sample of thirty three sets for performing a correlation analysis to determine if a relationship exists between the two parameters. If a relationship can be developed, the relationship can be used for converting the vastly available MTBF data to η values.

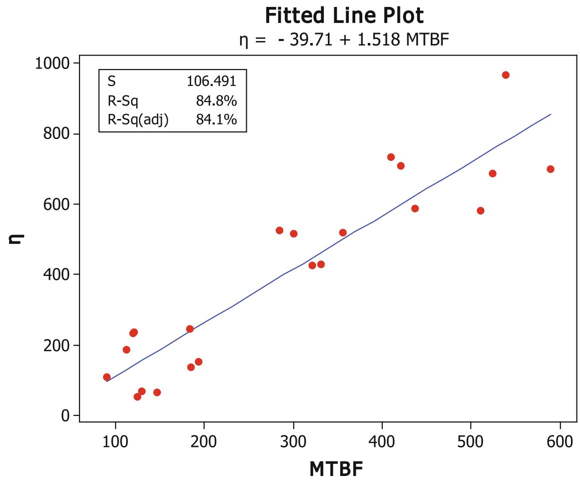

Fig. 9 Correlation between MTBF and η linear relationship

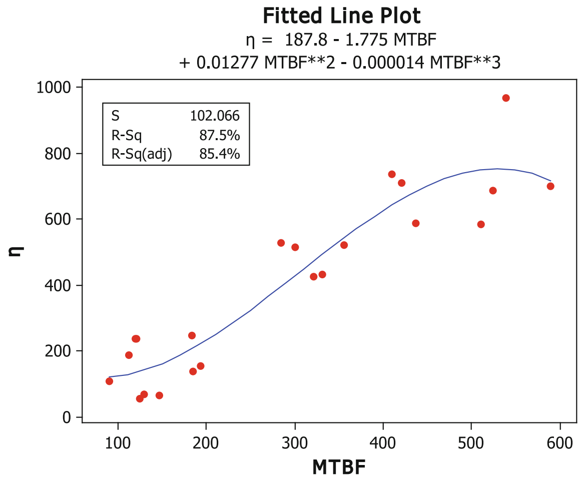

Fig. 10 Correlation between MTBF and η cubic relationship

The data was plotted and regression analyses were performed using linear and cubic fit. The linear regression curve is shown in Fig. 9

The linear regression equation is

$$\eta = 1.518 MTBF - 39.71 \tag{6}$$

The R^2 value is 84.8 %.

The adjusted R^2 value further improved to 87.4 % with a cubic regression equation as shown in Fig. 10

The regression equation is

$$\eta = 187.8 - 1.775MTBF + 0.01277MTBF^2 - 0.000014MTBF^3 \qquad (7)$$

The values can be further improved as Alstom collects more data in the future and the sample size increases.

As in LDA, the β value can be assumed based on the analyst's experience and expertise. Alstom performs a mini Failure Mode Effect Analysis (FMEA) with the System Owners, Operations personnel and Maintenance personnel at the plant to determine the expected number of failures for each component in the next five years and this information is converted to MTBF and β values. Once these values are determined, they can be easily converted to the Weibull parameters using the regression curve.

4 Conclusion

Utilities worldwide are facing many challenges to stay in business. The assets are getting old and many utility operators feel running existing power plants is more economical than building new ones. This required the utilities to improve the Reliability, Availability and Maintainability of the existing plants. There are methods to perform RAM analysis but most of them perform a static analysis. Most of the data available in the literature is failure rates and MTBF, and very few Weibull parameters are available. Even when this data is available, the equipment manufacturers or the equipment operators do not share this data. Alstom has established a database for collecting these parameters on Power Plant equipment. They attempted to determine the relationship between MTBF and Weibull parameters so the widely available MTBF and MTTR data can be converted to Weibull parameters and can be used for dynamic assessment using Monte Carlo simulations. As Alstom collects more data from various power plants, the accuracy of establishing a relationship between various parameters will increase. In addition, further research into developing these relationships should be pursued. Similarly, a database is required for β and η values for Power Plant equipment. Academia, equipment manufacturers, professional organizations and others should develop a repository for storing and making these parameters available for RAM practioners.

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Managing Industrial Maintenance—Networked Model

Olli Pekkarinen and Maaren Ali-Marttila

Abstract Industrial maintenance services are outsourced more and more as manufacturers' own maintenance units are nowadays rare. However, instead of outsourcing the maintenance as a whole, many companies are acquiring the needed resources from several actors. Thus, maintenance practices on a site can be performed by the customer itself, an equipment provider, or an independent maintenance company. How should this be orchestrated? We begin our study with explaining the current state of industrial maintenance business. Next, we offer insights from the services networks literature. Then we move on exploring maintenance through seven case companies, which brings us to our suggestions for two optional future maintenance models: (1) capacity-based maintenance and (2) locally networked maintenance framework.

1 Introduction

Industrial maintenance services are being outsourced more often making the manufacturers' own maintenance functions limited if not rare. Furthermore, companies are more often acquiring the needed resources across from several companies providing maintenance. These maintenance providers can be classified under two broad categories. First, equipment manufacturers are driven to provide more comprehensive offerings that go beyond the traditional product, e.g. by providing various services including maintenance. Second, specialized maintenance companies are enlarging their offerings from basic operations to cover more complex maintenance

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processes. A maintenance customer often uses both of these types when outsourcing the maintenance function. Hence, a network of maintenance providers takes often part in maintaining a particular site. This can be regarded as *networked maintenance offering* from the customer's viewpoint.

B2B services have received growing academic attention but the lack of further studies is still acknowledged (Ostrom et al. 2010). Moreover, services networks (e.g., Henneberg et al. 2013) have been studied mainly in the B2C context (e.g., Morgan et al. 2007). Also, extant literature on offering concept (e.g., Ulaga and Reinartz 2011) points out the variety of different elements. Hence, we acknowledge the importance of context when studying the concept of offering. The scarcity of studies on maintenance offerings, with few exceptions (see e.g., Stremersch et al. 2001) demonstrates a research gap on this area. Lastly, maintenance related research has focused mostly on technical issues and studies regarding the management of maintenance service are yet quite scarce.

Accordingly, our research aims to analyse the current maintenance operations within seven case companies and to develop a networked offering framework. This framework is aimed to help to understand the complexity of service networks, which is one of the Henneberg et al.'s (2013) service network research agendas. The study contributes to B2B service and network literatures by answering to the following research questions: (1) How maintenance is currently managed? and (2) What could be the role of networks in industrial maintenance?

2 Industrial Maintenance

Traditionally industrial companies have had quite massive departments. Maintenance has been seen merely as a necessary expense and its status and role is not highly recognized among companies (Alsyouf 2009). Alsyouf (2009) argues that maintenance strategies, functional organizational structures, top management support, and impact on performance should be highlighted when developing maintenance as a part of overall manufacturing and corporate strategy. However, operation efficiency, quality and effectiveness are all consequences of proper maintenance practices that together contribute to overall business performance (Alsyouf 2009). Regarding to different maintenance strategies, Swanson (2001) suggest three different approaches; reactive, proactive, and aggressive. In the era of harsh competition and tight process schedules, industrial companies cannot count on reactive strategies, which result in massive costs and time losses compared to a more planned maintenance strategy.

Instead of developing maintenance internally, many industrial companies have outsourced their maintenance function, which has created a new market for maintenance services (see e.g., Muchiri et al. 2011). To satisfy the need, often the outsourced maintenance unit has been established as an independent maintenance company (see e.g. Hatinen et al. 2012). On the other hand, also equipment providers are eagerly developing their offerings to cover more and more services including maintenance. Thus, maintenance practices of a plant can be performed by the plant (customer) itself, an equipment provider, or an independent maintenance company. Nowadays at industrial plants, maintenance is usually done by combining these options. A customer and an equipment provider can agree on sharing the maintenance practices together or a maintenance company can take an integrator role and provide all maintenance services. Thus, the customer believes that there is a chance for added value from a new kind of network model.

Offering means the variety of goods and services a company can deliver, it explains both what and how for the customer. Shepherd et al. (2000, p. 101) argue that instead of increasing different service elements in an offering, companies should develop their integrating capabilities and change business models—and become more customer centric. Our aim is to understand different maintenance actors and their offerings that exist in industrial maintenance arena. In the following, we examine the offerings from both the equipment providers' and the maintenance companies' perspectives.

Equipment providers have long traditions for offering basic service, such as spare parts and warranties, with their products. However, they have quite recently developed more strategic service elements to differentiate their products. Industrial offerings have shifted away from product-centric with customer ownership and only supporting services to value co-creating and sharing solutions for customer's specific challenges (see e.g. Kindström and Kowalkowski 2009). Many equipment providers see services as a tool for ensuring long term customer relationships where different kinds of operating agreements are the key element. Their offerings form a continuum (see e.g. Penttinen and Palmer 2007) of services from less binding training services to closer operational relationships, in which the provider might even own the customer's operation facilities. Often, the services are mainly focusing on the specific equipment provided. This is due to the background of the companies, usually their businesses have started with products and the services are heavily bounded to these products. Although equipment providers may have made a clear strategic choice towards operation agreements, but due to their background, the development of turnkey offerings has shown to be quite an obstacle (Tuli et al. 2007).

Maintenance companies often root from the discontinued maintenance departments, with few exceptions. These companies are offering usually a variety of maintenance services. There are mainly two types of maintenance companies. Some maintenance companies are highly focused with in-depth knowledge on few specific services, while others offer turnkey maintenance solutions by acting as an integrator towards the customer. These maintenance contracts cover the needed practices in order to avoid production downtimes. However, in some cases the maintenance company handles only customer's auxiliary equipment.

3 Services Networks

Business-to-business services have had significant growth worldwide but the area is still quite underrepresented in service research (e.g. Kunz and Hogreve 2011; Ostrom et al. 2010). Furthermore, as industrial business actions are often formed by a web of multiple actors influencing each other, it is essential to examine also services from a networked perspective. This perspective has also been the topic of a recent special issue in the Industrial Marketing Management (see Henneberg et al. 2013). While competition gets tighter, companies have to collaborate more intensively to be able to meet their customers' needs more effectively and efficiently (Bititci et al. 2012, 2004).

In their article, Henneberg et al. (2013) offer a sort of conceptualization for services network. Their view of services networks involve three layers or dimensions of services networks; first, second, and third order, representing "different intensities of possible service network constellations" (Henneberg et al. 2013, p. 5). While the first order of services networks depicts relationships with more traditional services elements, the second order of services networks carries on the relationship to a deeper level by focusing on solutions which combine products and services more seamlessly. The third order of services networks can occur when the emphasis shifts from products to services as the main contributor of value in offerings. Maintenance offerings can vary within this scale. When an equipment provider takes fully care of the plant, meaning a sort of operation or even leasing plan, and utilizes a network of partners, then maintenance can be a part of third order service networks. However, usually maintenance networks are best described as first or second order services networks.

Ahonen et al. (2010) acknowledge the lack of methods, models and practical business scenarios within maintenance service networks. They propose a type of consortium, maintenance community, to orchestrate maintenance operations in a given plant. In this model, deeper relationships are tied in order to orchestrate the maintenance practices as efficiently as possible. The partners share common development targets and objectives.

4 Research Method and Data

We conducted a classic qualitative case study (Dyer and Wilkins 1991; Yin 2009) with a dialogue between data and theory (see e.g. Eisenhardt and Graebner 2007). We focused on seven Finnish case companies. Among these companies, there are three types of maintenance actors; customers (plants), equipment providers, and maintenance companies. Altogether, nine interviews were conducted, of which four were persons from equipment manufacturers (three separate companies, cases A, B, and C), two from maintenance companies (cases D and E), and three from customer companies (cases F and G). Eight of the interviews were face-to-face, while one interviewee submitted his answers via email. Interviews were tape-recorded and transcribed for qualitative analysis.

Case A is an equipment manufacturer that offers contract-based maintenance on their own equipment. Their main driver for offering maintenance contract is long-lasting and closer customer relationships during various economic cycles—but also lowered profits from product business. Service business provides also knowledge on how their equipment performs in real life. They see short response times and geographical closeness as their strength. Case A offers different maintenance packages with highly varying content from basic operations to tailor made expert services. In their way, the content of maintenance agreements needs to be strictly negotiated with clear responsibilities. Case A sees challenges in the current business environment, where they often do not possess a straight connection with the customer but need to communicate through separate maintenance companies. This affects information flow on how well the maintained process is actually operating. Case A is developing their services towards an outsourced model, where they would took responsibility of a certain customer process, offering capacity instead of products through a lifecycle service. Case A would like to have a transparent networked model, where the customer has direct connections to each actor. Their responsibilities would be on special equipment knowledge, whereas a maintenance company would take care of basic operations. However, they see that the customer selects the model and they adapt to it. Case A sees contractual aspects as a major key to the success of a networked maintenance model. Transparent operations and clear responsibilities with straight connections among different network partners. However, they fear that if the needed openness level would be reached, the knowledge tranfer would soon make some actors useless some actors useless. Also, current customer's buying procedures often restrict innovative forms of maintenance services—it often neglects the longer perspective but concentrates on more transactional short term value.

Case B, a large equipment manufacturer, has developed its maintenance services heavily during the last decade. Their massive organization structure has made the development quite a challenge, but the reasons are familiar: longer customer relationships and smoothening the business cycles. Case B offers as extensive maintenance as the customer demands on their own products. Being a global provider, a major challenge has been to find well-trained work force. Also, their complex palette of different products and services has made the sales phase difficult. Regarding the networked maintenance model, case B sees challenges in contractual agreements and responsibilities—and how the costs and profits should be divided. Opening the books seems too difficult with multiple actors involved.

Case C is an equipment manufacturer that has developed its service operations from repairs to full scale maintenance on their own equipment. They see maintenance as a prerequisite for a successful equipment provider, it provides steady income in turbulent business environment but also enhances customer satisfaction and reputation. The challenge is in ever growing complexity and extent of maintenance operations—it has shown to be difficult to develop the business model and service organization enough before the actual commitment. However, they see that customers are willing to outsource maintenance more and more extensively. Reasons for this are focusing on core competences, enhancing cost efficiency, retirement of skilful employees, and the grown complexity of modern process equipment. Case C sees that networked maintenance is challenging mainly due to self-centred reasons: sales profits are difficult in a network setting where each actor aims for largest possible share. Also, network level monitoring and development is largely missing. To function, a networked maintenance model would need a strong leader as well as clear division of responsibilities among network actors. Furthermore, willingness to collaborate with each other is a key element.

Case D is a maintenance service provider that was established from an outsourced maintenance function in the beginning of 1990s. It operates mainly locally, doing basic maintenance tasks based on unwritten verbal agreements. Their offering is based on tasks fulfilled through manual labour, they do not offer e.g., planning services. A particular feature has been that their customers are buying personal skills and knowledge rather than a service. Often, a single workman can affect to who will win a maintenance deal. However, they do offer entities that might require subcontracting. They see that maintenance could benefit from more comprehensive agreements framing clearly the mutual goals for all the participants. Lack of information and unclear goals often leads to unnecessary work during maintenance operations. Case D would like to participate closer with their customers' maintenance planning and development. Furthermore, they see that different functions, such as financing and technical, should communicate better with each other. Through better communication, the long-term benefits could be better managed. Regarding future developments, case D believes that maintenance will be managed through close partnerships, if not reverse outsourced back to the plants. Extensive maintenance collaboration among multiple actors each focusing on their core skills interests. However, attempts towards it have proven to fail, mainly because of disagrees on financial issues. With appropriate measurement tools, open books and extensive agreements, a networked maintenance, with clear responsibilities, could be an effective business model. In general, case D sees that maintenance is undervalued—without a major mind-set change regarding maintenance development, customers' process equipment can wear out faster than planned.

Case E is a full maintenance service provider with an extensive offering covering e.g., productivity, cost efficiency, EHSQ (environment, health, safety and quality), and change leadership. The company operates in several countries and has focused on developing different modules or maintenance products. These modules are then selected and used depending on the particular customer need. They strive for open collaboration with their customers with strictly defined maintenance goals. Initial customer negotiations are done with care to ensure mutual understanding of the needs and wishes. During negotiations, it is essential to address your message to a right respondent. This highlights that maintenance cannot be taken as an expenditure, it rather reflects to the overall performance of a customer's industrial process. Also, the more the customer's processes are defined, the better maintenance can be planned and performed. Case E has also developed internal protocols and reporting systems for different tasks to ensure steady quality. Their customer base is extensive, through which they have learnt that customers' expectations differ a lot. Depending on the customer case, company E leads the maintenance, is an equal partner, or acts as a subcontractor. They see that the maintenance model should be adaptive to customer needs where the most suitable partners perform maintenance operations as a network. While case E has focused on developing maintenance concepts, a general challenge regarding customers is a mind-set change—how to update maintenance from a mandatory cost to a process enhancing service.

Case F is an industrial supplier operating in mining industry with eight sites in Finland. The sites use external maintenance services varyingly, some even do maintenance fully in-house. Developing maintenance is still in its early steps because measuring the results is not systematic, meaning weak comparison ability among their sites. One reason for this is the multitude of different monitoring systems used among companies. Mutually negotiated goals and compatible systems is seen as a main key for better maintenance. For a maintenance service provider, case F expects that the price is in line with quality. Also, previous experiences regarding e.g., scheduling, additional pricing, and quality are decisive. Besides own opinions, they use general purchasing criteria. However, even lower quality in line with price is acceptable if it does not compromise the maintained process. On the other hand, in more demanding tasks the maintenance is often acquired based on individual persons, even though they might have changed the employer. As a challenge, they see limited resources—often many sites have their yearly shutdowns simultaneously. Also, more detailed plans would benefit the site in organizing the maintenance as a whole. This would help also the change towards network-based maintenance. Case F sees that it would be better to have multiple partners instead of a giant one. They emphasize the importance of choosing right partners through common values. Furthermore, a common goal for developing the maintenance should be set. One form of operations was presented—a sort of industrial cluster through which geographically near actors would organize the needed maintenance.

Case G is a large supplier in the energy sector. For them, a producer of energy and heat, reliability is essential. They have outsourced around 80 % of their maintenance to a wide array of different service providers. Usually, they have own contracts with all individual providers. An issue that was raised here relates to efficiency. How can one measure how efficiently maintenance is done? To outsource this dilemma, a different kind of business model could be used: buying capacity instead of hourly-feed based services. A challenge here is to understand what is needed and what it would mean. Hence, maintenance-based knowledge on their processes as a whole should be increased and based on that different maintenance concepts developed. Case G would like to preserve an overall view on the maintenance in-house, but is eager to move towards networked maintenance management. However, greed is seen as a challenge for optimally operating a networked model. A mind-set change is needed to overcome the competition between maintenance operators—not only for companies but also for individuals. Another option would be to outsource large entities for a single operator, who then builds the needed network.

Table 1 Summary of the case data

Case	Type	Motivation for maintenance development	Network model requirements
A	Equipment provider	Feedback on products, new business opportunities, long-term customer relationships	**Transparent** network, direct connections among members, **clear responsibilities**
B	Equipment provider	Long-term customer relationships, smoothening the business cycles	Well-planned contractual **agreements** and responsibilities, agreed **division** of costs and profits. **Open books** too difficult.
C	Equipment provider	Steady income, also enhances customer satisfaction and reputation	From self-centricity to **collaboration**—clear division of profits, network level **monitoring** and development, a strong **leader**
D	Maintenance company	Established from an outsourced maintenance function, local kiosk for maintenance	Appropriate **measuring**, open books, **shared mindset** on mutual goals, **open communication**
E	Maintenance company	How to update maintenance from a mandatory cost to a process enhancing service	**Adaptive** to a customer need, **mindset change** from a cost to a process enhancement
F	Customer	Low maintenance development skills	**Mutually** negotiated goals, efficient **resource distribution**, **local network**
G	Customer	Increasing the maintenance-based knowledge on their processes	**Overcoming greed**, mindset change

Table 1 summarizes the motivations for developing maintenance as well as the requirements for a networked operation. Next, we move on to propose how maintenance could be orchestrated in the future.

5 Maintenance—Present and Future

The current maintenance field is quite scattered, e.g., companies buying maintenance use different approaches in different sites. While one site might be fully outsourced, others are still maintained in-house. This highlights that maintenance as a function is still a bit underdeveloped. In many cases, respondents see that there is room for more comprehensive measurement and new kinds of business models in maintenance. A common problem seems to be how to measure what is the most effective way for a certain maintenance task. Also, communication is seen as a challenge. In cases where there is one main contractor, the subcontractors feel their role too distant towards the end customer. In these settings, mutually beneficial development can be difficult to perform, while the main contractor blocks the communication. As a result, maintenance development still lags behind compared to other business functions. Maintenance is still considered as an obligatory cost instead of part of process optimization.

Currently there are four categories of maintenance providers. First, the in-house maintenance is still in place in many sites, even thought it might not perform the most demanding tasks. The general comment from all the respondents was also that at least some level of knowledge should be maintained in-house in the future. Second, there are equipment providers that have expanded their product business towards service. Usually they offer specialized maintenance for their own products, but can as well serve as a main contractor. Third, there are mainly locally operating maintenance companies, which are often established as an outsourced maintenance function. Their main responsibilities are within general maintenance. The fourth category are maintenance companies that cover geographically wide areas. While these are low in number, they are considerably larger size-wise. Also, they have usually put effort on maintenance development. As a downside, while having functioning concepts and business models, these companies are somewhat restrained resource-wise. Maintenance is massively labour intensive, which restricts the growth in some extent.

The main challenges that restrict maintenance development, based on our case evidence, were insufficient measuring, lack of development, lack of mutual trust, lack of communication, timing problems for larger maintenance breaks, and a primitive mind-set in understanding and organizing maintenance. Hence, we would like to suggest two different business models for organizing maintenance in industrial settings: *a capacity-based maintenance* and *a locally networked maintenance framework*. The first option would be optimal for companies that have let go most of their maintenance personnel and lack a will and/or knowledge on efficient maintenance operations. Here, two options prevail (see the roles in Table 2). An equipment provider could offer a capacity deal instead of plain hardware when new investments are made. This way the equipment provider puts the needed network together but the customer communicates only with the main contractor. Also, especially with current machinery a suitable maintenance company could offer a capacity agreement, where they would take the responsibility of the whole process. As a downside, while simpler, the main contractor model might be more expensive for the customer.

Table 2 Possible roles within two maintenance models

Maintenance model	Customer	Equipment provider	Maintenance provider
Capacity-based maintenance	Participant bystander	Integrator/capacity-based investment sub-contractor	Integrator/capacity agreement
Networked maintenance	Integrator participant	Integrator participant—core equipment	Integrator participant—auxiliary equipment

However, our data suggests that a single service provider is rarely the optimum case for maintenance. Often, maintenance companies have certain key competencies but lack knowledge on other areas. Customers are aware of this. With multiple actors, key knowhow on different systems could be better utilized. Due to these characteristics, we propose a locally networked maintenance framework which benefits all the parties within the maintenance network. Within a locally established maintenance network, actors share their key competencies, individual needs, scheduling information, etc., in order to outperform the traditional way of individual maintenance operations. Also, the local network could have several customer sites in it. Many customers have their yearly shutdowns simultaneously, which causes momentary lack of maintenance workforce. A smarter way for organizing maintenance operations locally could enhance the timing challenges.

The aim in networked maintenance is to develop a setting where the added value is distributed evenly enough for the whole network. The main question is that which maintenance practices would be performed by which actor. This leads to different roles actors can possess, see Table 2. One of the key issues when developing a maintenance network is forming of mutual trust and commitment across network participants. Companies need to work closely together to find the most profitable setting for every participant. Quite unusual way to accomplish this could be that the participants open their books to reveal cost structures and value creating potential to each other (see Grönroos and Helle 2010, 2012). By doing this the network can then organize itself so that the value is maximized and shared between participants in an acceptable manner. Furthermore, a networked model could be first piloted for a sub-process within customer's processes. This would allow the operations to develop before launching a networked maintenance model to the whole process. As a conclusion, the networked maintenance model requires a notable change in the mind-sets of each actor. Instead of individual companies developing comprehensive maintenance offerings, a networked offering with multiple actors concentrating on their core competencies could result in a better outcome.

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Advanced Fault Tree Analysis for Improved Quality and Risk Assessment

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Abstract Traditional fault tree analysis (FTA) has formed a common language for the modelling and analysis of risks of complex systems. The approach can be used for a large variety of cases, and several tools exists for the method. Advanced FTA is needed to apply the FTA approach also for dynamic systems with time dependent activities. The traditional FTA is extended by including for example modelling and simulation of operation or phase changes of the systems, stochasticity and delays of relations, and maintenance actions for the components. The rules between the failures and other simulated properties are defined by including Java-based scripts to the model. This allows a great freedom to model any type of dynamic situations. A tool named ELMAS has been created to make the use of the advanced FTA approach as straightforward as possible. It allows to model the static and simple relations by using the traditional FTA method. Complex and dynamic relations are included by using modules that can be freely defined based on the needs of the case.

1 Introduction

It is very beneficial, or even mandatory, to be able to verify the quality and to assess (identify, analyse, and evaluate) the risks of the system. This requires explicit understanding of risk related system quality attributes, such as reliability, availability, maintainability and safety. Processing of data into information and gradually to knowledge about these essential factors is also needed for making rational decisions on how to improve the system most efficiently.

At design phase the alternatives can be compared by creating and analysing a model that describes the features of the system under design. For already existing systems it is possible through modelling to predict the overall effect of proposed

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modifications. Without any major modifications and investments the maintenance and spare part policy optimization can be used to improve the performance of the current system. In each of these three situations all the knowledge must be collected, combined and analysed to obtain the ideal solution.

It is most effective to have a single method for a variety of systems and cases. Consistent method forms a common language for separate systems engineering projects. This method must be expressive enough to handle complex cases but still as easy to adopt as possible. The method should be never a reason to make any compromise in modelling or analysis. Also it must be systematic and explicit so that the results obtained from it are clear and unambiguous. A need of a tool is obvious to simplify the use of the method so that the efforts can be directed solely to the features of the studied system.

Fault tree analysis (FTA) has been traditionally applied for complex systems engineering projects. (Roberts et al. 1981) Improvements are needed for this over 50 year old method to make it more suitable for various needs related to comprehensive risk assessment. (Virtanen et al. 2006) With traditional fault tree it is not straightforward to model for example systems with several operating modes or phases, exclusive alternative consequences with stochasticity, relations that contain delays, cold redundancy with start-up time, other dynamic structures, nor effects of maintenance actions. Also for quantitative FTA there is more feasible and detailed input data for the events than a probability.

Advanced FTA uses improved fault tree model to collect efficiently experts' knowledge about the system operation profile, structure and cause-consequence-relations. This skeleton model is combined with the information related to failure, restoration, maintenance and other events. The information can be read and processed for example directly from available big data. The advanced analytics tool ELMAS (Event Logic Modelling and Analysis Software) offers a graphical user interface for the sophisticated modelling, efficient data import and stochastic discrete event simulation based analysis that is used for the overall model. The explicit analysis results can be improved to be more concrete and versatile by including for example data related to repair and maintenance costs, other expenses, production profiles or any other information available for the model.

2 Risk Assessment and RAMS

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. (ISO GUIDE 73 2009) The first step risk identification includes finding, recognizing and describing risks. In advanced FTA approach this means collecting the available information to a comprehensive model. The second step, risk analysis, aims to comprehend the nature and determine the level of risk. In advanced FTA approach this is done with stochastic discrete event simulation of the model. The last step, risk evaluation, compares the results with risk criteria to determine whether the risk and its magnitude is acceptable or tolerable. In advanced FTA approach this is done with the help of ELMAS tool by creating reports of explicit results and comparing various scenarios.

The risk assessment is a part of risk management, which means the coordinated activities to direct and control an organization with regard to risk. (ISO 31000 2009) The risk management process is included in the systems engineering approach. Systems engineering is a methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system. (NASA SE 2007) The three steps of the risk assessment and the general idea of the risk management process are illustrated in Fig. 1.

An acronym RAMS is used for terms reliability, availability, maintainability and safety. These essential risk related system quality attributes are generic. They can be used for all types of risk management irrespective of the type of item considered. An item is defined as part, component, device, subsystem, functional unit, equipment or system that can be individually described and considered. (EN 13306 2010).

Risk is defined as an effect of uncertainty on objectives. (ISO GUIDE 73 2009) The risks of a system can be divided to availability and safety risks. The combination of likelihoods and consequences of dependability related risk sources form availability risks of the system. Similarly, the combination of likelihoods and consequences of hazards form safety risks of the system. RAMS includes dependability (RAM) and safety (S). The terms of the risks and RAMS are illustrated in Fig. 2.

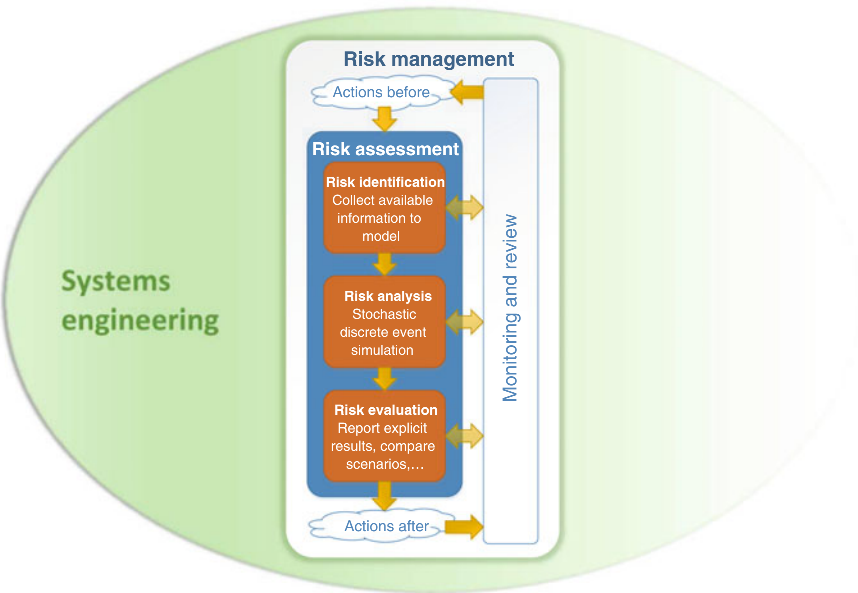

Fig. 1 Risk assessment process as a part of risk management and systems engineering

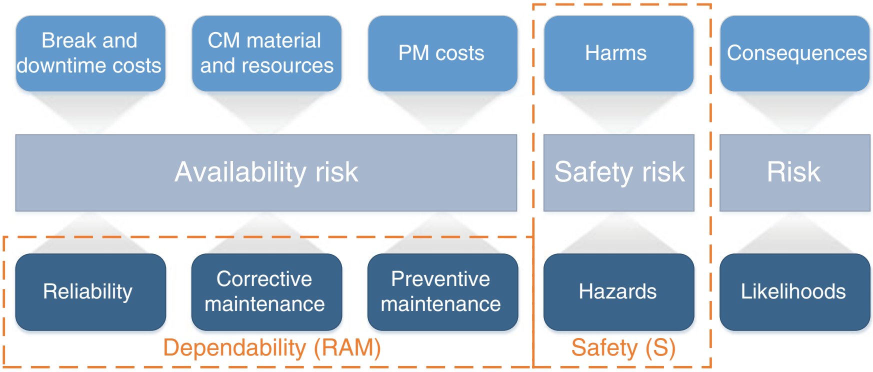

Fig. 2 The terms of risk and RAMS

3 Advanced Fault Tree Model

The advanced fault tree model is created on based on a general analysis of things (AoT) base model that consists of nodes and relations. The base model allows to define variables and parameters needed for each node to model the properties of an item of the studied entity. Also relations between nodes are freely defined so that for example logic and stochastic rules, delays and operation profile connections can be modelled as needed.

3.1 Analysis of Things (AoT) Base Model

The fundamental principle of the AoT base model is that the models of the standard quantitative RAMS analysis methods should be included easily. Such analysis methods are for example Failure modes and effects and criticality analysis (FMECA), Fault tree analysis (FTA), Event tree analysis (ETA), Cause-consequence analysis and Markov analysis. (EN 31010 2010).

The same AoT base model data structure also able to store data related to qualitative RAMS analysis methods. Such analysis methods are for example Failure modes and effects analysis (FMEA), Reliability centred maintenance (RCM), Root cause analysis (RCA, “5 whys”), Hazard and operability studies (HAZOP) and Check-lists. (EN 31010 2010) It is beneficial to have common data model that collects all the data required for different analyses. The similar data used by separate analyses needs to be updated only once and connections between results of different analyses can be easily pointed out.

3.2 Nodes of the Advanced Fault Tree Model

In advanced fault tree model each node has a state variable that defines whether an item of the studied entity can perform a required function. There can be also parameters related to the state variable, for example a cost of a spare part spent each time the restoration is made after the fault state. A node can have also for example a parameter related to its production capability that can be used in process diagrams to calculate total production speed of the system.

In addition to a state parameter related to ability to perform a required function, there can be for example a phase parameter for each node that defines whether the item should operate or not. This parameter is needed in simulation of batch production. The approach is that there can be more or less parameters and variables depending of the needs of the studied case. For example the preventive maintenance actions are included to the model by adding a variable that defines whether the maintenance action is currently made for the item.

3.3 Relations of the Advanced Fault Tree Model

Relations are defined from a group of input nodes to a group of output nodes. The output node of a relation is for example the node that models the system and the input nodes of a relation are all its sub systems. In addition to these lists, parameters are used to define the nature of the relation. For example min and max parameters can be used to model the logic rule. (Virtanen et al. 2006) In addition a probability parameter can be used for stochastic relation or some parameters can be used to define the delay distribution between the input and output nodes.

A special relation, called root relation, of a node contains only the node itself in both input and output nodes lists. A root relation can contain for example mean time to failure (MTTF) and mean time to restoration (MTTR) parameters that are used to define the cumulative distribution function (CDF) for the lengths of states of the node. After each state change new delay time is defined, the new state change is handled after the delay and this procedure is continued independently.

Phase relations are other special relations that define when the item is needed and when it can be idle. These can be defined similarly with state relations by using parameters that define delay between phase changes. For more complex phase changes, freely defined scripts can be defined to model the various phase change situations. Also maintenance actions are defined similarly with phase and state relations.

3.4 Stochastic Discrete Event Simulation

The created model is analysed through stochastic discrete event simulation. Events in the simulation mean a change of a state parameter value. Similarly phase parameter values are changed by events. At the beginning of each simulation round first events are defined for root relations. If needed a freely defined script can be given to define the initial phase of a round.

When an event is handled the needed variable value changes are made for the node. After the changes all the relations that has the node as an input node are also handled. The relations will define for example whether a state change of a system is needed after a state change of its sub-system. Also the root relation is handled again after a state change of previous root relation to define the timing of the next state change.

Data is collected during the simulation process for example by counting the number of state changes made for each node or the cumulative time the node spends in some state. The data of each simulation round is combined so that distributions can be drawn and mean and quantile values can be calculated.

4 Improvements to the Traditional FTA

Following chapters define simple example cases in which different properties of the advanced fault tree model are needed.

4.1 Operation Phases

The traditional fault tree model is a static structure. Advanced FTA approach is needed for systems with separate operation phases or other dynamic properties. For example each phase of a patch process can have different failure modes or the same failure modes can have different failure distributions. Also the failures in each phase can have different consequences, for example the time to restart after a failure can be different for each phase. In addition to this system level dynamic properties there can be component level dynamic properties, for example cold redundancy.

A phase variable added to nodes of a model can be used to simulate dynamic changes. The variable tells whether the system or component is currently used or not. The changes of these phase variables can be simulated independently similarly with the simulation of failures. For example by using parameters the distribution of the duration of each phase can be defined. After previous phase ends the next phase simulation is started.

Rules are defined to model the relations between states and phases. For example the normal path of phases can be interrupted when failure occurs and restarted after some delay. Also with cold redundancy the redundant component is started after a failure of the main component with some delay and possibly also failure probability. The relation can be also to opposite direction, for example at some phase some subsystems are not needed and their failures can be ignored or the operation is paused during the phase and failures do not even occur. In advanced FTA approach the rules of these relations are defined by writing Java based script.

4.2 Stochastic and Delay Relations

In traditional fault tree the relations are immediate, but sometimes delays between events need to be modelled. In advanced FTA approach the delay between events is modelled similarly with the definition root relations. In root relation the node itself triggers the new delay time but in delay relation the trigger event is a state change of any other node.

There can be delay after a failure for example related to costs. For example the downtime cost can get larger after some failed time. There can be also with some probability some cost if the fault is long enough. Also after restoration there can be delay before the system can be started again. Delays between phases and possible probabilities related to the phase changes are modelled and simulated similarly with the stochasticity and delays between state changes.

4.3 Maintenance Plan of Inspection Actions

Preventive maintenance actions are not included in the traditional fault tree. In advanced FTA approach these are modelled and simulated similarly with the state and phase changes by defining a maintenance variable for the nodes. At some predefined, stochastic or condition based time intervals a maintenance action is made for a node that may affects to its state or the phase of the system. The optimal maintenance plan is tried to be reached by analysing how the changes in maintenance schedule of a component affects to the whole system.

The moment of the action is defined similarly with root relations by using cumulative distribution functions (CDF) or static time intervals. Other possibility is to define rules when the action is made by using Java based scripts. Also the effect of an action can be defined by using a script. There are also predefined actions for the most common maintenance actions. For example inspection action can be modelled just by defining the symptom time and the probability that the symptom is recognized and the starting failure can be prevented before it occurs.

5 ELMAS

ELMAS is a tool that helps to use the advanced FTA approach by producing graphical user interface to create hierarchies, flow diagrams and other structures of nodes and their relations. From the options the used parameters and variables are selected for nodes and relations and the corresponding fields are shown in the user interface. Also an interface to include freely defined Java-based scripts is included to model more complex relations.

ELMAS produces also interfaces to import parameter data from the databases. For example failure history data can be used to create distribution that models the delay before next failure. The simulation results can be exported for example to data tables or various visual presentations of the results can be shown directly from the ELMAS.

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Supporting Asset Management Decision-Making—New Value Creation Perspective

Minna Räikkönen, Tero Välisalo, Daryna Shylina and Sara Tilabi

Abstract The current transition in value formation is forcing companies to seek new models and ways of operating and supporting their business and related investments. Therefore, the need for integrating the wider value perspective into the asset management and consequently, on asset management decision-making is increasing. Investments on engineered assets should be evaluated, selected and prioritized not only in terms of money but also with regard to sustainability, safety, quality, social acceptability and other typically intangible criteria. However, the evaluation of intangible and indirect impacts has rarely been included in the assessment up to now. This knowledge gap will be filled by this paper by proposing a preliminary framework for integrating wider value creation perspective into the asset management decision-making. It is aimed at decision-makers and intended to support decision-making on investments on engineered assets.

1 Introduction

Investment decisions are among the most important decisions made by companies. Since neither under- nor over-investment is desirable, decision-makers should understand factors that adversely affect their decision-making process and may prevent sound investment decisions. In addition, the transition in value formation is forcing companies to seek new models and ways of operating and supporting their

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business and related investments. Furthermore, the need for integrating the wider value perspective into the asset management and consequently, on asset management decision-making is increasing. Investments on engineered assets should be evaluated, selected and prioritized not only in terms of money but also with regard to sustainability, safety, quality, social acceptability and other typically intangible criteria.

However, the wider value perspective has rarely been included in the assessment up to now. This is mainly because these value elements are typically difficult to measure solely in economic terms and there is a lack of models and approaches to address the importance of indirect and intangible effects. In addition, the assessments are often under pressure to demonstrate short-term effects rather than emphasizing the whole investment's life cycle. However, for example investments on sub-systems for machinery as well as electricity and water supply networks can do and have indirect impacts on profitability and sustainability. Such effects may sometimes constitute a significant part of the overall benefits (profit) they should be considered and also integrated in investment assessments.

This paper proposes a preliminary framework for integrating wider value creation perspective into the asset management decision-making. It is aimed at decision-makers and intended to support decision-making on investments on engineered assets. The purpose of the paper is to contribute to the understanding of value creation, value growth and investment decision-making, addressing how to ensure that the most suitable investments get appropriate focus and that the goals for the decisions can be reached. The paper is based on the preliminary results of MittaMerkki, a research project partly funded by Tekes (the Finnish Funding Agency for Innovation) in the call "New value creation". MittaMerkki aims to advance companies' ability to create value and to provide decision models and tools to evaluate investments and to assess uncertainty and risk. The project is carried out in close operation between two research organisations and four companies from different sectors of industry and service business in Finland.

2 Concept of New Value Creation

Although the concept of value creation is the most ill-defined in management, it can be simply defined as a "better off" for user in some respect (Grönroos 2008). The complex nature of value creation becomes clear when it is asked where, when, how and by whom this value is created. This complexity emphasizes that the concept of value creation is different from different perspectives and for different stakeholders (Voima et al. 2010). While traditional perspective emphasizes only on company role in value creation and investment decision-making, new perspective considers customer as an important player (Meyer and Schwager 2007). In the process of value creation, company and customers have different responsibilities meaning that the firms are responsible for production and services process and related investments while customers contribute in co-producing process and resources (Grönroos 2008, 2011).

From the economical perspective view, value is created when the price which consumer pays for goods/services is higher than the cost of producing them. This happens when a product or a service and related investments are able to satisfy current customer needs without losing any capacity to satisfy future needs. Considering social value (Jensen 2001) the social value is maximized, when companies are able to maximize the profit of their owners and consumers are able to maximize their utility (Williamson 1984). In this model three factors should be considered: (1) All the elements which create value for companies are assumed also as risks either internally or externally, (2) To guarantee an optimum economic value, all the stakeholders should be taken into account and considering only the companies and customers is not enough, (3) Considering relationship between stakeholders and companies besides exchanges of good, other variable should be taken into account like other alternatives and all the relevant information about the potential alternatives (Argandona 2011).

Attempting to maximize the benefit and to optimize the value from the wider perspective, a new generation of companies can be perceived: transformational companies. Transformational companies believe in combining the best properties of high growth technology business and high impact of social enterprise to be able to optimize their value creation. Transformational companies start from the big goal by looking for current problem and asking what would be the companies' role to solve the problem or eliminate the negative effect. This purpose helps the companies to attract investors and talent, motivate internal resources and bring the best customers. Transformational companies are able to solve fundamental problem of customers in a systematic way and create value in many social scales at once (A Guide to Creating Exponentially Better Companies 2014).

3 New Value Creation and Investment Decisions

As investment decisions are usually taken in complex and turbulent business environment, the decision-maker is typically confronted with multiple needs, requirements and values. To make good and justifiable decisions, the decision maker needs to assess investment alternatives available in order to find an option that delivers maximum profit whilst satisfying the requirements and expectations of the parties involved in the decision-making. This concludes that various aspects should be taken into account in the investment appraisal especially when the wider value perspective is taken into account. In other words, the assessment should comprise the analysis of risks and uncertainties and cover both quantitative and qualitative factors.

Financial assessment. Financial methods are most commonly used for investment appraisal in companies, typically to rank alternatives. It is generally accepted that some investments on production assets are harder to appraise than others, because of their indirect future effects. It is also evident that the direct costs are most straightforwardly expressed in monetary terms. It is also relatively simple to find data on direct costs. (Farr 2011; Frezatti et al. 2013) Therefore, the assessment of investments emphasizes typically too often the evaluation of direct costs, rather than indirect or intangible costs. However, especially investments in sub-systems for machinery and other production systems can and do have indirect impacts on profitability and sustainability. For example, the loss of opportunity through disruption of business is typically difficult to assess. (Komonen et al. 2012; Ojanen et al. 2012) Furthermore, production assets in the capital intensive-industry have long life cycles and during the operating time numerous rebuilds, replacements and expansion investments take place which effects are both direct and indirect and which have a strong effect on profitability and sustainability.

Traditional financial methods include discounted cash flow (DCF, including net present value (NPV) and the internal rate of return (IRR), return on investment (ROI) and payback analysis. Life cycle cost (LCC) evaluation takes also into account the costs of usage, maintenance and disposal and the profits the investment generates during its lifetime. Thus, it is a practical solution to compare alternatives which have tangible value. A solution with high life cycle costs might generate a high profit. If only costs are used as a basis for a decision, the alternatives with intangible and indirect profits might be ignored and opportunity might be lost. Earned value analysis, the productivity index and expected commercial value are more recent examples of the analysis methods that can also be applied. The application of real options methodology (or options pricing theory) in terms of seeing projects as a series of investment decisions helps to reduce the risk through investing in each stage as the uncertainty decreases and more information is available. Finally, numerical probability-based assessment methods such as Monte Carlo simulations and stochastic programming facilitate probabilistic modelling. (Götze et al. 2008; Farr 2011).

Empirical findings show that although financial methods are typically the most popular, companies using them as their primary decision-making criteria can, however, have lower outcome levels in terms of performance (Cooper et al. 2001). This means that in practice, quantitative financial measures should be used as a guide rather than as the sole basis for the approval or rejection of specific investment alternatives. Decision makers should also understand the key assumptions behind the evaluation, how the analysis and calculations were carried out, and what the final results really mean.

Societal impact assessment can be applied to review the societal effects of investments. The societal impact assessment is focusing mainly on the criteria which cannot be expressed in monetary, physical, logical or other quantitative terms. These factors include decision criteria in different categories, analysing effects on e.g. social, environmental, ethical, individual and political level or with respect to law and regulations. Effective societal impact assessment generates value for all investment stakeholders, mobilizes greater capital, and increases the transparency and accountability of the investment impact delivered (Working group on Impact Measurement 2014).

Some methods are developed for quantifying intangible value, e.g. The Value Creation Index, VCI (Kalafut and Low 2001). VCI combines nine value drivers into a single index, which represents the sum total of company's performance across the most critical intangible categories. These nine value drivers are: (1) innovation, (2) quality, (3) customer relations, (4) management capabilities, (5) alliances, (6) technology, (7) brand value, (8) employee relations and (9) environmental and community issues. VCI has been used comparing the companies' potential for creating value through intangible assets (Kalafut and Low 2001).

In addition, for example, GIIRS (Global Impact Investing Rating System) is a comprehensive and transparent rating system for assessing social and ecological performance. It provides a tool for decision-makers to make sure that their investments have a positive social and environmental impact while they also try to earn a financial return. (Jones 2009). Consequently, the method that can be applied to evaluate societal impacts is the Analytical Hierarchy Process (AHP) (Saaty 1980). The AHP splits the decision process into partial problems in order to structure and simplify it. There is a hierarchy containing multiple target levels, such that the main target is broken down into sub-targets. At the lowest level of the hierarchy, the alternatives are included. Using the AHP, both qualitative and quantitative criteria can be considered. In each case, the relative importance (weightings) of the different criteria, and the relative profitability of alternatives, is determined with respect to each element of at the higher level by using pair comparisons. Then, a total value is calculated for sub-targets so as to determine their relative importance for the whole hierarchy, and, ultimately, to assess the overall profitability of the alternatives. (Götze et al. 2008).

Risk and opportunity management. Risk is a topic that receives much attention in the decision-making literature. In many cases, non-controllable events that may affect the decision outcome can be identified (Millet and Wedley 2002). Complex situations with many risks form the essence of investment decision-making, with systematic risk assessment being an important stage. Risk management is defined in ISO 31000 Risk Management standard as "coordinated activities to direct and control an organization with regard to risk". Risk is often considered as an uncertainty with negative effects (ISO 31000 2013). Opportunity management is defined as an "upside risk", an uncertainty with positive effects (Hillson 2002). Both risk and opportunity management is based on the identification of events that can have effect on a physical system (e.g. an industrial process) or a function. Identification of possible events has to be based on a defined framework to make the identification process complete. Also investment planning should include risk and opportunity identification phase where possible scenarios are built, their importance is defined and some corrective actions are suggested.

An essential part of risk management is a risk analysis which is defined in standard ISO 31000 as "process to comprehend the nature of risk and to determine the level of risk". In risk analysis different scenarios are built to make a thorough understanding how e.g. a failure affects the output of an industrial system. In investment decision-making the situation is similar: the effects of different alternatives should be identified (ISO 31000 2013).

To make a risk analysis for alternative investment proposals, the investment should be described in a systematic way. One solution is to make a qualitative estimation of risks and opportunities for an investment alternative is the Double Probability-Impact Matrix for opportunities and threats (Hillson 2002). In risk analysis the main focus is to find factors that might prevent the plan from realising. In opportunity analysis the main focus is to find possibilities to succeed in the best possible way. Because of the opposite nature of these two approaches, the analyses should be accomplished separately. Some of the opportunities might e.g. have a huge economic potential but, at the same time, they might cause some really serious consequences to the company if failed.

4 The Conceptual Evaluation Framework

In order to set the research frame, a conceptual investment evaluation framework indicating the main inputs, outputs and linkages between different analyses has been developed and is depicted in Fig. 1. The starting point of applying the assessment methodology is a perceived need for investments, for example, in productivity, replacement and maintenance and for capacity expansion. Thus, assessing the value of investments can be considered a continuing process. Additionally, decision-making can be considered a multidimensional problem wherein any of purely economic, strategic, or risk-related assessment can be deemed inadequate for consideration of all relevant elements.

The conceptual framework indicates that the assessment should be integrated and thus include the financial assessment, risk assessment, as well as the analysis of the societal impacts. The framework itself includes many steps and consists of

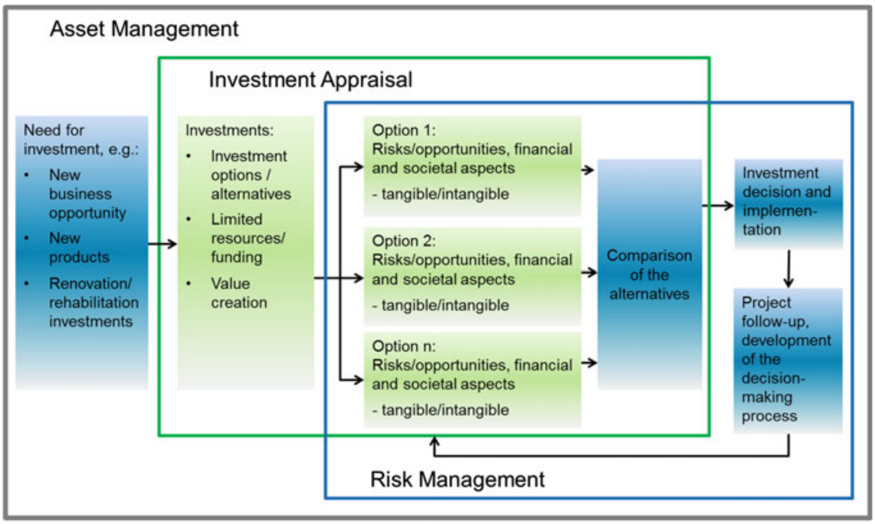

Fig. 1 The conceptual investment evaluation framework

structuring the decision situation and the investment in question, setting the boundaries and framing conditions for the assessment. The essential part of the framework is the assessment of risks, costs, and benefits, along with, finally, synthesis to reach an overall ranking of different investment options. More importantly, the framework provides a loose coupling between different methods and modules.

The framework is based on the preliminary results of the MittaMerkki project. This means that the framework needs still to be further refined and developed. In the next phases of the MittaMerkki project, the framework and different steps of the framework will be evaluated and tested in the MittaMerkki company case studies. In addition, a practical tool for linking quantitative assessments with qualitative assessments of societal values to support decision-makers will be developed.

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A Framework for Implementing Value-Based Approach in Asset Management

Irene Roda, Ajith Kumar Parlikad, Marco Macchi and Marco Garetti

Abstract ISO 55000 puts 'value' at the core of asset management. This paper provides a framework to help production companies implement value-based Asset Management (AM) in a way that it contributes to operational excellence. Value-based AM is achieved when the value delivered by assets is used by the organization as the key decision criterion to choose between different AM options (both at tactical and operational level). Given this perspective, it is vital that organizations are able to quantify the value delivered by their assets and manage that value through informed and coherent decision-making. Value-based AM is still a concept more quoted in theory than described in practical terms. A clear understanding about the main elements that are needed to enable it is still missing in industrial practice. The framework presented in this paper provides the key elements needed for successful integration of a value quantification model with the AM system to ensure the effective implementation of value-based approach in AM.

1 Introduction

Asset Management (AM) is a value-adding process to the core business of an organisation and should be considered so by companies (Liyanage and Kumar 2003; Amadi-Echendu et al. 2010; El-Akruti et al. 2013; ISO 55000:2014(E) 2014).

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Indeed, AM has a key role in strategy development and implementation. This strategic role is maintained based on planning and control of the asset-related activities (El-Akruti et al. 2013).

As stated in the ISO5500x series of standards on AM (released on January 2014), the concept of value is at the heart of Asset Management. AM is in fact defined as the coordinated activity of an organization to realize value from assets (ISO 55000:2014(E) 2014). Value is obtained through providing assets that allow an organization to fulfil its strategic intent (El-Akruti et al. 2013). No single detailed definition of 'value' delivered by assets can be found in the literature. In fact, its specific definition is very much dependent on the company's purpose, the nature of its assets, its objectives and the expectations of its stakeholders. It can be tangible or intangible, financial or non-financial (ISO 55000:2014(E) 2014). What is agreed is that the realization of value involves balancing costs, risks, opportunities and benefits arising from the way assets are specified, procured, deployed, used, maintained and disposed. Each company has to define its own conception of value, given the specific context in which it operates. Despite the increasing body of academic literature and industrial interest on AM process and systems and the strategic role of AM (El-Akruti et al. 2013), value-based AM is still a concept much more quoted in theory than described in practical terms. A clear understanding within companies about the key elements needed to enable it is still required. The assumption is that value-based AM is achieved when the value delivered by assets is used as the decision criterion to choose among different AM options (both at tactical and operational level). The aim of this paper is to provide a framework that drives production companies towards the implementation of value-based AM contributing to operations excellence.

2 Value-Based AM Framework

The idea that proper lifecycle management of physical assets is an essential activity to contribute to the value delivered by an organization is becoming more widely accepted nowadays. The AM perspective is set on the management of an asset in a way to create and/or sustain value during each life-cycle stage, and throughout the asset's life. Therefore, to ensure value-based AM, it is important that value delivered by assets along its life cycle is used as the decision criterion to choose among various AM options. Hence, a model able to quantify such value is required. The "value-model" is intended to be used whenever an AM decision has to be taken. Several value-models have been proposed so far depending on the specific

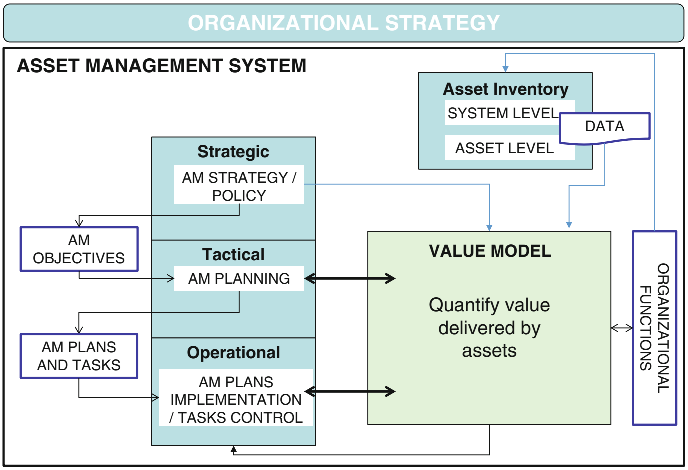

Fig. 1 The value-model integrated in the AM System

interpretation given to value in different contexts (e.g. Total Cost of Ownership (Roda and Garetti 2015), Value Mapping (Srinivasan and Parlikad 2015). Figure 1 shows how the value-model sits within the AM System.

The expected main functions of the value-model are:

- To enable and control AM planning and implementation by supporting decision making and options/scenario analysis;
- To support communication of asset value contribution internally and externally to the organization enhancing commitment and continuous improvement;
- To control alignment between the AM plans and operations and the AM strategy.

This paper aims at providing a vision of the key elements needed for a successful integration of a value-model with the AMS to ensure the effective implementation of value-based approach in AM.

Our research reveals that there are some key elements needed to ensure proper value-based decision making in general for any company, independent of the definition given to value. Those key elements have been categorized and outlined within a framework as shown in Fig. 2. The framework was depicted in line with the IDEF0 standard. The seven key elements are represented under the following categories—control factors, inputs and resources—in the context of the asset value model. We will now describe each of these in detail in the next section.

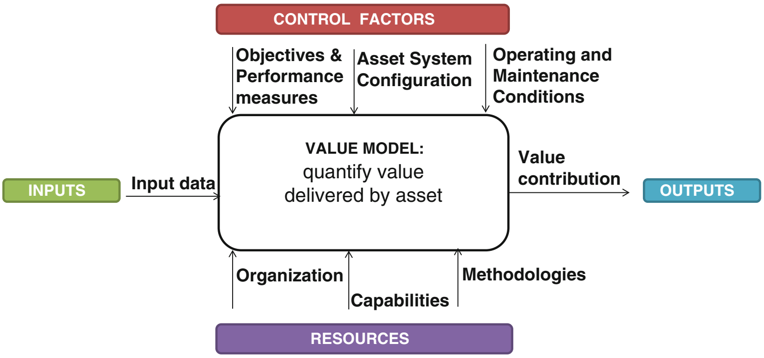

Fig. 2 Value-based Asset Management framework

3 Key Elements of Value-Based AM

3.1 Control Factors

Control factors are the conditions to the value-model affecting the outputs.

3.1.1 Objectives and Performance Measures

As stated in ISO55000, AM involves the balancing of costs, opportunities and risks against the desired performance of assets, to achieve the organizational objectives. Therefore, the first requirement for proper value-based AM implementation is that AM objectives are clearly identified and that they are SMART (Specific, Measurable, Achievable, Realistic and Timely) and aligned with the organizational objectives. Alignment should exist between the company's fundamental strategic objectives (what the company wants to be), the plant-specific strategic objectives (what the company aims in operating the plant) and the AM objectives (what is the aim of the company in managing the production assets) (Liyanage and Kumar 2003). The overall alignment should be checked periodically to ensure that the value-model is actually based on the value drivers of the company (may it be for example profit, environmental impact, safety, customer satisfaction, etc.).

In addition, the organization (or its AM function) needs to identify the desired performance targets and measures for each asset as well as for the AM system (Parlikad and Wang 2015). The AMS performance measures need to encompass technical (at system level and equipment level), economical and organizational dimensions reflecting the holistic characteristic of AM.

3.1.2 Asset System Configuration

An asset system such as a production plant must be viewed as a collection of assets that interact, and interdependencies between the assets can affect the systemic value contribution. For instance, interdependencies imply that failure/deterioration of any asset within the system can have knock-on effects throughout the system and might create additional costs or risks, and this might not be clear when managing each asset independently.

While individual asset-level analysis estimates performances with respect to a single component (OEE is the performance measure best representing this concept), system-level analysis allows considering systemic value contribution arising from components' interdependencies (Xu et al. 2013; Liang and Parlikad 2015a, b). Depending on the objectives and the AM KPIs and value drivers, specific kinds of interdependencies are to be considered in order to evaluate the value contribution of a local intervention at the system level. Possible kinds of interdependencies among assets can be economic, stochastic and structural dependencies (Nicolai and Dekker 2008), and functional—logical interdependency (assets jointly contribute to the delivery of a function as required). In most cases, a subset of interdependencies are modelled depending on the problem at hand, and the resources the organization wants to spend on modelling. This is essential to strike the right balance between modelling complexity and accuracy. It is essential to use a reasonable model of the system to control and influence the value-model's output.

3.1.3 Operating Conditions & Maintenance

Different operating conditions and maintenance management policies affect the level of value provided by the assets. Operating conditions include the specific function executed by the system, the environment in which it works, the available working time for it to produce etc. In any of these cases, it is clear that in the event of a change, that influences the value contribution realized by the system, hence the value-model should integrate it. The same is valid for maintenance policies implemented in the system. For example, the execution of pure corrective maintenance or the implementation of preventive and predictive maintenance directly affect the way the system can generate value. It is then essential to ensure that these control factors are integrated in a value-model that is used to support decision-making. It allows setting the proper operating condition and maintenance activities to increase value contribution, given the AM objectives.

3.2 Inputs

Inputs are the data transformed/consumed by the value-model to produce outputs.

3.2.1 Input Data

Data is a critical asset in today's organizations (Borek et al. 2014) and the availability of useful data is paramount to making the best decision in AM. Bringing all of disparate data together into widespread asset-centric information is yet a key challenge facing asset users today; an integrated asset information management strategy would be required (Ouertani et al. 2008). When considering which data are needed for supporting informed AM decision making, it must be taken into account that the data that are required can vary from case to case depending on the definition given to value. What is generally recognized is that both technical and financial data are needed. The major challenge in obtaining the required data is that they are heterogeneous, hence they are usually scattered among separate information systems (administrative IT systems, industrial IT and non-automatic sources) (Moore and Starr 2006; Kans and Ingwald 2008). May it be at IT level or not, it is widely agreed that integration must facilitate the bi-directional flow of data and information into the decision-making at all levels (Moore and Starr 2006). The core idea is that, a *common asset database* should be developed where for each asset, at different aggregation level different data can be stored all together. The asset database would provide basic reference to information regarding assets' properties for strategic decisions (Kans and Ingwald 2008; Tam and Price 2008).

Data quality is also a critical aspect to consider to ensure proper decision-making. The first step towards high quality data for any organisation is the Data Quality (DQ) assessment (more information on this can be found in Borek et al. (2014)).

3.3 *Resources*

Resources are the means that support the execution of the value-model.

3.3.1 Organization

The application of the value-based AM concept in a company calls for an organizational architecture and culture that promote the concept of whole-life value-based system-wide asset management and its reception as an effective process (Liyanage and Kumar 2003). Different organizational functions are involved in the AM process with their specific role in the organization's structure. In order to integrate AM in a company as a single process, two main requirements should be complied: (i) integration among different organizational functions that contribute in the AM value-chain; (ii) clear definition of AM related roles, authority and responsibilities.

The first thing to be considered is the interdisciplinary and collaborative nature of the AM system that can be gleaned from the definition of asset life cycle from a user viewpoint itself (El-Akruti et al. 2013). At each life cycle stage of an asset, different disciplines and hence different organizational functions are needed. The success of a capital intensive organization often depends on its ability to coordinate activities efficiently and effectively among the various asset-related activities (El-Akruti et al.2013).

Secondly, as it is stated in the ISO55000 as well, leadership and workplace culture are determinants of realization of value and this includes clearly defined roles, responsibilities and authorities. It is advocated that the existing organization roles involved in asset management value chain are modified to include AM responsibilities and accountabilities. One ramification for this is that conventional process control rooms may need to be converted into ownership, management, and utilization centres (Amadi-Echendu 2004).

3.3.2 Capabilities

Capability is the measure of capacity and the ability of an entity (system, person or organization) to achieve its objectives. In order to implement value-based AM, certain capabilities are needed in an organization. AM capabilities include processes, competences and technologies to enable the effective and efficient development and delivery of AM plans and asset life activities, and their continual improvement (ISO55000). It is important for a company to put effort to foster them. Regarding required AM competencies, given by the ability to apply knowledge and skills to achieve intended results, details can be found in the IAM report (Competence Framework 2008). Concerning the required technologies, a reliable and flexible IT system should be integrated allowing the use of an asset common database and the implementation of the needed AM process activities (see (Koronios et al. 2006). Proper DDSs need to be adopted as well.

3.3.3 Methodologies

Companies need to use specific methodologies to set the value-model and integrate it as a support in decision-making. Different methodologies will be required depending on the specific case. Some examples are: Root Cause Analysis (RCA), FMEA, etc., that help identifying criticalities and defining the reference system model. Moreover, methodologies such as data analytics methods, RAM analysis and risk evaluation approaches should be integral part of the AM approach.

3.4 Outputs

The envisioned output of the value-model is the quantification of value delivered by assets and it is the criterion guiding the decision-making.

4 Conclusions and Future Research

In the paper, a framework has been proposed highlighting and categorizing the key elements to be considered to enable the integration of a value-model with the AMS ensuring the effective implementation of value-based approach in AM in production companies. In fact, value-based AM is implemented when the value delivered by assets is taken as the decision criterion whenever a decision about assets must be taken (at operational or tactical level). The framework is addressed to the decision makers in the company to support them ensuring that they take informed decisions contributing to value generation.

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Integrated Planning in Autonomous Shipping—Application of Maintenance Management and KPIs

Harald Rødseth and Brage Mo

Abstract Within the maritime sector, a vision has been established which comprise safe, sustainable and efficient waterborne transport (1), competitive European waterborne industry (2), and growth in transport volumes and changes in trade patterns (3). This vision, in combination of increasing interest for reducing operating costs, has resulted in the concept of "Autonomous Ship" and unmanned shipping. In order to realise this concept in the operation phase, a robust maintenance concept must be developed. The purpose of this paper is therefore to evaluate a maintenance management concept for unmanned shipping based on a storyboard approach. In particular both maintenance key performance indicators (KPIs) and technical issues such as leakage through piston rings are evaluated in this maintenance concept. The result in this paper is an Integrated Planning concept for unmanned shipping. This planning concept will enable faster and better decisions between the maintenance department and other offices which are responsible for operating the vessels. As a conclusion both leading and lagging KPIs must be included in IPL and aligned with existing Asset Management standards.

1 Introduction

In the EU project MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) an autonomous bulk vessel has been established in the conceptual stage (Rodseth et al. 2013). As a concept, this vessel will be autonomous during the

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deep-sea voyage that relies on a manned shore control centre (SSC). The autonomous vessel will have four operational modes with explanation:

1. *Autonomous execution*. The vessel follow a programmed track and speed instructions where environment is monitored through sensors.
2. *Autonomous control*. If the vessel has minor problems, it can handle the situation with its own predefined counter-measure.
3. *Remote control*. If the problem is too major to be handled from the vessel alone, it is need to involve the SSC completely overriding the vessels own control.
4. *Fail to safe*. If no control is possible to achieve anymore of the vessel, the vessel will go into a “fail to safe” mode.

The autonomous vessel should be considered as a game change in maritime business models where the way of operating an autonomous fleet and vessels will be significantly different from today’s maritime business environment. This innovative maritime business models should also have inspirations and recommendations from other novel initiatives such as Asset Management (Hollywood and Shea n.d.) and Industrie 4.0 (Drath and Horch 2014). Asset Management as a concept will through a systematic approach of the asset in the enterprise ensure that maximum values are created for the stakeholders. Furthermore, Industrie 4.0 will through advances in ICT solutions establish tools and methods for cyber physical systems (CPS) where data gathering, processing, visualisation and analysis is performed real-time partly based on the ability of connecting all vessels on internet.

Currently, a novel maintenance concept suitable for autonomous shipping has been proposed (Rødseth and Mo 2014). In this work, a structured approach for developing the maintenance concept was proposed. To finally develop the maintenance concept, the approach was evaluated with a result in a maintenance management framework. This maintenance concept is regarded to be quite generic and it is therefore necessary to provide a concrete example how this concept is operationalised.

An essential part of the proposed maintenance management framework in MUNIN is developing a novel concept of maintenance plan (Rødseth and Mo 2014). Furthermore, the maintenance plans should be integrated with other plans that affect the maintenance plan, e.g. the route plan. Therefore, these plans should be integrated into Integrated Planning (IPL) where several organisations and stakeholders can perform a multi-disciplined decision for the maintenance plan. This concept has been given attention as an important research area with development of key performance indicators (KPIs) in both petroleum industry (Ramstad et al. 2010) and in the manufacturing industry (Powell and Rødseth 2013). Furthermore, it has been emphasized that insight in Asset Management has been used for updating IPL (Rødseth and Schjølberg 2014). It has also been pointed out that that shipping industry should share experience with other branches such as the aviation industry and manufacturing industry (Rødseth and Mo 2014). Hence, since

Asset Management and Industrie 4.0 origin from other industry branches, it is in particular of interest to investigate how both Asset Management and Industrie 4.0 will play a significant role in improving the maintenance management framework for the autonomous vessel.

The objective of this paper is therefore to investigate in essential aspects in Asset Management based on ISO 55000 and Industrie 4.0 and further demonstrate how these principles can be applied within maintenance management for autonomous ships. The method applied in this article is first a literature study, then a demonstration of the MUNIN concept through a storyboard.

The remaining of the article is organised as follows. In Sect. 2 the Integrated Planning in MUNIN is introduced in terms of Asset Management and Industrie 4.0. Further, a technical issue is elaborated that is relevant for the storyboard in this section. Based on the elements in Sect. 2, a storyboard is demonstrated in Sect. 3 where the importance of Asset Management is elaborated. Final conclusions are drawn in Sect. 4.

2 Integrated Planning in MUNIN

IPL integrates maintenance planning into other disciplines that affect the technical condition. Asset Management plays a significant role (Rødseth and Schjølberg 2014) and should also include concepts such as Industrie 4.0.

2.1 Asset Management and Industrie 4.0

Likewise the automotive industry where Asset Management is a key role with assets worth billions of euros and intense competition (BEMAS 2014) the maritime industry should also adopt the overall philosophy within Asset Management. This concept is defined in ISO 55000 as "*coordinated activity of an organisation to realize value from assets*" (ISO 2014). To emphasize the harmonization of continuous improvement for the enterprise, Fig. 1 visualize and structure this concept from ISO 55000 through the Deming cycle with the logic PLAN-DO-CHECK-ACT. In particular it is of interest in this concept to evaluate the interrelationships between maintaining and operating the asset (CEN 2015). For the MUNIN vessel the asset will not only comprise the autonomous vessel but also the Shore Control Centre (SCC) with the knowledge from the maintenance planners and their support. When evaluating the performance in Fig. 1, a framework has been proposed that connects the Asset Management system, Asset Performance and Business Performance (Attwater et al. 2014). In MUNIN technical issues will be linked to these perspective of performance measurement.

Another concept that has an emerging trend in Europe is Industrie 4.0 in the Manufacturing industry enabled by the technological evolution in Internet of

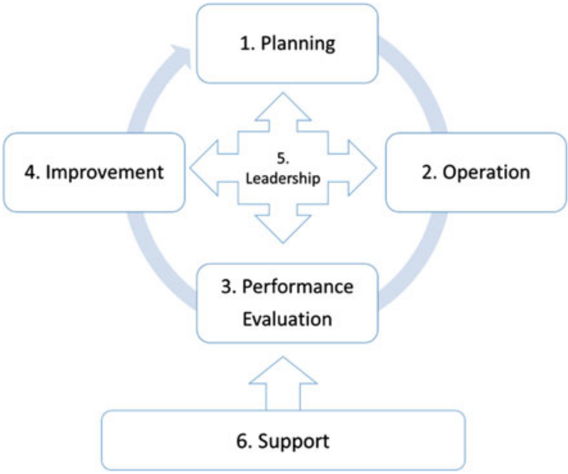

Fig. 1 Asset Management cycle inspired by ISO 55000 (ISO 2014) and the Deming cycle

Things and Services (Kagermann et al. 2013). Through ICT innovations, Industrie 4.0 will provide game changing capabilities for new approaches and methods, e.g. visualization of augmented reality based maintenance by using smart devices in real-time (Abramovici et al. 2015). A Core element in Industire 4.0 is the Cyber Physical System (CPS) (Kagermann et al. 2013). A further structuring of CPS and relevance for MUININ concept is shown in Table 1 and is adapted from Schuh et al. (2014).

2.2 Technical Case and Condition Monitoring

The maintenance intervals for cylinder units have improved over time. In fact, it is claimed that todays experience "*…clearly indicates that overhaul intervals for cylinder units may be expended far beyond the mentioned 30.000 h interval*" (Toft et al. 2013). One important measure for achieving this is introduction heavy duty components in the main engine. In fact, it is also concluded that operation of 2-stroke main engines largely beyond 6000 h should be practically achievable without comprising the engine performance and the reliability (Toft et al. 2013). For an autonomous ship with engines either fitted with heavy duty components or not it is of high importance for the engine reliability to monitor its operational conditions and the wear of essential components with sufficient monitoring methods. The piston rings condition and lubrication of the cylinders is the case subject to maintenance management by improved monitoring. Monitoring piston rings wear and their operational environment with respect to lubrication, gas leakage through the piston ring-pack and carry water overflow into the scavenging air are of interest.

Several condition monitoring methods for the piston rings have been simulated. Magneto-resistive sensors (Peng et al. 2011) and acoustic emission measurements

Table 1 Categorization of CPS, adapted from Schuh et al. (2014)

	Software	Hardware
Cyber	*Single Source of Truth* ERP systems, mathematical models, visualisation of KPIs *MUNIN:* Computerised Maintenance Management System	*IT-Globalisation* Access and storage in cloud, big data, data mining and high speed computing *MUNIN:* Autonomous "black box" servers on-board, data extraction and data mining from fleet server on land
Physical	*Cooperation* Business communities *MUNIN:* Shore Control Centre Community of maintenance planners, ship owners, engine builder, ship builder, suppliers and researches	*Automation* Sensor technology, ICT structure for the fleet *MUNIN:* Temperature sensors, pressure sensors, satellite communication, RFID technology of spare parts on land

for stress wave analysis for the surface (Douglas et al. 2006). In addition to monitoring methods, physical friction model of the piston has also been developed and evaluated (Livanos and Kyrtatos 2007). Many systems is incapable in detecting the initial stage of the scuffing that may lead to the excessive wear of the piston rings and cylinders (Saito et al. 2007). The installation of an automatic analyser of iron content in the cylinder drain oil at a piston that predicts potential mechanisms of the excessive wear is an interesting option. This analysis method has shown that the iron content tends to increase by the unsteady operations on arrival or departure from a port and at the low speed regions. This phenomena leads to unstable oil film thickness or the formation of thinner oil films in the engine (Saito et al. 2007).

3 Storyboard of Maintenance Concept

The technical case selected in the storyboard is piston blow-by due to wear and tear in the piston rings. Based on the technical description of piston ring and possible technology in condition monitoring, a storyboard of the maintenance concept for MUNIN has been developed, see Fig. 2. On the status bar on the right side it is possible for the maintenance planner to observe and evaluate the current situation. In this case it is an issue about blow-by past piston rings where increased exhaust gas temperature is an indication of this problem (MAN 2004). In addition, visualization with graphs and figures are also provided for the maintenance planner.

The next step is to send out a maintenance notification. If the maintenance planner has conflicts with the route plan of the vessel, this will require contact with other stakeholders that can lead to a change in both the maintenance and route plan. It is also necessary to perform an analysis of the maintenance backlog that will occur by updating the maintenance programme. For this purpose own leading and

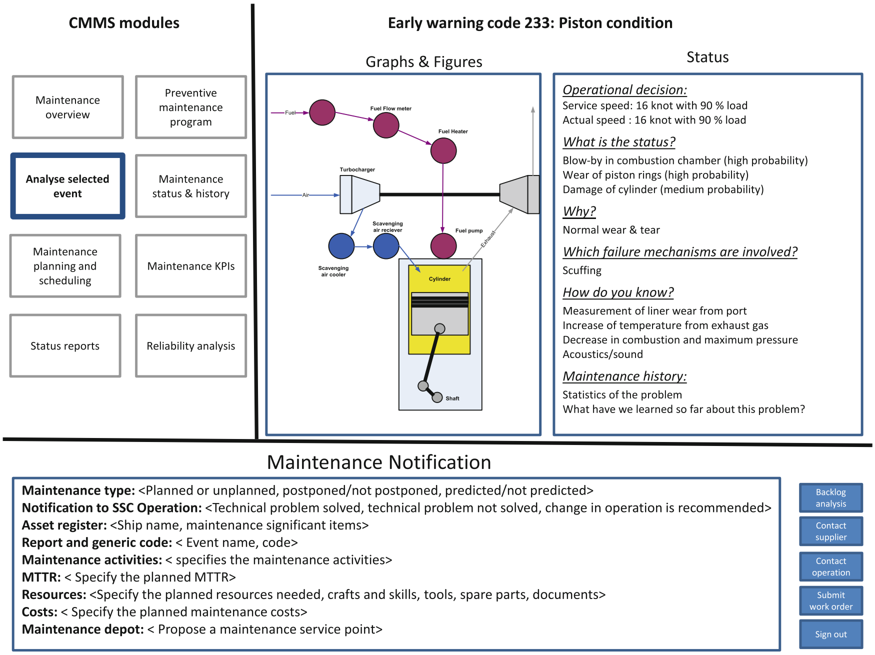

Fig. 2 Presentation of the storyboard shown as a maintenance dashboard

lagging KPIs will be shown for further analysis. It is also possible for the maintenance planner to contact suppliers in order to achieve technical advices for the planned maintenance activity. When the maintenance planner has sufficient information from both the route planner and relevant suppliers he can fill in a maintenance notification and submit it and sign out the notification.

4 Conclusion

This article has through a storyboard demonstrated how the principles from Asset Management and Industrie 4.0 can be applied in the MUNIN context. In particular a leading KPI for maintenance backlog will be a pivotal element in this storyboard and should be aggregated both from the technical issue such as the condition of the piston ring and from a planning perspective in maintenance. When the maintenance plan is changed due to external causes from the route plan, IPL will find a balanced decision between the route planner and the maintenance planner. Further research will require modelling of maintenance backlog build on principles both from maintenance planning and the technical condition of the asset itself.

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Increased Profit and Technical Condition Through New KPIs in Maintenance Management

Harald Rødseth, Per Schjølberg, Martin Kirknes and Thor Inge Bernhardsen

Abstract With the onset of Statoil Technical Efficiency Programme (STEP), a significant strategic focus has been allocated in Statoil with the purpose to reduce costs and increase productivity. In addition, the Oil and Gas industry has through the research activity Integrated Planning (IPL) developed frameworks and is related to the ISO 55000 standards for Asset Management. The purpose for IPL is to plan for technical condition which requires participation from several disciplines in production such as maintenance, production and logistics. In particular the key performance indicator (KPI) denoted as Profit Loss Indicator (PLI) is an essential tool for IPL. The core of this KPI is to measure the "hidden factory" through a financial number. In this article the "hidden factory" will comprise both time losses and waste in production. The aim of this article is to demonstrate PLI as a case study within the O&G industry for technical equipment. The result in the case study is an evaluation of the existing maintenance programme at Statoil and different strategies for updating the maintenance programme. Furthermore, PLI is evaluated for how it can be implemented within Asset Management.

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1 Introduction

In production companies today, it is of interest in reducing the operational costs and increasing the production assurance that result in increased productivity. In particular the Oil and Gas (O&G) industry is challenged more recently with this issue where the oil prices has decreased significantly during the last years. Nevertheless, it is believed that there can be at least 50 years with activities in Norway within this branch in terms of workplaces and investments (Norsk Olje and Gass 2015). One relevant future initiative for the Norwegian government is to have a tax structure that stimulates to increased oil and gas recovery and improvement of resource exploitation. The interest of increasing oil and gas recovery and improved resource exploitation is also of relevance through Statoil Technical Efficiency Programme (STEP). With increasing global competition and more strict requirements from stakeholders, todays existing business models are challenged for improvements and updates. In particular, the maintenance function in a company must be under development in order to have the status as World Class Maintenance (WCM). Such a company follows the maintenance practice that enable a competitive advantage in the organisation (Wireman 2005). Through time, several maintenance concepts and strategies such as Reliability Centered Maintenance (RCM) and Total Productive Maintenance (TPM) has been both successfully developed and implemented in several organisations (Ahuja and Khamba 2008).

In newer time, Asset Management is developed and implemented in industry. In fact, this concept has also been specified through the ISO 55000 (ISO 2014). The core in this concept is that the asset creates value for the stakeholders. Despite that Asset Management has been specified through a standard, this concept lacks a mechanism for Integrated Planning (IPL) where relevant departments and disciplines in an enterprise that affect the technical condition has integrated their plans with the maintenance plan. In this concept, key performance indicators (KPIs) are developed as a tool for improving the overall planning of technical condition at a physical asset. In this article the KPI denoted as Profit Loss Indicator (PLI) is evaluated more in detail. Industrie 4.0 is another novel initiative origin from Germany and Federal Ministry of Education and Research (Kagermann et al. 2013). In this concept, machinery and production facilities is embedded in Cyber-Physical Systems (CPS) and comprise smart machines, storage systems and production facility in order to exchange information in real-time and autonomously. As a key area, Industrie 4.0 addresses novel planning models of complex systems and should be further supported by application of PLI.

The aim of this article is to demonstrate how PLI is calculated through a case study within the O&G industry at Statoil facilities for technical equipment and elaborate how this indicator is aligned with IPL.

The remainder of this article is as follows: In Sect. 2 the IPL concept is presented and where the relevance for Asset Management and Industrie 4.0 is evaluated in detail. Further in Sect. 3 the indicator PLI is presented and described how it is applied in the O&G industry. In Sect. 4 the case in the O&G industry is presented and a PLI calculation is performed. Finally in Sect. 5, discussions of the results are made and final conclusions drawn.

2 Integrated Planning for Technical Condition

The need for IPL is evident in different industries such as manufacturing industry (Xiang et al. 2014) and O&G industry (Ramstad et al. 2010). For manufacturing industry, mathematic models have been constructed that combine manufacturing planning with deterioration models (Xiang et al. 2014). In O&G industry, specific key performance indicators has been regarded as a essential tool in IPL (Bai and Liyanage 2012). Despite these efforts, models for IPL from a maintenance management perspective is still lacking in O&G industry. In particular, it is of interest to develop indicators that can communicate to stakeholders "outside" the maintenance department and which is affected by the decision.

The IPL framework should be both inspired from and harmonized with similar concepts. Asset Management is such a concept where the ISO 55 0000 standards have recently been published (ISO 2014). The need for this standard has been identified based on findings from a technical committee (Life Cycle Engineering 2013). The world had suffered from financial crisis and recession and several business executives and government officials had become significant focused on risk awareness. It was therefore a need to develop an element of stability, and ISO 55 000 series was such a remedy. The need for stability is also important in O&G industry and hence this standard should be thoroughly considered with interest to improve both HSE risk management and productivity (Hollywood and Shea 2013). From a maintenance perspective, Asset Management should comprise operational, tactical and strategic decisions. A definition of Asset Management supported by the authors is from ISO 55 000 (ISO 2014): "*Coordinated activity of an organisation to realize value from assets.*" From this definition, the term value is of particular relevance as a financial understanding. Automation is one important reason for implementing asset management (Zuashkiani et al. 2011) and the perspectives of cost centre view (1), production capacity assurance view (2), and strategic view (3) have been evaluated. The cost centre view outlines that the maintenance departments have more influence on the top management where maintenance costs comprise a significant amount of the operating costs. The production capacity assurance view is reflecting the measure overall equipment effectiveness (OEE) where 85 % OEE value is regarded to be measured for a WCM organisation. In the strategic view, OEE also plays an important role in maintaining the competitive advantage for the company where small changes can lead into significant changes in the profit of the business.

IPL is also aligned with the Industrie 4.0 concept in terms of more novel planning models (Kagermann et al. 2013). The benefit for such models is that value-added activity is being brought forward to an earlier stage where the long term economic losses are reduced. This is also one important capability of IPL which is explained more in detail in next section. IPL will in addition be strongly user focused with real-time decision support and intuitive visualization which is also one main characteristic related to Industrie 4.0 (Abramovici et al. 2015).

3 Profit Loss Indicator for Oil and Gas Industry

The development of PLI has been developed (Rødseth and Schjølberg 2014) and tested further in saw mill industry (Rødseth et al. 2015). The core of PLI is to combine a financial understanding of "the hidden factory" that also includes waste in production. From a financial perspective the profit loss is the sum of turnover loss and extra costs. PLI is calculated not only for the specific equipment, but can also be aggregated up to a process and plant level. This indicator has a monetary value and ranges from zero and upwards. PLI has also some correlations to Life Cycle Profit (LCP) (Räsänen et al. 2008) where for example increase of maintenance costs and reduction of availability results in an reduced LCP value and increased PLI value. However, PLI expands the term of turnover loss not only to comprise availability loss, but for example other time losses such as reduced speed and production of scrap. It is important that PLI as a KPI is not evaluated in isolation but has a target value as a result of alignment of the both cooperative business objective and maintenance objectives. When this KPI is linked to objectives it should be possible to receive increased support from top management in terms of necessary investments.

In the case study, PLI is used to evaluate if the maintenance programme should be updated which would require a significant investment. The economical method is Net Present Value (NPV) method where the investment can only be justified if the discounted reduction in PLI for each year is greater than the investment cost.

The case relevant part of the PLI cube is shown in Fig. 1 and is used both for estimating future PLI values based on historical data and registering real-time measurement of PLI after the investment in the planning process. Today, Statoil does not measure OEE, but production efficiency (PE) shown in Eq. 1:

$$PE = \frac{Oil\,produced}{Oil\,produced + Oil\,production\,loss} \tag{1}$$

PE is a volume based parameter expressing regularity, i.e. amount produced (oil, condensate and gas) related to theoretical possible. In principle only processing plant/installation has PE. "External" volumes processed by plant are included in plant PE-calculations. However, the availability loss is possible to measure and is in the case used to measure the PLI of availability losses.

The oil price has been historically high during the last decade. This means that shutdowns have generated very big losses in turnover/incomes. Traditionally, it is smart to allocate an uplanned failure to the next planned maintenance windows,

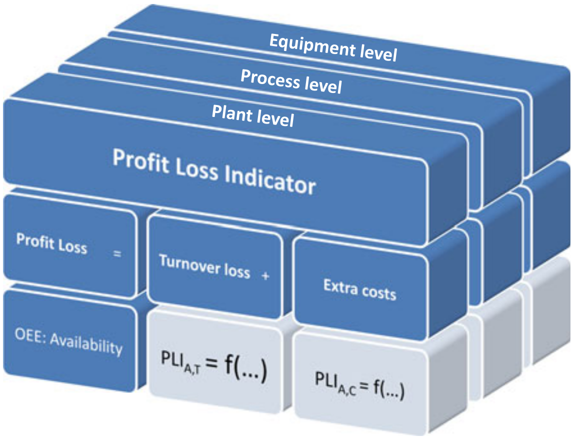

Fig. 1 PLI cube adapted from Rødseth et al. (2015)

with less focus on actual extra cost to keep the machine in duty. This because of extra costs in keeping the system up and running, was negligible compared to the high impact in turnover. The oil price have dramatically declined the last years, meaning that the oil companies have to focus more on costs than before.

4 PLI Calculations from Case Study

A typical gas export system on an offshore platform consists of a gas turbine, gear and a gas compressor. This is the major components. The gas compressor sends the gas to the export pipe line. This system is classified as a critical system regarding production. If a failure occurs in this system, the gas compressor train will stop, hence no gas will be exported. A stop in the gas export system will stop the incomes. Therefore, it is very important to keep the system running at all times. The integrity of this system is taken care of by having a good maintenance programme. In this case there will be focused on the gas turbine. Figure 2 shows a typical offshore gas compression train and the specific turbine that is of interest in this article.

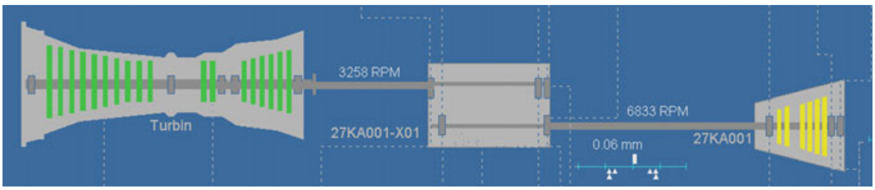

Fig. 2 Typical offshore gas compression train from Statoil

Table 1 PLI calculatioins from case study where numbers are in million USD

Year	1	2	3	4	5	6	$NPV_{PLI\_Reduced}$
	2.5	2.5	2.5	2.5	2.5	2.5	≈10.9

The gas turbine consists of the turbine itself and several auxiliary systems, and is the heart of the gas export system. This involves many disciplines such as rotating, static, process, instrument, technical safety and electro, in addition to operations and maintenance. This comprise in total a complex system, with many stakeholders when decisions shall be made.

The maintenance philosophy for offshore gas turbines is to keep the planned maintenance at a minimum, while at the same time keeping the risk for unplanned maintenance as low as reasonably possible. This can be regarded as a contradictory decision-making. If an unplanned failure occurs, it is always a question if the repair can be postponed to the next planned maintenance window, depending on the failure mode and criticality. The maintenance interval for offshore gas turbines can typically be 2000–6000 h, depending on type, configuration, environmental conditions, redundancy etc. Table 1 shows the PLI calculation based on Eq. 2 when the maintenance programme has been updated from four maintenance activities each year down to three maintenance activities each year. The NPV of the reduced PLI is from the case calculated to be 10.9 million USD. The reduced PLI Cash Flow (CF) is the reduced PLI due to reduction of one maintenance activity each year, in time t. The internal interest rate i, is set to be 10 %. In the PLI calculation, it is only the turnover loss in availability which has been calculated. Furthermore, the input data for the PLI is not accurate due to anonymity, but should still be considered to be realistic.

$$NPV_{PLI\_Reduced} = \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} \quad (2)$$

5 Discussions and Final Conclusions

This article has demonstrated PLI calculations in the O&G industry. In order to justify the investment of updating the maintenance programme, the NPV of the reduced PLI shown as a gain in Table 1, must be significant larger than the expected investment cost for updating the maintenance programme. The article also demonstrates how PLI is calculated for a relevant issue concerning a strategic decision-making. This type of decision involves an integrated plan for both the maintenance and production disciplines and is therefore relevant for IPL.

In order to calculate the PLI it is of importance to have access to relevant databases for several disciplines such as computerized maintenance management systems, process and control systems, production planning systems and financial databases of oil prices.

It is concluded in this article that PLI is an important tool for strategic decision-making in IPL. The calculation of PLI based on the case is also of interest for Statoil in order to further evaluate PLI as decision tool in their own organisation. In future research more cases of PLI calculations should be performed in order to demonstrate other theoretical strategic aspects of PLI.

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Public Asset Management—Concept and Framework for Public Schools with the Life-Cycle Costing Model *Reversed LCC*

Erling Salicath and Jayantha P. Liyanage

Abstract The public sector in Norway is often challenged to improve the management of public sector assets with due focus on life cycle—and maintenance. In order to contribute to the life-cycle process, this paper brings the Life-Cycle Costing (LCC) framework Reversed LCC utilizing Depreciated Replacement Cost (DRC), Factor, and Monte Carlo-methods. The tool targeted some newly constructed or renovated schools, to highlight the possibility of accelerated depreciation for construction elements and technical equipment, based on how rates in operating leases correlate with the useful service-life. This can help simulate different rent-scenarios, for instance; 'rent up to date' with underfunded maintenance budgets, and 'activity-based rent' with activity-based rates in their leasing operations by including upgrading- and development costs. The paper underlines the usability of Reversed LCC as a decision basis for public sector assets with specific focus on public schools.

1 Introduction

Asset management is an emerging multi-disciplinary and professional engineering practice, and its practical impact has begun to develop rapidly. Public asset management is a specific field of management, including assets of public interest such as educational buildings, public housing, roads, tunnels, railways, airports and water-supply networks. Management of such assets are quite challenging in nature

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due to complex decision processes and multiple stakeholders. These respective public assets can greatly benefit from proper analytical techniques, which provide a decision basis for an effective life-cycle management practice. Hence, this paper emphases an analytical framework based on life-cycle costing (LCC) for public assets in Norway. This framework was part of a project conducted in close cooperation with the municipal agency Undervisningsbygg Oslo KF[1] (UBF) and had a specific focus on the development of a specific LCC-framework for public schools. This paper presents the resulted asset management-tool *Reversed LCC*, and discusses its practical relevance and usability as a proper decision basis in the public sector.

2 State of the Art—LCC in Norway

LCC in Norway started with the Association of Consulting Engineers (RIF) in 1978, who looked at the economical concept "Annual costs", i.e. the annuity of life-cycle costs. A milestone for LCC in Norway is the national standard NS3454 '*Life Cycle costs for construction works—principles and Classification*' (1988, Revised in 2000 and 2013), and '*annual costs—Calculation guide for buildings*' (Thorsnes and Bjørberg 1993). Statsbygg, Directorate for Building Quality, BuildingSmart Norway, LCC Forum—Network for LCC and Life Cycle Planning, Norwegian Facilities Management Association, and the Agency for Public Management and eGovernment are key contributors within the development of LCC in Norway. A Norwegian cost-database (found at www.norskprisbok.no) was updated in 2015 with LCC-costs, by adding the maintenance and replacement intervals for all building materials inside the building frame.

Thorsnes et al. (2001) has discussed a pre-project that presented the state-of-the-art on LCC in Scandinavia. The goal was to plan how to proceed with the development of LCC to design a common LCC-tool, which can easily be adapted to national cost-standards. The project explicitly stated that the LCC-method has matured in Norway compared to the four other countries in this project (Denmark, Sweden, Iceland, Finland), and that Statsbygg developed an Excel-model (see www.lccweb.no), which made it possible to perform a "whole life-cycle cost analysis" with input of cost-data for specific cost-categories. The municipality of Oslo along with UBF published an LCC-standard for public schools in 2012, Felles Kravspesifikasjon Oslo kommune *Miljø og livssykluskostnader*

[1]Undervisningsbygg Oslo KF (UBF) is a municipal agency in Oslo municipality, who has a portfolio of public property equal 177 Schools and about 750 Buildings in total. Core business operations are Development, Maintenance, Construction and Upgrading of schools.

Table 1 Unique challenges within asset management in the municipality of Oslo

Factor	Relevant issues in the municipality of Oslo
Power and politics	Largely distributed responsibilities across many stakeholders, the balance of long versus short term incentives for long-term utilization planning and maintenance, capital rent is based on P50-cost estimates—not actual cost, diverse practices of 'purchaser-provider model' regarding how efficient agencies can operate their budgets and decision processes
Finance	The ministry of education has the mandate to order projects from the landlord, which in practice can cause conflict of interest with regard to project-cost estimates and the time-schedule; the basic need of increased capacity and financing for specific schools is prioritized rather than upgrading/renovating existing schools; diverse financial decision criteria among involved agencies can lead to suboptimal investment decisions and high process costs lead to an ineffective communication-flow
Culture	Relative high degree of bureaucracy, public leadership culture, distributed accountability

(FKOK 2012), which includes a service-live reference for relevant construction elements, environmental requirements, required LCC-data and a detailed description on which costs should be assigned to respective cost-elements according to NS3454:2000 (FKOK 2012 have not adapted the guidelines in the updated NS3454:2013, but recommends practitioners to use the newest national LCC-standard up to date).

2.1 *Challenges with LCC in the Municipality of Oslo*

With regard to politics, finance and culture within asset management practices, Table 1 briefly presents certain general challenges related to life-cycle practices in the public management of assets.

2.2 *Specific Features of LCC for Public Schools*

The use of LCC has its greatest potential during the implementation of engineering-design (early project phases and feasibility studies), which has a significant impact on potential cost drivers (Emblemsvåg 2003; Barringer 1998; Kayrbekova 2011; Fabrycky and Blanchard 1991; Schade 2009; Korpi and Ala-Risku 2008; Ruitenberg et al. 2014; Fuller and Petersen 1995). Seven relevant features for LCC-thinking for public schools are highlighted in Table 2.

Table 2 Relevant features of the LCC-mindset

• Analyze long-term investment scenarios (e.g. upgrade existing assets or dispose and construct new buildings)
• Choose the cost-optimal design, where all alternatives meets the performance criteria
• Estimate development- and upgrading costs to cover the tenants future needs
• Redefine political decision criteria with respect to actual requirements and functionality in an LCC-perspective to define optimal utilization and capacity
• Continuous evaluation of maintenance- and operational needs and the financial effect of decisions on the residual value
• Apply Activity-based LCC to differ overhead- and direct costs, and calculate activity-based rates to cover all necessary activities through the lifetime of lease agreements
• Concise life-cycle framework if the mean service-life for exteriors, interior and technical equipment cannot be greater than 40 years due to accounting regulations

2.3 *Activity-Based LCC-Method*

Activity-based costing (ABC) provides a framework on how to distribute overhead-costs accurately and highlight cost drivers in life-cycle activities. ABC suggest that changes in resources indirectly changes cost elements by directly changing the consumption of activities (and vice versa). This method can be applied to public schools when buildings are defined as unique physical products. Table 3 defines five cost-levels in accordance with the ABC-framework.

Table 3 Activity-based cost categories

Cost level	Brief description
Level 1. Cost-category	NS3454:2013 includes relevant cost-categories for LCC-analyses in Norwegian construction projects
Level 2. Cost-element	NS3454:2013 includes relevant cost-elements
Level 3. Define tasks for each cost-element	The cost-element “maintenance cost” is used as a simple example. Relevant tasks for maintenance of construction elements such as the building-frame (windows, doors, floor etc.), playground, interiors, security barriers and other relevant construction elements should be specified for a realistic LCC-analysis
Level 4. Define activities for each task	Relevant activities can be inspection-routines, cleaning-intervals and sanitation of hazards with regard to environmental issues
Level 5. Cost of resources in each activity	Activities (such as inspection routines) consume resources, and changes in respective activities have influence on cost-elements

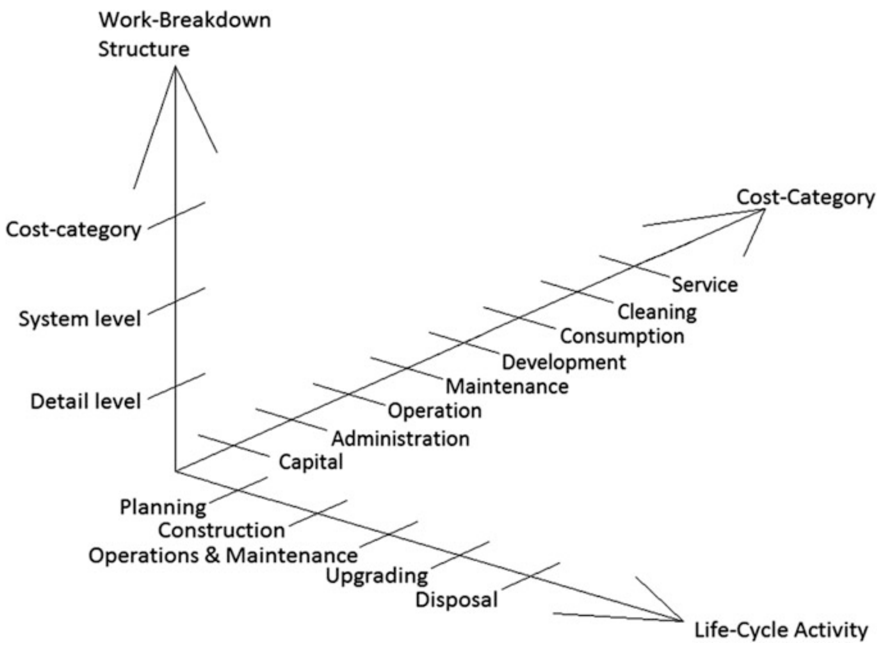

Fig. 1 LCC-concept: relation between WBS, life-cycle phases and cost-categories

Figure 1 illustrates the relation between Work Breakdown structures, LCC-categories and life-cycle phases. The sum of all relevant cost categories gives the final LCC. The WBS can be divided into specific construction elements (system level) and further into relevant activities (detailed level) for the cost categories.

3 Framework for Public Assets with *Reversed LCC*

3.1 Equations Used in Reversed LCC

The Reversed LCC in principal comprises the 3 major components of; Net present value of LCC, Estimated residual value, and Estimated service life. The equations are highlighted in Table 4.

The equations in Table 4 assume public schools are not exposed to the open market and that operating leases are renewed after 25 years. Plimmer and Sayce (2006) outlines the DRC-method; the only difference in this paper is that Eq. (2) in Table 4 takes into account capitalized costs due to upgrading of assets before renewal of the operating leases. *Reversed LCC* uses Monte Carlo simulation and Beta-PERT distribution for relevant factors and cost-elements.

Table 4 Equations used in *Reversed LCC*

$LCC = \sum_{0}^{N} \frac{C_t}{(1+d)^t}$	(1)
LCC—net present value of life-cycle costs *N*—number of years (e.g. $N = 25$ years means $t = 0$ up to $t = 25$ in the cash-flow) C_t—sum of life-cycle costs associated with year *t* *t*—specific year in cash-flow from year 0 up to year *N* *d*—discount rate adjusting cash-flows to present value	
$R = \frac{\sum_{1}^{n} Y_n - X}{Y_n} * Z$	(2)
R—estimated residual value *X*—analysis period—length of rent for tenants of public schools in Oslo is 25 years Y_1—estimated service life for original asset $Y_2 + (\cdots) + (Y_n)$—estimated service life for upgraded or replaced assets *Z*—real value of asset up to date	
$ESL = RSL * A * B * C * D * E * F * G$	(3)
ESL; RSL—estimated service life and reference service life respectively A; B; C; D; E; F; G—quality of component, design level, work execution level, indoor environment, outdoor environment, in use condition and maintenance levels respectively	

3.2 *Suggested Approach for LCC-Analysis of Public Assets*

Figure 2 presents a framework illustrating the input of relevant LCC-data and the output from the cash-flow simulation in *Reversed LCC*.

Certain relevant costing methods are traditional costing, activity-based costing and target life-cycle costing. Relevant LCC-data are: price-development index; discounted bank-rate; existing book value; life-cycle costs (capital costs, operating costs, upgrading costs, other costs); analysis period; factors in Factor-method (see Eq. 3 in Table 4). Upgrading costs and service lives is estimated for both scenarios. Rates in the existing operating lease is plotted in Scenario 1. Activity-based rates is estimated in Scenario 2. The net present value (NPV) is calculated respectively for Scenario 1 and Scenario 2 (see Eq. 1 in Table 3).

Stochastic simulation (e.g. Monte Carlo simulation) is utilized for relevant factors and cost elements with suitable probability distributions. Beta-PERT—or triangular distributions is recommended in *Reversed LCC*; the financial effect of changing the rates in operating leases to activity-based rates is simulated by comparing Scenario 1 and Scenario 2 (NPV in Scenario 2 minus NPV in Scenario 1). The asset-decision depends on the executive's strategic goals; results can be used to consider whether to upgrade or dispose public assets, or change the rates in operating leases.

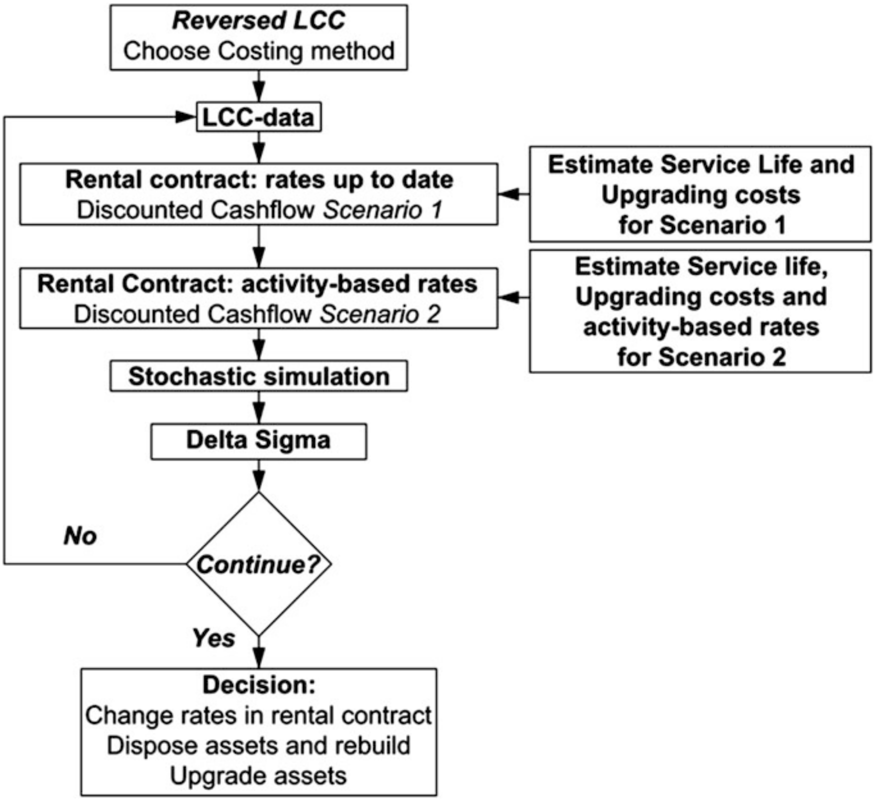

Fig. 2 Framework for *Reversed LCC*

4 Discussion

Public sector is fundamentally different compared to private sector, partly because political factors affect resource allocation, agencies respond to the treasury with limited resources (Winch 2010), and public projects are of public interest. LCC should therefore be utilized as soon as reasonably possible for strategic analysis of public assets' requirements to meet the needs of involved stakeholders (maintenance and operational activities should adapt the strategic and operational goals). The LCC-framework presented in this paper is relevant for public assets in practice, particularly because long term consequences are highlighted due to underestimated budget consumption behaviors (e.g. unforeseen maintenance- and upgrading needs) and lack of continuous public funds towards critical operational activities spanning through the life-cycle of respective assets. *Reversed LCC* is flexible, and can be customized for specific public assets (e.g. school projects), which means that cost managers can easily change cost elements and simulate different scenarios as required according to the type and scope of needs.

5 Conclusion

Activity-based costing has interesting benefits for the public sector, including the adaptability to accurately distribute overhead-costs, highlight cost drivers and calculate activity-based rates in the operating leases. The suggested framework in this paper uses factors in the factor method and residual values as performance based LCC-parameters that can be used to analyze service-life costs of public assets, e.g. correlation between maintenance levels, upgrading costs, and degradation mechanisms. The framework can potentially improve life-cycle practices based on LCC-analysis to calculate necessary change of rates in the operating leases to an activity-based level. This does potentially release tied up-capital, even after the first few years during the service life. *Reversed LCC* can be further developed to simulate optimal asset utilization decisions, which is highly relevant for the public sector.

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Activity-Based Life-Cycle Costing of Public Assets: A Case Study of Schools in Norway

Erling Salicath, Jayantha P. Liyanage and Didrik Fladberg

Abstract ‘State of the Nation 2015’, a Norwegian nation-wide report created by RIF (Association of Consulting Engineers, Norway), concludes that the maintenance backlog for around 30,000 municipal buildings is approximately 1060 billion NOK. Undervisningsbygg Oslo KF (UBF), established in 2002 as a municipal agency, has on the contrary reduced their maintenance backlog with alternative funding of maintenance costs through operational initiatives. Based on the Life-Cycle Costing (LCC) tool Reversed LCC, this paper presents key findings from a study on public asset management, involving case studies featuring four public schools in the municipality of Oslo. This paper concludes that the municipality of Oslo can potentially reduce life-cycle costs based on the recent implementation of activity-based rates in the municipality’s leasing operations between UBF as the landlord, and Utdanningsetaten (UDE) as the tenant. The paper also highlights recommendation of strategic measures for UBF that focuses on activity-based rates for public schools as a measure to enhance the utilization value of public assets over a long period of time.

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1 Introduction

Life-cycle analysis has a considerable practical importance within the field of Asset management. For instance, highly industrialized countries such as Japan, Norway, Switzerland, UK, USA, etc. have been utilizing Life-Cycle Costing (LCC) methods within specific fields of asset management for various applications both in public and private sectors. 'LCC Forum', created in 2011, is a recent example of a national effort to develop knowledge related to LCC in the Norwegian industry. Through the years, LCC has become an important decision tool and requirement for relevant stakeholders. The public sector in particular can largely benefit from using such techniques to help support internal decision processes (e.g. IISD 2009). This paper explores the life-cycle processes further, focusing on school buildings in the municipality of Oslo.

Chapter 2 highlights certain public asset management practices in Norway, with specific focus on the purchaser-provider model and the life-cycle process for public schools in the municipality of Oslo. Chapter 3 displays relevant case-study data: LCC-data and the factors used in accordance with the factor method. Chapter 4 presents results from the LCC-analysis for the case-study. Chapter 5 recommends strategic measures for UBF, with a general focus on LCC and leasing operations. The discussion and conclusion highlights the importance of proactive maintenance; an activity-based LCC approach is potentially a valuable strategy toward a value-added life-cycle process.

2 Public Asset Management Practices in Norway

2.1 Public Stakeholders' Impact on Public Assets

In general, management of public assets is a relatively demanding process due to complex roles of stakeholders and specific demand-supply patterns. This is particularly visible within economical and operational processes. For instance, in the Oslo region, the investment framework is subject to the purchaser-provider model. The investment decision is separated from the operational and asset management side of UBF to various degrees. This framework does not necessarily lay the foundation for optimized LCC-driven decisions for the municipality as a whole, and UBF in particular. In other words, Utdanningsetaten (UDE) has the sole authority to initiate investment decisions with no responsibility for maintenance, while UBF who has the responsibility of maintenance have no authority to initiate investments in their approach to maintain real asset value.

Table 1 Life-cycle phases for public schools in the municipality of Oslo

Project phase	Brief description of life-cycle phases
Planning/initiation	UDE is responsible for the project objectives and defines the project-scope: *what, where when and conceptually how* to do it. Involvement from UBF during the pre-study happens only upon formal request by UDE. The local government has the mandate to select projects—UBF execute directly from the *pre project* order, without direct involvement in the concept and feasibility study
Execution/implementation	The governing body of Oslo evaluates the project cost with a P50-estimate (equal probability of 50 % the cost will be higher or lower), based on an external *quality assurance 2*. The P50-value is the available project funds for UBF. The local government has the mandate to decide whether UBF can increase their budget to the P85-estimate (the cost-frame between P50 and P85 is a contingency reserve, and is defined after the *quality assurance 2* process)
Delivery/operational phase	UBF (property owner) delivers the project output to UDE (tenant). The property department in UBF has the mandate to manage rental contracts, and maintain- and operate the asset portfolio
Upgrade	Public property must be developed and assets upgraded sometime during the assets useful life to adapt technology and societal needs
Disposal	The school is disposed/liquidated and either replaced with a new school or other type of building

2.2 *Life-Cycle Phases for Public Schools*

The life-cycle of public schools in general consists of five major phases: project planning, execution, operations, upgrading and disposal/liquidation. Table 1 briefly describes certain parts of these phases related to responsibilities, calculation of project costs and operating leases for the municipality of Oslo.

3 Introduction of the Four Case Studies

The case study includes LCC-analyses of four school buildings located in Oslo. In this paper, each school has been anonymized as: (A), (B), (C) and (D). Their size and operating scales are given in Table 2 using the term operating expenses (OPEX) for the rates in existing public lease agreements.

As the initial case data revealed, the potential cost drivers for schools include common regulations for Oslo municipality (FKOK), and cost of project- and site managers due to a large amount of documentation and quality requirements (e.g. specific performance criteria on air-flow in ventilation and interior walls).

Table 2 OPEX up to date in the four cases (Salicath 2015)

School	Area (m^2)	OPEX (NOK/m^2)
(A) Rehabilitated 2014	11,687	364
(B) Rehabilitated 2012	11,115	338
(C) Newly built 2013	32,280 (excluded 10,000 m^2)	380
(D) Newly built 2014	8816	359

Table 3 Specific life-cycle cost categories relevant for public schools

Cost-categories	Activities related to cost-category
Investment cost	Acquisition, feasibility study, development, design and construction
Management costs	Asset management activities (insurance, asset plans/action plan, contracts etc.) and other management costs connected to core business operations
Operating costs	Operational activities connected to core business operations and administration costs
Maintenance costs	Maintenance activities connected to core business operation
Overhead costs	Energy costs, municipal taxes and interior maintenance costs, which do not directly contribute to core business
Upgrading costs	Increased capacity, such as extended service-life or added functionality. This cost element is capitalized and depreciated
Residual value	In accounting terms, the "residual value" is the market value of assets after they are fully depreciated, end of its lease or after the end of its useful life

Observations suggested that Case-(A) is exposed to rough use. Case-(B) has many local activities not related to education, which might cause an accelerated reduction of the useful service-life. Case-(C) can be seen as a complex project with diverse technical equipment due to school regulations that can become a cost driving factor through the life-cycle. The building design of Case-(D) specifically focused on reducing life-cycle costs, which means this school in theory requires a lower activity-based lease compared to the three other schools. This study took into account life-cycle cost categories relevant for public schools as shown in Table 3.

3.1 LCC-Data for the Case Study: Activity-Based Rates, Factor-Method, Cost-Data and Upgrading Costs

The case study includes cost-data, which is based on the cost-categories in Table 3; the capital cost equals the investment cost; management, operating, maintenance and overhead costs are granted through the operating lease. The Activity-based OPEX is the necessary rate to fully depreciate the capital cost (depreciation and interest rates) through its accounting period, and to manage the quality of the assets to stay above a minimum quality-level through the planned life-cycle. The residual value and upgrading costs is calculated based on the capital

Table 4 Activity-based OPEX in the four case studies (Salicath 2015)

School	(A) (NOK/m^2)	(B) (NOK/m^2)	(C) (NOK/m^2)	(D) (NOK/m^2)
Intensity	Medium/high	Medium/high	Low/medium	Low
Activity-based OPEX-rates	608	587	531	447

cost, factor method and remaining service-life after the first 25 years of the buildings' life-cycle, which is the length of the public lease agreements in the case studies.

Table 4 displays the estimated activity-based rates utilized in the case study, based on low-medium-high rates in UBF's activity-based cost matrix. The estimated activity-based OPEX-rates are chosen based on the required maintenance-intensity, labeled 'Intensity' with a low-medium-high rating, for each case.

Factor analysis is a main research method and statistical technique, which can be used to reduce the amount of data into relatively independent factors. The case study utilized the factor method with one factor for each relevant cost-element, which is based on seven relatively independent factors that correlates with the service-life of buildings. Since the length of the service-life can greatly influence the size of upgrading costs, the input of factors can have a great impact on the LCC-analysis, especially because an extended service-life of 5 years does potentially reduce the total life-cycle cost significantly, even though this requires an increased funding toward OPEX-rates and specifically maintenance activities.

The case study achieved a more realistic LCC-analysis by setting an interval for the factors between 0.8 and 1.1. Factors between 0.8 and 1.0 translates to a 'negative effect' (reduced service-life), while factors between 1.0 and 1.1 translates to a 'positive effect' (extended service-life). In this case the 'negative effect' is assumed to have a greater impact on the useful service-life, compared to the 'positive effect', which is why the interval 0.8–1.1 is utilized. Relevant literature discusses practical issues related to the case study and the factor method (e.g. Marteinsson 2005; Listerud et al. 2011; McDuling 2011).

The factors for the case studies are given in Table 5. A character-grade system 1–10 was used; 1 worst and 10 best; the character-grade '5' does for example equal

Table 5 Factors gathered for the four case studies (Salicath 2015)

Cost-element	(A)	(B)	(C)	(D)
Exterior closure and exterior wall	10–1.0	7–0.88	7–0.88	10–1.0
Foundation	10–1.1	10–1.1	10–1.1	10–1.1
Structural frame	10–1.1	10–1.1	10–1.1	10–1.1
Interiors	5–0.8	6–0.84	8–0.92	10–1.0
Equipment and furnishing	6–0.84	6–0.84	5–0.8	10–1.0
HVAC	7–0.88	6–0.84	6–0.84	10–1.0
Automation (automatic operators)	6–0.84	7–0.88	5–0.8	10–1.0
Electricity	10–1.0	8–0.92	6–0.84	10–1.0

Table 6 Approach for factor method and estimating upgrading costs (Salicath 2015)

Scenario	Rent up to date		Activity-based rent	
	Upgrading cost	Factors	Upgrading cost	Factors
1	70 % of acquisition cost	Table 5	70 % of acquisition cost	1.0/1.05
2	70 % of acquisition cost	Table 5	40 % of acquisition cost	1.0/1.05

a 50 % reduction of the service-life compared to the reference life, but does still equal the lowest possible factor 0.8 as displayed in Table 5.

Two scenarios are illustrated in Table 6 with estimates on upgrading costs, and factors for the 'rent up to date' and 'activity-based rent. The upgrading cost is estimated with a percentage of the original acquisition cost. Four results are generated in total: the factor 1.0 is manually plotted in the 'activity-based rent' for scenario 1 and 2; then a manual input of the factor 1.05 is separately plotted for both scenarios respectively in the 'activity-based rent' (displayed as '1.0/1.05' in Table 6). Factors for 'rent up to date' as displayed in Table 5 remains unchanged in all cases; the factor 1.1 for the cost elements 'Foundation' and 'Structural frame' remains the same in all scenarios.

4 Results

4.1 LCC-Results from the Conducted Case Study

Table 7 presents the results generated by *Reversed LCC* (Salicath 2015; Salicath and Liyanage 2015). The *P50-* and *P85 Delta Sigma* values were extracted. The P15-value is useful when highlighting the risk associated with increasing OPEX-rates. This value is not taken into account due to the difficulty comprehending uncertainty and risk, which can become too theoretical for practical relevance.

Monte Carlo simulation for P50 and P85 gives an approximated total NPV (Net Present Value) of 8–17M NOK for the four cases in Table 7. This indicates a potential to release tied up-capital annually for 25 years. Excluding (C), the total

Table 7 Result from LCC-calculations in Reversed LCC (Salicath 2015)

School	(A) (NOK)	(B) (NOK)	(C) (NOK)	(D) (NOK)
P50 Delta Sigma	530,000	8.7M	130M	550,000
P85 Delta Sigma	24.15M	32.1M	188M	17M
P50 Annuity	34,500	570,000	8.1M	35,000
P85 Annuity	1.57M	2.1M	12.2M	1.1M

potential saving is approximately 10–70M NOK in NPV for 25 years. In its current form, these results should only be used as base data for asset decisions. Sensitivity can be increased with incorporation of other forms of uncertainties, cost drivers and costs, either quantitatively or qualitatively.

5 Recommended Strategic Measures for UBF

This study generated some valuable insight about current practices of public assets, and 4 Cases elaborated the potential use of LCC. In general, based on the study, the following three recommendations were made for UBF.

- UBF should initiate an internal program to calculate activity-based cost rates for every public school in their portfolio for active use of different economical scenarios as decision base.
- UBF should prioritize increasing the rates in their operating leases up to an activity-based cost level (LCC-rates) for each public school in their asset portfolio. By doing so, the LCC-rate can become either lower or higher than the pre-defined rates in UBF's activity-based cost matrix. The activity-based cost matrix is the basis for operating leases signed *after* January 2014; this cost matrix is not applied to operating leases signed *before* 2014.
- The Property management department should communicate their requirements on LCC-rates, such as 'exterior maintenance', 'interior maintenance', 'operations' and 'energy' for each school. This mandate is reasonable in accordance with their competence and expertise on schools, regardless of the responsibilities and practices in the purchaser-provider model.

6 Discussion

The results presented in this paper suggest that a proactive maintenance strategy is a good measure to reduce life-cycle costs of public assets, particularly under complex development and utilization processes. Understanding accounting practices as well as technical aspects associated with aging assets is important to perform practical and realistic LCC-analysis. While the uncertainty of data is a well-known weakness with LCC-methods, this costing-method can provide an effective decision basis with additional quantitative or qualitative data; Monte Carlo simulation helps reduce uncertainty, but does not eliminate risks. Developing an optimal renovation and upgrading program, with a strategic focus on when- and how to allocate public funds toward maintenance- and upgrading costs is one example on how the LCC-method can be applied in practice. Combining strategic rehabilitation-programs with designed LCC-tools for public assets is a good approach to raise awareness about the importance and potentially improve asset management practices in the public sector.

7 Conclusion

The conclusion is that a proactive activity-based approach does potentially add value for public schools; this requires strategic awareness about the LCC-method to have relevance in practice. This strategic approach does fundamentally require a change in the OPEX-rates of UBF's operating leases signed prior to 2014, and their mandate to independently obtain funding for renovation and upgrading projects. Recognizing performance-based parameters and value-added activities is relevant for executives to implement strategies, and reduce both the risk of cost-drivers and external factors which affects the real value of assets. LCC-data can then be presented to demonstrate how strategic decisions impact the financial and operating effect of owned assets throughout the useful life, and highlight the funds needed to reach optimal life-cycles for schools from a portfolio perspective.

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Capturing Value-Added Processes During Service Life of Public Assets in Norway—Learning from ISO 55000

Erling Salicath, Jayantha P. Liyanage and Didrik Fladberg

Abstract Real estate projects are capital-intensive and prone to macro-economic changes in supply and demand. They are also associated with high overhead and direct costs in a Life-Cycle Costing (LCC) context. Buildings have a long life-cycle in a LCC-perspective; strategic asset management is as such a key element in sustaining the operational and technical standard of the building. The ISO 55000-series, based on PAS 55, provides guidance for asset management systems, including public assets. Based on the parent—and second paper, this third paper features the municipal agency Undervisningsbygg Oslo KF (UBF), who manages a portfolio of 177 schools and approximately 750 educational buildings, in a case study; data are gathered through a survey based on ISO 55000 and public value. The contribution of this paper is two surveys, which is designed to identify potential measures on how UBF can further optimize their asset management practice during the construction and operational phase of schools. Based on the results from the case-study, key-strategic improvements with reference to ISO 55000 is suggested for UBF's executives who has the mandate to invest in public assets. The discussion is connected to LCC as a required performance-based parameter for public assets.

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1 Introduction

The recognition of the need for professional asset management has gained increasing acceptance in recent years among practitioners from all over the world. Despite some major development-trends in the commercial sector, public organizations in general still have a potential to optimize their asset management strategies- and practices. Some of the best examples from the public sector are reported from Japan, Hong Kong, and Australia with a specific focus on public infrastructures. The pioneering work of Sendai municipality in Japan is an excellent example of a dedicated initiative, reporting considerable growth of public value based on the real use of ISO 55000.

The guidelines in the ISO 55000-series set a minimum requirement for assets and asset owners, and as such a significant potential for optimizing asset management processes in public organizations. The present paper elaborates on a study conducted in Norway regarding Public assets (in this case school buildings), and is designed for the public agency Undervisningsbygg Oslo KF (UBF) in the municipality of Oslo. The purpose is to identify value-added processes for schools, and thus learning from ISO 55000 by highlighting principal areas of value-driving potentials within UBF's current asset portfolio and asset management practices.

2 Added Value of Public Assets and Use of ISO 55000

The new standard ISO 55000 provides a generic set of principles suitable for most type of assets. Using this ISO-standard as a governing framework for different asset types require suitable adjustments. This needs to be reflective and sensitive with regard to the value-adding processes. For public assets, the added value is largely influenced by political, social, and operational circumstances (see Fig. 1), which also influences the management style of public agencies.

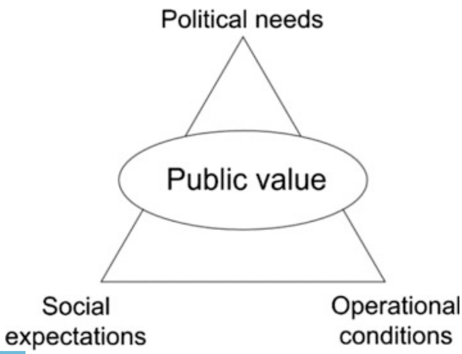

Fig. 1 Principal factors that influence public value

As Moore (2012), Moore and Khagram (2004), Newcomer and Allen (2010), Talbot (2008) discuss, public value primarily involves processes that include operations, politics, authority and legitimacy. The market is worth what the customer is willing to pay for; likewise, public value depends on the values, expectations and needs of the public stakeholders. One similarity between public and private sector, is the need for an asset management-tool to optimize utilization of assets through the life-cycle.

UBF as a public agency is driven by adding public value for schools through the whole life-cycle. This strategic approach is different compared to the private sector, which typically focuses on maximizing return on capital employed for shareholders. UBF's main concern is therefore how to integrate the time limited investment phase (acquisition, development and construction) with the long-term operational phase. ISO 55000 is to a large extent able to provide a useful template illustrated in Fig. 2 that can help support public assets and the management approach used by asset owners/operators.

The asset management process in public sector is unique and complex due to stakeholders' roles, responsibilities, authorities, and conflicting strategies. Based on ISO 55000 and the aspects of adding public value, relevant issues and the importance of phases displayed in Fig. 1 (*Strategy*, *Leadership*, *Operations* and *Monitoring and review*) are addressed in Table 1.

Fig. 2 Generic management template for public assets based on ISO 55000

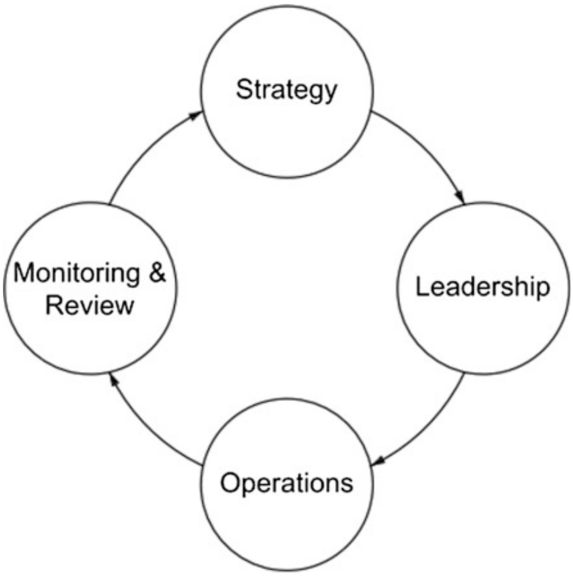

Table 1 Issues and importance of the generic management template based on ISO 55000

	Issues	Importance
Strategy	Optimize decision making processes based on politics, financial models and other strategic areas; e.g. communicating the strategy with due focus on creating public value (performance based incentives, political criteria's, contract strategies, development of employees etc.)	Developing the strategy is important to manage future business trends. A strategic focus on public value is essential to initiate value-adding processes through investment- maintenance- and operational strategies
Leadership	Employee behaviours and motivation, roles, responsibilities and authorities, integration of politics and business operations, organizational performances and operations (budget cutting, efficiency of resources, shortage of manpower, accountability of public services)	Dedicating leadership-commitment towards the motivation of relevant employees, and effectively manage available resources is important in accordance with the vision and cultural context. This is relevant in public sector due to employer-protection, and absence of significant financial incentives and fast promotions (Ferguson et al. 2014)
Operations	Development of life-cycle planning to optimize the ratio between life-cycle costs, risks and performances within a controlled environment	Goals are achieved through managing and distributing available resources between operational activities, which must meet technical requirements
Monitor and control	Review and control how the operational conditions meet the public assets' objectives, strategies and social expectations, evaluation of risks and consequences	Processes that identifies which risk factors are relevant within the asset management system is relevant to further direct optimization of operational processes, where social expectations is an important factor for politicians

3 Results and Recommendations

The survey was conducted within UBF and divided into two separate parts; part-1 was for the top management, while part-2 covered leaders, project leaders, asset managers, operational managers, advisors, developers and other engineering managers. The survey is anonymized with a summary of the weighted average. Both surveys were analysed qualitatively with the goal of drawing conclusions based on empirical data. The survey covers some of the issues addressed in Table 1. Specific recommendations based on ISO 55000 is presented in Sect. 3.2.

3.1 Results Emerged from the Survey

Table 2 presents the weighted average of survey 1 and 2. From a quantitative perspective (assuming 2.5 is average) UBF is to some extent above average, but the

Table 2 Weighted average of Survey 1 and 2

Survey 1	Weighted average	Survey 2	Weighted average
Question 1	4.0 of 5	Question 1	3.29 of 5
Question 2	4.0 of 5	Question 2	3.12 of 5
Question 3	3.6 of 5	Question 3	4.02 of 5
Question 4	3.0 of 5	Question 4	3.38 of 5
Question 5	See[a]	Question 5	3.27 of 5
		Question 6	2.97 of 5
		Question 7	3.16 of 5
		Question 8	See[a]

[a]According to question 5 in survey 1 and question 8 in survey 2, Table 3 presents findings concerning the most relevant processes that influences public-value

qualitative data address issues that suggest UBF has room to improve asset management processes with regard to the questions.

These factors should be aligned with political goals and communicated with tenants. The results from the survey does indicate that an improved focus on UBF's asset management strategy and implementation of their asset management system is necessary for UBF to reach their potential on improving the quality output of asset management processes, and be able to develop- and capture public value through the constructional- and operational phases.

3.2 *Specific Recommendations for UBF*

Based on the surveys, UBF is recommended to focus on the following sections in ISO 55001, to improve their asset management processes:

Section 5 Leadership and commitment

> Leaders have a responsibility for processes, which must perform and meet the strategic requirements, political regulations and asset management goals. One of the important leadership qualities is an agreement of a strategic platform and shared commitment among leaders who are responsible for executing strategies into operational activities, which must be consistent with the policy and objectives of the organization.

Table 3 Relevant factors influencing public value

• Reduce operating costs without reducing quality (for example with Kaizen costing, which is a control technique of managing actual costs compared to the preset cost standards)
• Increase funds towards maintenance and upgrading costs to increase the quality of technical equipment and building components, including extended service-life, reduced down-time etc
• Organize and gather asset-data to document operational needs (maintenance- upgrading needs etc.) in accordance with political and social expectations
• Utilize LCC-tools to improve the decision-basis by calculating the cost-optimal investment in accordance with the principal factors that influence public value
• Continuously develop the competence of employees with concise job descriptions
• Effective communication of the asset management system between departments and sections to manage and deliver a high quality public services within maintenance- and operational processes
• Develop a strategic rehabilitation program for schools to optimize upgrading-intervals and disposal of aging assets in the asset-portfolio

Section 7.4 Communication

UBF have potential to improve their communication tools for leaders to continuously build organizational awareness about their measurable asset management goals, their plans to execute defined strategic goals and how their asset management processes are aligned with their policies. ISO 55002 gives guidance on communication plans, which should include specific reasons for how the implementation of activities and programs is collectively, or individually beneficial for stakeholders, and how relevant political implementations have an impact on assets. FutureBuilt (http://www.futurebuilt.no) is a relevant example for schools; the positive effect should be communicated with involved stakeholders.

Section 9.1 Monitoring, measurement, analysis and evaluation

ISO 55000 is concerned with what should be monitored and measured, when to monitor and how to measure, which methods to utilize to generate valid results, and when results shall be analysed and evaluated. UBF should evaluate and report the effectiveness on managing risk factors for schools.

Evaluating all risk elements, and estimating realistic consequences and improvements are important factors to manage risks of their critical assets at an acceptable level. UBF can successfully evaluate risks, where the leaders must align their ideas with the department and communicate acceptable risk-profiles vertically within its organization to avoid individual bias. Evaluation of relevant risks is also necessary to meet the requirements in *Section 5 Leadership and commitment*.

Section 9.2 Internal audit

Evaluating critical information within the asset management system is necessary to document activities in processes that are not aligned with the asset management system; examples are evaluation of the working condition, to what extent human resources meet licensing requirements and expected competence with relevant tools, and monitor and control of relevant risk-elements. Since the basic goal with internal audits is to correct and prevent unconformities in processes, the audit itself should focus on the performance output of asset management processes, not on specific performances of employees within the relevant processes. The guidance provided in ISO 55000 can potentially improve UBF's effectiveness of their audits.

4 Discussion

The parent paper focused on the conceptual level of LCC (Salicath and Liyanage 2015), while the second paper presented a case-study, which included practical LCC-analysis of four schools (Salicath et al. 2015). This paper focused on public value for public assets and life-cycle planning for schools in this case. LCC applied to political decision-making processes adds public value throughout the life-cycle economy by identifying all relevant capital costs, and operating expenditures. UBF will benefit from communicating how performance-based LCC-data meet public stakeholders' requirements due to a possible increase of authority and greater influence on decision-making processes. This authority should be utilized to highlight how the asset management system can be improved through strategic, operational and financial measures, such as changing incentive-structures in contracts and formalizing specific processes on gathering asset-data.

UBF should also communicate their need for a sustainable life-cycle economy more effectively by describing complex building-related issues and explain explicitly how lack of maintenance funds have a negative impact on the useful life of their assets. Due to the political and financial nature of life-cycle planning in the public sector, LCC should be an incentive-mechanism in itself, which will help relevant stakeholders understand the underlying problems and risk factors in physical assets. Since an asset management system is necessary to improve and formalize relevant processes through the life-cycle, UBF can learn from ISO 55000 and adapt specific guidelines in accordance with their organizational body, to identify potential improvements and optimize public assets' operational performances.

5 Conclusion

The survey, designed for UBF, identifies leadership, communication, control-mechanisms and auditing as potential improvements within the asset management process. Therefore, a necessary ability to capture and utilize public value is by understanding how the political decision-making processes have an impact on UBF's operational conditions in accordance with the influential principal factors (politics, operational conditions, social expectations). Understanding UBF's operational needs is necessary to improve processes within the political and bureaucratic environment, which either can undermine or support the ability to maintain a sustainable life-cycle economy. UBF is recommended to evaluate and take into account the definitions in the ISO 55000-series, and apply measures aligned with the survey, which should support and further advance their asset management system.

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Downtime Costing—Attitudes in Swedish Manufacturing Industry

Antti Salonen and Mohamad Tabikh

Abstract While the process industry, generally shows a high awareness on the financial implications of low availability, the manufacturing industry is still quite ignorant. The traditional setup of discrete item manufacturing systems has been fairly forgiving of low availability. However, by applying lean principles, the discrete item production system resembles process industry, regarding sensitivity to disturbances. Still, the awareness of the financial impact of downtime seems to be low in manufacturing industry. This is a problem since it makes it harder to justify costs for investments in increased availability. This paper presents a study of the view and attitudes towards the cost of downtime in Swedish manufacturing industry. The answers indicate that the respondents have rather vague ideas of the costs associated with downtime. Further, they rarely quantify the downtime costs that often associated with maintenance of production equipment. However, without any proper financial measures for downtime costs, the companies lack proper incentives for investing time and resources on the necessary optimization of their maintenance programs.

1 Introduction

The term downtime in manufacturing context is related to the period that a system or critical machine is unavailable due to planned or unplanned stoppages. Typical causes for unplanned downtime are e.g. equipment breakdown or lack of material. Planned downtime is associated with e.g. planned maintenance, setups, adjustments, inspections, shutdowns, training, breaks, cleaning, standby state, software and hardware upgrade or update (Muchiri and Pintelon 2008).

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There is a vast array of factors influencing the equipment downtime. Nepal and Park (2004) sort these factors into: human factors, company's strategy, projects, site, equipment, and management actions. Each of those factors has a significant effect on equipment downtime. For instance, equipment- related factors as the age, quality, operations complexity, and degree of usage have increased equipment downtime risks.

Several models for downtime costing have been presented in research. Typically, these models distinguish between the direct costs, i.e. labor, material, etc. and indirect costs, i.e. the consequences of recovery production (Naiknaware and Pimplikar 2013; Wiersema 2005; Crumrine and Post 2006; Gryna 1999; Fuerst et al. 1991). Further, Ahlman (2002) adds a third category, namely non-realized revenue. In order to connect the incurred costs to the downtime occasion, authors like Sondalini (2011) and Lincoln (2013) have developed costing models, based on Activity Based Costing. Ståhl et al. (2012) presents a part cost model that aims to connect the statistical analysis of downtime with those of costs. Fox et al. (2008) criticize the existing downtime models, stating that they seldom consider more than a subset of the cost and therefore lead to overly conservative estimations.

While the process industry, generally shows a high awareness on the financial implications of low availability, the manufacturing industry is still quite ignorant. One reason for this is probably that traditional discrete manufacturing industry has applied process layouts, allowing alternative routings of work through the production system. Further, the use of buffers between operations and fairly large storages of finished goods have effectively compensated for variations in production capacity.

Holmberg (2001) states that the use of automated and interrelated complex systems especially in the existence of lean manufacturing philosophy have made production equipment progressively vulnerable to risks and subject to frequent downtimes. However, the recurrent occurrences of downtime events and its diverse consequential effects are seldom undertaken in costing measures within manufacturing organizations. Each event of equipment downtime is very costly, since the production lines are associated directly to the efficiency and effectiveness of the individual machinery that forms the wholeness of production behaviors (Plant2Business report 2001; Fox et al. 2008). The inaccuracy of determining the real cost of downtime could lead to missing out on valuable opportunities for facility improvement.

Crumrine and Post (2006) found, according to experts' appraisal, that 80 % of industrial plants are incapable to estimate their downtime precisely and many of these facilities are miscalculating their total downtime cost by a factor of 200–300 %. The causality of this erroneous assessment is based on the fact that the downtime costs are hidden in other manufacturing cost areas. Too often the managers only emphasize on evaluating the direct cost of downtime and neglect the intangible costs, mainly constituting a large part of labor, overhead and product cost categories (Sondalini 2011). This is a problem since it makes it harder to justify costs for investments in increased availability. This paper presents a study of the view and attitudes towards the cost of downtime in Swedish manufacturing industry.

2 Methodology

The study is mainly based on a survey, with 69 respondents in Swedish manufacturing industry. Also, in order to obtain a good view of the scientific view of downtime costing, a literature survey was performed. The participants' rate and their positions were distributed as followings:

- 18.8 % of the total respondents' rate were financial managers
- 49.2, 13 and 18.8 % were production, technical and maintenance managers respectively.

The respondents represented the following type of manufacturing industries:

- 10.1 % of the participants represented metal and steel work industry
- 10.1 % were related to construction work
- 14.5 % within electrical engineering
- 65.2 %, from mechanical engineering industry respectively.

In the questionnaire, structured questions were adopted in order to allow participants to pick an answer from a set of listed possibilities. Also, an open-ended option was possible for enabling them to elucidate their opinions as intended.

3 Results

In the following section some results and findings obtained from the conducted survey are presented. The results are presented based on answers for 6 of the 13 questions (*Q1–Q6*) used in the survey.

Q1. *What is the level of knowledge of downtime costing in your company?*
The answers were mainly located within the range of 2 and 3, low to moderate item on Likert- scale with an average of 2.75, see Table 1.

Q2. *What is the estimated downtime ratio of the planned production time and of the total manufacturing cost and what proportion of the total downtime cost relates to planned downtime?*
In average, the respondents assessed the total downtime to count for 12.7 % of the planned production time with a financial impact estimated to be 22.3 % of the total manufacturing cost. Further, the planned downtime stands for 37 % of the total downtime cost.

Table 1 Assessed knowledge of downtime costing within the companies

Answers	1	2	3	4	5	Average
%	17.39	23.19	30.43	24.64	4.35	2.75

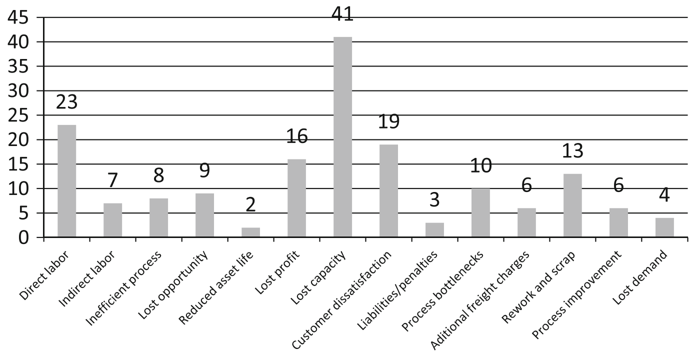

Fig. 1 Cost categories associated with downtime in the surveyed companies

Q3. *What are the main cost categories associated with downtime at your company?*
As shown in Fig. 1, lost capacity is the major cost associated with downtime, being nearly twice as big as the second factor; costs for direct labour.

Q4. *Select the main cause for planned stoppages at your company?*
The respondent's answers, presented in Fig. 2 clearly show that planned maintenance is the major cause for planned downtime in the surveyed companies.

Q5. *What is the cost of one hour planned/unplanned downtime?*
The answers varied quite a lot between 18–500 € for planned downtime and 40–5000 € for unplanned downtime, with averages of 180 and 890 €, respectively.

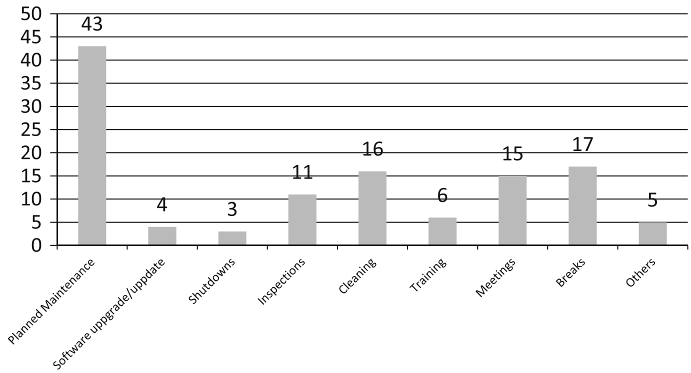

Fig. 2 Main causes for planned downtime in the surveyed companies

Q6. *Is there any systematic model used by the company for evaluating and quantifying the cost of downtime?*
Of the respondents, only 18 % used systematic models. However, due to the design of the survey it is not known what kind of models the surveyed companies used.

4 Discussion and Conclusion

The results presented in this paper are just a first sample from a minor study. Still, many arguable points can be drawn from these. What is obvious from the answers is that the respondents assess their organizations' knowledge within maintenance costing fairly low. This assessment is strengthened by the fact that only 18 % of the surveyed companies use systematic models for quantification and evaluation of their downtime costs. However, for the manufacturing industry it is often rather complex to determine the true value of downtime. While large parts of the process industry can assess the downtime costs, simply by multiplying the max capacity with the current OEE and the financial margin, the situation is rather different in discrete manufacturing. Often companies have mixed products in the same production line and varying production load. Attempts to quantify downtime in such production systems have been made, e.g. by Sondalini (2011), Lincoln (2013), and Ståhl, et al. (2012). However, these models are rather resource demanding to use, and require that the organization have vast formal knowledge of downtime costing.

Another interesting finding is the assessed costs of downtime. The answers varied extensively, between 18–500 € for planned downtime and 40–5000 € for unplanned downtime. This may be due to various business situations, but when taking the low awareness into account, there is a possibility that the organizations have little knowledge of the true cost of their downtime. Also, when comparing the average estimates, being 180 €/h planned downtime and 890 €/h unplanned downtime, it is apparent that the respondents typically assess the cost of unplanned downtime being five times as high as planned downtime.

According to the respondents, the cost of downtime is assessed to be about 22 % of the manufacturing cost. Of these costs, the respondents believe that about 63 % are related to unplanned downtime. This means that the manufacturing industry should be able to decrease its manufacturing cost by 7 % if the unplanned downtime could be reduced by half. Acting in a competitive market, e.g. the automotive industry, a 7 % cost cut would provide an essential contribution to the competitiveness of a company.

As stated before, the results, presented in this paper only provide indications of the attitudes on downtime costing in Swedish manufacturing industry. The intentions are that this survey should be broadened and also that an additional interview study should provide data in order to provide a deeper understanding of the attitudes and the challenges that the manufacturing industry have to face in order to increase the competitiveness of its production systems.

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Simulator-Based Eco-drive Training for Fleet Drivers

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Abstract This paper investigates the role of human factors, in particular driving behaviour, in managing fleet fuel consumption. The results presented are from the Driving Simulator Eco-Drive Training (DSET) project, a collaborative project with a municipal fleet in Ontario, Canada, to test the effectiveness of simulator-based training in eco-driving techniques. Likert-scale questionnaires assessed the drivers' self-reported motivation toward the training programme. In the six weeks following their simulator training session, we found that the average rate of hard acceleration (≥ 1.5 m/s^2) among all acceleration events decreased from 13.3 to 11.4 % and the average rate of hard deceleration (≤ -1.5 m/s^2) decreased from 10.5 to 9.8 %. Based on these reductions in average acceleration and deceleration, approximately 18 % savings in fuel consumption is possible.

1 Introduction

Vehicle emission is a major contributor of Greenhouse Gas (GHG) emissions worldwide. In the United States, personal transportation, along with household energy use constitute anywhere from 32 to 41 % of total Carbon Dioxide (CO_2)

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emissions (with CO_2 being the primary GHG) which is roughly about 8 % of the world total of CO_2 emissions (Barkenbus 2010). EUROSTAT Statistics Explained (2011) reported an overall reduction of 9.3 % in GHG emissions in the European Union (EU) for the period 2000–2009. However, the transportation sector was the only source that experienced an increase, contributing 20.2 % of GHG emissions in 2009, making it second behind the Energy Industries sector. In Canada, the trucking industry spends approximately $35 billion CDN in fuel costs per year, and road transportation is the second highest source of GHG emissions, behind the Oil and Gas sector, with a total of 204 Mt CO_2 equivalent per year (Government of Canada 2015). The industry is understandably looking for ways to reduce both fuel costs and emissions.

The life cycle of an asset, such as a pickup truck, has three phases; Acquisition, Operations and Maintenance (O&M) and Disposal. For fleet managers, 80 % of life cycle costs of an asset occurs in the O&M phase (Gulati 2015). The O&M costs of an asset may decrease with improvements in the design stage, such as advancements in vehicle design using lightweight material. In addition, the use of alternative fuels may improve fleet-wide fuel economy and reduce GHG emissions (Barkenbus 2010). Relevant to the present work, several studies have investigated the effect of eco-driving on fuel consumption, emissions, and traffic safety (Ericsson 2001; af Wahlberg 2007; Brundell-Freij and Ericsson 2005; Beusen et al. 2009; Barth and Boriboonsomsin 2009).

Eco-driving involves accelerating moderately, anticipating traffic flow and signals thereby avoiding sudden starts and stops, maintaining an even driving pace, driving at or safely below the speed limit and eliminating excessive idling (af Wahlberg et al. 2011). The advantages of eco-driving go beyond CO_2 reductions to include reducing the cost of driving to the individual and producing tangible and well-known safety benefits (fewer accidents and traffic fatalities) (Barkenbus 2010). Beusen et al. (2009), studied the long-term impact of an eco-driving training course by monitoring driving behaviour and fuel consumption for several months before and after the course. Cars were equipped with an on-board logging device recording the position and speed of the vehicle using GPS tracking. Data gathered over 10 months for 10 drivers in real-life conditions enabled an individual drive style analysis. The mean change in fuel consumption for all drivers after their eco-driving course was a reduction of 5.8 %. Zarkadoula et al. (2007) conducted an eco-driving pilot study on urban bus drivers in which they found fuel savings of 4.4 % during a post-training monitoring period of two months.

An important part of eco-driving knowledge transfer is an effective training programme to motivate drivers to adopt and sustain eco-driving habits. Denver, USA, tracked the performance of 400 participating cars through the use of on-board telemetry devices. It provided drivers with a breakdown of their habits that cause excess carbon emissions, including idling, hard braking and hard acceleration events and the cost of excess fuel consumed. A 10 % overall improvement as measured by CO_2 per mile was achieved that included reductions in engine idling, fast accelerations and fast stops (Enviance 2009).

The development of a reliable off-road knowledge transfer procedure could reduce the need for expensive and time-consuming on-road instruction/assessment without compromising the quality of the procedure. Driving simulators provide a safe and economical means of testing driving performance. Various studies have supported the use of simulators, finding that simulator driving behaviour approximates, but does not replicate, on-road driving behaviour (Lee et al. 2003; Godley et al. 2002; Scott et al. 2012). In this work, the impact of a simulator-based eco-drive training course on the on-road behaviour of drivers from a municipal fleet in Ontario, Canada is investigated.

2 Project Outline

The three-phase Driving Simulator Eco-Drive Training (DSET) project is shown in Fig. 1. In the first phase, 20 vehicles from the municipal fleet of Waterloo, Ontario were equipped with data loggers which collected speed data at 1 Hz; the vehicles were chosen based on their compatibility with the data loggers. Forty drivers who typically drove these vehicles were selected to participate in a simulator-based training programme. The mean age of the participants was 44.6 years (mode 54 years), and ages ranged from 28 to 58 years. On-road data were logged for three weeks before training to establish a baseline for each driver as they performed their regular work duties. Drivers were asked to record the day and time when they drove the vehicle under study. Although 40 drivers received training, we received complete records of day and time of travel from only 15 drivers.

In the second phase, the drivers received the Virage Simulation Eco-drive Training Program™ on a Virage Simulation driving simulator. The simulator used real vehicle components and was equipped with visual systems comprising a 180° forward field of view plus inset rear view mirror, a driver seat, steering column and dashboard. It was mounted on a three degrees of freedom motion/vibration platform. Immediately before and following their simulator-based training session, drivers were asked to complete a 5-point Likert Scale Driver Behaviour Questionnaire designed to obtain information on their self-reported interest in the training programme and their environmental concerns. This paper focuses on the former interest.

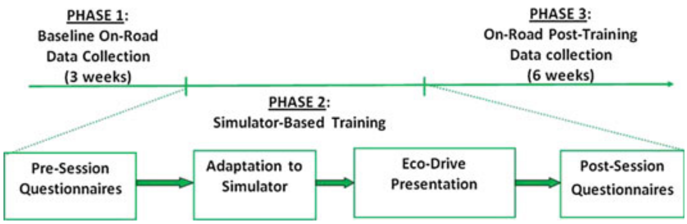

Fig. 1 Schematic representation of the three-phase DSET project

Table 1 Parameters monitored and calculated

Dependent variable	Description
Avg Acc	Average acceleration (m/s^2)
Avg Brk	Average deceleration (m/s^2)
% Hard Acc	Proportion of acceleration (among total acceleration events) ≥ 1.5 m/s^2
% Hard Brk	Proportion of deceleration (among total deceleration events) ≤ −1.5 m/s^2

In their simulator session, approximately 2 h in duration, the drivers drove a "pre-training" driving scenario to adapt to the simulator. They were then shown a presentation describing the basic principles of eco-driving, including the reduction of hard acceleration and deceleration by anticipating traffic flow and increased coasting. The drivers then drove a "post-training" scenario in the simulator to practice the eco-driving techniques they learnt.

In the third phase, for six weeks following training, data loggers still installed in fleet vehicles continued to monitor the behaviour of the fleet drivers whilst they performed their regular job duties. We compared their phase III driving to their phase I driving to look for changes in driving behaviour.

To identify hard acceleration or hard braking events, a threshold must be identified. We chose a threshold following a study by Ericsson (2001) where acceleration above 1.5 m/s^2 or deceleration below −1.5 m/s^2 had a significant positive effect on fuel consumption. A list of the dependent variables used to monitor driver behaviour is shown in Table 1.

3 Results

3.1 *Questionnaire Results*

The questionnaires were designed with four statements related to motivation (Table 2). Drivers were asked to circle one of five possible responses to each statement: Strongly Disagree, Mildly Disagree, Agree, Mildly Agree and Strongly Agree. To quantify the responses, the five possible answers, "strongly disagree" to "strongly agree," were assigned the numbers 1 to 5 respectively with 1 representing low motivation and 5 representing strong motivation.

Table 2 Mean scores for statements related to motivation

Statement	Mean	SD
1. I am enthusiastic about using a driving simulator in this session	3.67	0.99
2. I am enthusiastic about learning the eco-driving techniques in this session	3.70	1.05
3. I find the session today informative	4.73	0.52
4. I will apply the eco-driving techniques from this session at work	4.24	0.79

Questions 1 and 2 were asked before the training session and questions 3 and 4 immediately after. Before training, drivers' enthusiasm was not very high but improved immediately following the session. Generally, the variation in responses for each question, as observed by the standard deviation (SD), is not high.

3.2 *On-road Results*

Using the driving data from the 15 drivers who recorded complete day and time of travel, the phase III driving behaviour was compared to the baseline behaviour established in phase I. Table 3 shows the mean difference between phase III and phase I for each dependent variable. The mean values of the difference indicate reductions in all dependent variables with significant reductions in Avg Acc and % Hard Acc. The Avg Acc reduced from 0.93 m/s^2 in phase I to 0.84 m/s^2 in phase III and the % Hard Acc reduced from 13.3 % in phase I to 11.4 % in phase III. Although not a significant reduction, the Avg Brk reduced from −0.71 to −0.69 m/s^2 and the % Hard Brk reduced from 10.5 % in phase I and 9.8 % in phase III.

4 Eco-driving and Life Cycle Costs

Maintenance costs for a sample of fleet vehicles were gathered for the years 2012, 2013 and 2014. Vehicles were then classified according to their weight class categories as shown in Table 4. Age and type of usage varied across and among

Table 3 Differences in driving behaviour between phase III and phase I

Dependent variable	Phase III–Phase I		
	Mean	SD	95% confidence interval
Avg Acc	−0.09	0.14	−0.17, −0.004
Avg Brk	0.02	0.05	−0.01, 0.05
% Hard Acc	−1.96	2.39	−3.34, −0.59
% Hard Brk	−0.77	1.49	−1.63, 0.10

Table 4 Weight class identification of fleet vehicles

Class	Gross vehicle weight rating (GVWR) (lb)	Examples
1	0–6000	Toyota Tacoma, Ford Ranger, GMC Canyon
2a	6001–8500	GMC ½ ton, Ford ½ ton, Ford F-150
2b	8501–10,000	GMC ¾ ton, Ford ¾ ton, Ford F-250
3	10,001–14,000	Dodge Ram 3500, Ford F-350

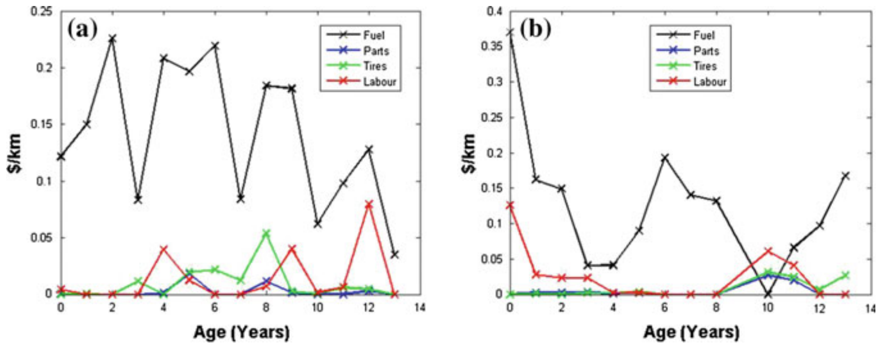

Fig. 2 Plots of average costs per km for Class 2a (*left*) and 2b (*right*) vehicles

classes. For each class, at the end of each data year, the vehicle age was noted. The costs associated with fuel, tires, labour and parts were calculated in present day dollars (CDN), thus producing costs by vehicle age. As we did not receive complete data for Class 1 vehicles, we focused on Class 2.

Based on data received, eighteen vehicles were identified as Class 2a vehicles and another 18 as Class 2b vehicles. Class 2a vehicles have an average yearly usage of 21,120 km; Class 2b vehicles have an average yearly usage of 30,028 km. The average yearly fuel consumption for Class 2a and 2b vehicles are 0.1210 and 0.1086 L/km respectively. Figure 2 shows the CDN$/km spent on fuel, parts, tires and labour costs for the two classes. As expected, fuel costs represent the highest O&M cost throughout the lifetime of the vehicles.

For every 0.1 m/s^2 decrease in deceleration (moving towards zero), fuel consumption will decrease 2.8 and 1.8 L/100 km for the same change in mean acceleration (af Wahlberg 2007). From Table 3, the drivers' phase III average acceleration and average deceleration reduced by 0.09 and 0.02 m/s^2 respectively. If the drivers maintain these values, the fuel savings, based on average utilisation, per year, are 447.8 and 636.6 L for Class 2a and 2b vehicles, respectively. Table 5 shows the average yearly fuel consumption, before and after eco-driving, based on average yearly utilisation.

Table 5 Approximate average yearly fuel consumption and % savings

Class	Utilisation (km)	Fuel consumption (L)		Fuel savings (%)
		Without eco-driving	With eco-driving	
2a	21,120	2555.5	2107.8	17.5
2b	30,028	3261.0	2624.5	19.5

5 Conclusion

The paper has discussed the potential benefit of eco-driving to reduce the life cycle costs of a fleet of pickup trucks by improved driving behaviour. From the results of our DSET project, we found reductions in hard acceleration and hard braking events in the six weeks following training leading to a potential average fuel saving of 18 %. The next step is to develop a tool for fleet managers to investigate the effect of eco-driving on fleet vehicles' economic life.

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Evaluation of Feature Extraction Techniques for Intelligent Fault Diagnostics of High-Pressure LNG Pump

H.E. Kim and T.H. Jeon

Abstract The Liquefied Natural Gas (LNG) receiving terminal is designed to deliver a specified gas rate into a pipeline network, and High Pressure LNG pumps are crucial equipment because they determine the total supply capacity of natural gas in the terminal. Therefore, condition of HP-LNG pumps are regularly monitored and managed based on Condition Based Maintenance (CBM) technique. In general CBM system is composed of a number of functional capabilities such as data acquisition, signal processing, feature extraction, diagnostics, prognostics and decision reasoning. In this paper, a comparative study on evaluation of the performance of feature extraction techniques is carried out for intelligent fault diagnostics of HP-LNG pump using real industrial data. In order to estimate the abilities of feature extraction techniques, three methods such as Principal Component Analysis (PCA), Liner Discriminant Analysis (LDA) and Distance Evaluation Technique (DET) are employed and tested for the features based fault diagnostics. The accuracy of fault classification performance is estimated by using One-Against-All Multi-Class SVMs (MCSVMs) technique. The result shows that DET has a better capability than other conventional techniques as a feature extraction technique for fault diagnostics of HP-LNG pump.

Keywords Feature extraction · Diagnostics, Principal component analysis · Liner discriminant analysis · Distance evaluation technique · LNG pump

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1 Introduction

Liquefied natural gas (LNG) takes up six hundreds of the volume of natural gas at or below the boiling temperature (−162 °C), which can make economical storage and easy transportation of natural gas. In LNG receiving terminal, high pressure LNG pump (HP-LNG pump) is used to boost LNG pressure up to 80 bar for evaporation of LNG into highly compressed natural gas in order to deliver natural gas via a pipeline network across nation. Therefore, HP-LNG pump is a key equipment in LNG receiving terminal process because it determines the total capacity and stable supply of LNG. Normally condition monitoring and fault diagnostic technology are applied for HP-LNG pump to evaluation of machine health and early detection before the catastrophic pump failures (Kim et al. 2012).

Feature extraction technique is one of key elements to implement effective condition based maintenance (CBM) strategy, and recently number of feature extraction techniques have been proposed for intelligent fault diagnostics of machine. The signal processing and feature extraction technique are fundamental to the development of a robust diagnostics model for certain fault types and failure patterns. Some of traditional feature extraction techniques for intelligent fault diagnostics can be found in literatures (Yang et al. 2002; Peng et al. 2002; Jung and Lee 2012). Among various methods, conventional fault feature extraction techniques such as Principal Component Analysis (PCA) (Feng et al. 2011; Dong and Luo 2013) and Linear Discriminant Analysis (LDA) (Jin et al. 2014; Zhao et al. 2014) have been widely applied in fault diagnostics. One of feature selection techniques for well discriminated feature selecting is the Distance Evaluation Technique (DET). Generally DET finds a subset of fault signatures that yields higher sensitivities and shows satisfied performance in feature selection techniques (Yang et al. 2004; Lei et al. 2008). However, DET has a shortcoming in terms of sensitivity estimation. To solve this drawback, Enhanced Distance Evaluation Technique (EDET) has introduced recently by Jeong et al. (2015).

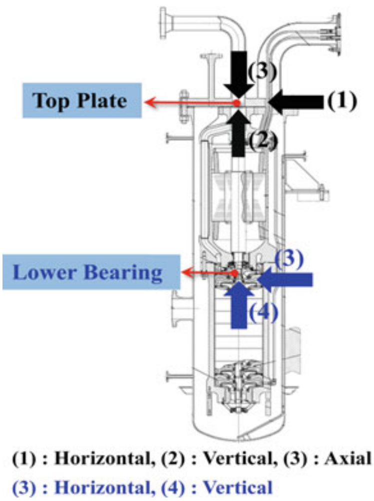
To evaluate the performance of feature extraction techniques for intelligent fault diagnostics of HP-LNG pump, One-Against-All Multi-Class Support Vector Machines (OAA MCSVMs) classifier has employed in this work because it has a good ability of classification and successfully applied in machine fault diagnosis over years (Li et al. 2015; Kang et al. 2015a, b).

This paper is organized as follows: Sect. 2 introduces HP-LNG Pump and historical pump failure analysis. Section 3 describes the signal processing from vibration data, feature extraction/selection and classification method. Finally comparative evaluation result of feature extraction techniques has been addressed in Sect. 4.

2 HP-LNG Pump and Historical Fault Data Analysis

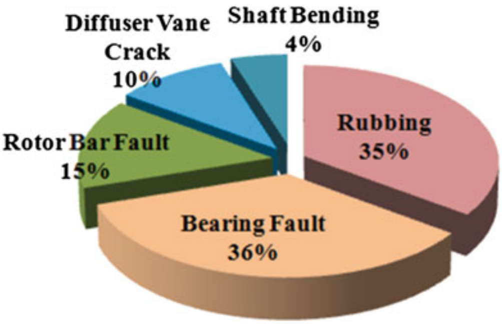
HP-LNG pump plays a vital role in LNG terminal process which delivers cryogenic fluid from LNG storage tank to high pressure vaporizer by boosting the LNG pressure up to 80 bar. It is submerged type and mounted with can vessel (Kim et al. 2012). Pump health condition is normally monitored and analyzed using a vibration monitoring system. Real time vibration data is collected through on-line monitoring system which has two vibration channels from the pump housing near lower bearing parts. Two accelerometers are installed near the lower bearing position with two radial directions (Horizontal and Vertical). In addition, off-line vibration signals can be achieved on the pump top plate using portable vibration device. In this paper, the vibration data measured on top plate used for evaluation of intelligent fault diagnostics. The HP-LNG pump schematic, vibration measuring points and pump specification are presented in the Fig. 1.

In this research, the historical fault data have been analysed to identify the main fault types of HP-LNG pump by using over 20 years maintenance records. Figure 2 shows the statistical analysis result of HP-LNG pump faults. From this result, three predominant faults have been defined as main faults of HP-LNG pump during pump operation such as bearing fault, rubbing of wearing part and rotor bar fault as shown in Fig. 2.



Capacity	Pressure	Impeller Stage
241.8 m³/hr	88.7 kg/cm². g	9
Upper Bearing No	**Bottom Bearing No**	**No. of Pole**
6314	6314	2
Speed	**Voltage**	**Rating**
3,585 RPM	6,600V	746 kW
Rotor Bar Quantity	**Diffuser Vane No**	**Current**
41 EA	8 EA	84.5 A

Fig. 1 HP-LNG pump schematic and pump specification



No.	Component	
1	Bearing Fault	36%
2	Rubbing	35%
3	Rotor Bar Fault	15%
4	Diffuser Vane Crack	10%
5	Shaft Bending	9%

Fig. 2 Result of historical fault data analysis

3 Proposed Fault Diagnostics Methodology

In this paper, the proposed fault diagnostics method for HP-LNG pump is following the conventional feature based fault diagnostics, which consist of signal processing, feature extraction/selection and fault classification. Following sub-sections present these three steps and applied methodologies.

3.1 Data Collection

To estimate the proposed methodology, the historical condition monitoring data collected on top plate point (Horizontal, Vertical, Axial) from nine HP-LNG pumps are used in this work. As shown in Table 1, total 80 vibration samples of 4 types (Rotor Bar Fault, Rubbing, Bearing Fault and Normal Condition) are obtained as described in Sect. 2. Each fault condition has 360 features which have calculated from frequency domain and time domain vibration data.

3.2 Signal Processing

Most of the significant information of rotating machine is contained in vibration signals in time-domain and frequency-domain. As shown in Table 2, twenty

Table 1 Historical HP-PUMP fault data set

Port No.	Fault condition	Number of sample	Number of features	Sampling frequency
P702(F)	Rotor bar fault (RBF)	20	360	12,480
P701(B, D, E, F)	Rubbing (RB)	20	360	12,480
P701(F), 702(D)	Bearing fault (BF)	20	360	12,480
P701(F), 702(C)	Normal (NOR)	20	360	12,480

Table 2 Statistical features from time domain and frequency domain

Time-domain parameters (12)		Frequency-domain parameters (8)	
f_1	Mean (MN)	f_{13}	$\sum_i^N f_i S(f_i) / \sum_i^N S(f_i)$
f_2	Root mean square (RMS)	f_{14}	$\sqrt{\left(\sum_i^N (f_i - P1)^2 S(f_i)\right)/(N-1)}$
f_3	Shape factor (SF)	f_{15}	$\sqrt{(\sum_i^N f_i^2 S(f_i))/(\sum_i^N S(f_i))}$
f_4	Crest factor (CF)	f_{16}	$\sqrt{(\sum_i^N f_i^4 S(f_i))/(\sum_i^N f_i^2 S(f_i))}$
f_5	Skewness (SKEW)	f_{17}	$(\sum_i^N f_i^2 S(f_i))/(\sum_i^N S(f_i) \sum_i^N f_i^4 S(f_i))$
f_6	Kurtosis (KURT)	f_{18}	$P2/P1$
f_7	Entropy estimation (EE)	f_{19}	$\left(\sum_i^N (f_i - P1)^3 S(f_i)\right)/(P2^3 N)$
f_8	Entropy estimation error (EEE)	f_{20}	$(\sum_i^N \sqrt{\lvert f_i - P_i \rvert} S(f_i))/(\sqrt{P2} N)$
f_9	Lower-bound of histogram (LB)		
f_{10}	Upper-bound of histogram (UB)		
f_{11}	Standard deviation (STD)		
f_{12}	Normal negative log-likelihood (NNL)		

parameters which are widely utilized for rotating machine diagnostics (Jung and Lee 2012) are used in this study. Time-domain statistical features are usually used to detect abnormalities, which may be reflected from the vibration amplitude, energy and distribution. Furthermore, frequency domain parameters represent fluctuated properties of vibration signal and can reveal some information, which represent specific quantitative measures of the shape and power content that cannot be found in time-domain. Thus, statistical parameters in time domain and frequency domain can provide useful information for detecting complex faults of HP LNG pump. Frequency domain parameters in Table 2, N is the number of spectrum lines and $S(f_i)$ is a power spectrum.

In addition, significant information about various faults is existed in frequency bands because measuring point is near the source of faults such as bearing, shaft and motor. Thus, we exploit Discrete Wavelet Transform (DWT) which has been extensively used to analysis frequency bands using one level with daubechies function. Also Hilbert-Huang Transform (HHT) method is applied to calculate features to represent an envelope of fault condition.

3.3 Feature Extraction/Selection

Principal component analysis (PCA) is a well-known method for feature extraction, which has benefits unsupervised classification. The purpose of this method linearly transforms a high-dimensional vector into a low-dimensional vector by calculating the eigenvectors of the covariance matrix. In low-dimension, uncorrelated variables is remained as called principal components, it contains most of the information in the large set. The Linear Discriminant Analysis (LDA) is used as a class specific discriminative, it is an effective method on supervised classification to find a set of base vectors in fault diagnostics. However, they have some problems in the process of reducing dimensionality because some features are not related to the fault. Theses redundant features may lead to poor performance of fault diagnostics in real applications.

For outstanding performance of fault classification and reduction of computational effort, effective features were selected using the distance evaluation technique of feature effectiveness introduced by Knerr et al. (1990) as depicted below.

The average distance ($d_{i,j}$) of all the features in state i can be defined as follows:

$$d_{i,j} = \frac{1}{N \times (N-1)} \sum_{m,n=1}^{N} \left| P_{i,j}(m) - P_{i,j}(n) \right| \tag{1}$$

The average distance ($d'_{i,j}$) of all the features in different states is

$$d'_{i,j} = \frac{1}{M \times (M-1)} \sum_{m,n=1}^{M} \left| P_{ai,m} - P_{ai,n} \right| \tag{2}$$

where, m, n = 1, 2, …, N, m ≠ n, $P_{i,j}$: eigen value, i: data index, j: class index, a: average, N: number of feature and M: number of class.

When the average distance ($d_{i,j}$) inside a certain class is small and the average distance ($d'_{i,j}$) between different classes is big, these averages represent that the features are well separated among the classes. Therefore, the distance evaluation criteria (α_i) can be defined as

$$\alpha_i = d'_{ai} / d_{ai} \tag{3}$$

3.4 Classification

In this study, to classify a variety of reality practical problems for HP-LNG pump, MCSVMs method is employed to verify the ability of feature extraction techniques in intelligent fault diagnostics because it offers high classification accuracy with limited training data and does not require heuristic parameters for detecting discriminative faults.

Several methods have been proposed regarding MCSVMs such as one-against-one (OAO), one-against-all (OAA) and one-acyclic-graph (OAG). Among these methods, OAA method is employed in this research because this method is a simple and effective for multi-class classification, and has been successively demonstrated with its high classification performance in Li et al. (2015)

and Kang et al. (2015a, b). In addition, selection of appropriate kernel function is very important to classify in feature space. In various kernel functions, the radial basis function (RBF) is the most popular kernel type for fault diagnostics because it finds a set weights for a curve fitting problem in complex faults feature set as stated below:

$$K_{RBF} = \exp(x - x')/\gamma \tag{4}$$

where $\gamma = \frac{1}{2\sigma^2}$, σ can decide more flexible degree of boundary.

4 Comparative Test Result

In general, the extracted fault parameters may not be equally useful for accurate fault diagnostics. Therefore, the comparative evaluation test of feature extraction techniques for intelligent fault diagnostics of HP-LNG pump is conducted in this study. Tables 3, 4 and 5 presents the confusion matrix to show detailed classification results from three conventional fault extraction methods such as DET, LDA and PCA respectively. Specifically, for evaluating classification accuracy via confusion matrix is calculated, which can be defined as follows:

$$Classification\ Accuracy = \frac{Number\ of\ TP}{Number\ of\ Samples} \times 100\,(\%) \tag{5}$$

where TP is a true positives that are properly classified from HP-LNG pump fault data.

Table 3 Classification results and confusion matrix using DET

	RBF	RB	BF	NOR
RBF	7	0	0	2
RB	0	2	1	0
BF	0	5	7	1
NOR	1	1	0	5
Accuracy (%)	87.5	25	87.5	62.5
Avg (%)	65.6			

Table 4 Classification results and confusion matrix using LDA

	RBF	RB	BF	NOR
RBF	6	5	4	5
RB	0	2	0	0
BF	0	1	4	2
NOR	2	0	0	1
Accuracy (%)	75	25	50	12.5
Avg (%)	40.6			

Table 5 Classification results and confusion matrix using PCA

	RBF	RB	BF	NOR
RBF	6	3	6	4
RB	2	3	0	0
BF	0	0	1	2
NOR	0	2	1	2
Accuracy (%)	75	37.5	12.5	25
Avg (%)	37.5			

As shown in Tables 3, 4 and 5, LDA and PCA show lower average classification performances than DET method. These results are normally caused by effect of number of features because discriminative characteristics for pump's faults are decreasing in feature space as long as increasing a number of features in LDA and PCA. Furthermore, the results of overall classification performance are originated from real industrial vibration data which have more dynamic and variable characteristics. On the other hand, DET method indicates higher classification accuracy than other methods with average classification performance of 65.6 %. As shown in Table 3, classification performances of BF and RBF of HP-LNG pump show relatively good accuracies while RB and NOR show lower classification rates. In general, fault characteristics are variable depending on fault severity in real environment. Figure 3 presents the comparative test results of three feature extraction techniques.

In this paper, the authors have calculated a large number of features through diverse signal processing techniques such as DWT and HHT, etc. to represent dynamic characteristics in real industrial environment. Most of selected features using DET method are mainly extracted from low frequency band rather than high frequency band in this study.

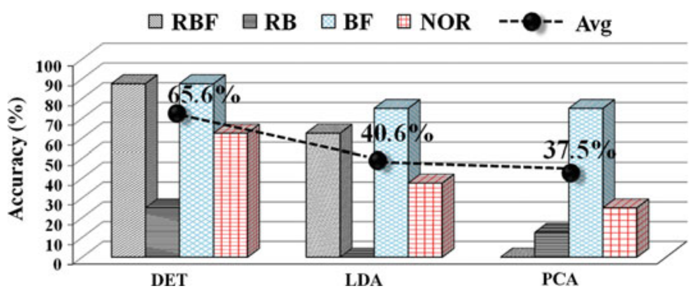


Fig. 3 Comparative result of three feature extraction techniques

5 Conclusion

In this study, a comparative study on evaluation of the performance of feature extraction techniques is carried out for intelligent fault diagnostics of HP-LNG pump using real industrial data. In order to identify the main fault types of HP-LNG pump, the historical fault data have been analysed using over 20 years maintenance records. Total 80 vibration samples of four fault types are used to validate the ability of three feature extraction techniques such as DET, LDA and PCA using OAA MCSVMs. Furthermore, a large number of features are applied in this work to represent dynamic characteristics in real industrial environment using diverse signal processing techniques. Comparative testing results indicate that DET among feature extraction approaches provide more accurate performance for fault classification of HP-LNG pump comparing with other feature extraction approaches. However, further verification is still remained for many other features types from various fault signals in future work.

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Comparison of the Sensitivity of Different Sensor Technologies to Imbalance Severity in Low Speed Wind Turbines

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Abstract Imbalance is not only a direct major cause of downtime in wind turbines, but also accelerates the degradation of neighbouring and downstream components (e.g. main bearing, generator). Along with detection, the imbalance quantification is also essential as some residual imbalance always exist even in a healthy turbine. Three different commonly used sensor technologies (vibration, acoustic emission and electrical measurements) are investigated in this work to verify their sensitivity to different imbalance grades. This study is based on data obtained by experimental tests performed on a small scale wind turbine drive train test-rig for different shaft speeds and imbalance levels. According to the analysis results, electrical measurements seem to be the most suitable for tracking the development of imbalance.

1 Introduction

Imbalanced operation of wind turbines (WTs) is common according to published statistical analysis (Kusnick et al. 2015). Even a perfectly balanced new rotor can develop imbalance during operation as a result of icing, moisture and water penetration, and blade structural damages. The traditional rotordynamic approach to imbalance detection, i.e. monitoring radial/axial oscillation of the rotor using vibration sensors mounted on the drive train components, has been extended to WTs (Yang et al. 2014). In addition, studies have suggested the possibility of imbalance detection using nacelle-mounted sensors (Kusnick et al. 2015; Caselitz and Giebhardt 2005). Another proposed approach utilises electrical measurements

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of generator to detect the speed variations induced by imbalance (Yang et al. 2010; Gong and Qiao 2012). Electrical measurements are particularly attractive because they do not require additional sensors to the layout already present on the generator to monitor the power generation. In the last decade, acoustic emission (AE) based condition monitoring techniques have also gained popularity in WT condition monitoring (Soua et al. 2013). However, their high frequency measurement bands seem unfit to detect imbalance, unless modulating strong high frequency carriers.

This research experimentally investigates and benchmarks the diagnostic capabilities of these three sensor technologies, in terms of sensitivity to different imbalance grades in operation. The study will be based on a small-scale test-rig simulating the layout and operating speed range typical of large scale (mainly direct-drive) WTs. Different degrees of mass imbalance are introduced in the system by means of eccentric masses installed on a disk rigidly rotating with the shaft.

2 Imbalance Detection by Different Sensors

It is expected that an imbalance will affect the different measurements through different physical mechanisms. The primary effect is generally related to *centrifugal force*, which in turns generates periodical radial vibrations. This phenomenon is however potentially compromised for incipient imbalance by the very low speeds characteristic of this application, which result in very low forces (quadratic dependency) and possibly noise-level vibrations.

Another direct effect of static mass imbalance is introduced by *gravity*. The gravitational pull introduces a periodically variable force on the rotating rotor disc, resulting in an alternate torque fluctuation on the shaft. This, if not fully corrected by a fast control loop, causes a 1xRev speed fluctuation with the shaft decelerating when the imbalance mass is lifted and accelerating when lowered. This phenomenon is also expected to increase with the magnitude of the imbalance. On the other hand, the effect of the nominal speed of the shaft on the magnitude of the fluctuations is difficult to predict, as it results from the combination of different factors: the amount of time for which gravity works for and against the rotational motion (higher speed—shorter intervals—lower fluctuations), the amount of compensation that the control loop is able to introduce (higher speed—less compensation—higher fluctuations), and indirect mechanical effects such as friction.

A series of secondary effects might be also indirectly produced by the centrifugal force, which is expected to amplitude modulate non-linear phenomena such as friction in bearings and contact forces in couplings.

2.1 Vibrations

The centrifugal force effect is traditionally detected analysing the magnitude of the 1st shaft vibration harmonics. In order to apply this methodology in case of speed fluctuations, the raw vibration signal will be first order tracked (OT) using the tachometer signal as a 1xRev reference (Fyfe and Munck 1997). The OT signal will be then Fourier transformed (DFT). The speed fluctuation introduced by the gravitational pull can also theoretically affect vibrations. In particular, for gearbox-driven WTs, a frequency modulation of the gearmesh is expected. To detect this phenomenon the vibration signal will be order tracked using the tachometer to remove the slow speed fluctuations (slower than 1xRev). The resulting signal will be filtered around the gearmesh harmonics and frequency demodulated by taking the angle of its analytic signal (Hilbert method). The gearmesh angular speed is then obtained by differentiation and its fluctuation is quantified by the 1st harmonics (1xRev) of its DFT.

2.2 Acoustic Emissions

Acoustic emission sensors are expected to capture only the secondary and indirect effects of the imbalance centrifugal force modulating high frequency phenomena. Therefore the analysis will be conducted by band pass filtering and amplitude demodulation (absolute value of analytic signal). Then order tracking will be performed in the detected envelope and the 1xRev harmonic will be utilized to quantify imbalance.

2.3 Electrical Measurements

The magnitude of the electrical power produced by the generator is proportional to the rate of change of magnetic flux linkage between the rotor and stator. Therefore, electrical signals obtained from the generator are affected by any disturbance of the shaft speed which primarily acts as an amplitude modulation (AM) of the electrical signal (frequency modulation is a minor effect in case of limited speed fluctuations). As for vibrations, the electric measurements will be order tracked using the tachometer signal as a reference to highlight the Nx-pole-pair harmonics and its sidebands carrying the AM information. A band-pass filtering is then applied to keep the main harmonics and its first sidebands. Finally amplitude demodulation is applied to the filtered signal using the traditional Hilbert-based approach and the 1xRev peak of the modulating signal spectrum is used as an indicator for imbalance grades.

3 Description of Test-Rig and Test Procedure

The tests have been performed on a WT drive train simulator situated at the Queensland University of Technology (Brisbane, Australia). This small scale test-rig has been designed to simulate the dynamics of a WT. It consists of an electric motor followed by a helical bevel reduction gearbox, simulating the torque produced by the wind, which is then coupled to the main shaft using a roller chain coupling. A circular disk is installed on the main shaft allowing the mounting of imbalance masses. This is followed by main bearing with cylindrical rolling elements. The shaft is then coupled to a permanent magnet synchronous generator and then to a resistive load bank. The following sensors are installed on the test rig (Fig. 1): (a) a B&K 4384 piezo-accelerometer on the bearing pedestal (0.1–12,600 Hz nominal frequency range), (b) a PAC R6α AE sensor on the bearing pedestal (with nominal range 35–100 kHz, but also velocity-sensitive below 35 kHz) and (c) a National Instrument NI 9227 current transducer measuring a generator phase. The shaft speed is controlled by a variable speed drive and the speed is measured by (d) a 1xRev tachometer. Each of the acquired signals has a length of 100s with sampling frequency of 512 kHz for AE signals and 25.6 kHz for other sensors. A side view of the test-rig is provided in Fig. 1.

Imbalance of different severity levels have been simulated by attaching different masses to the rotating disk. Tests were performed at different shaft speeds to verify the robustness of each technique to this key parameter. Specifications of the test conditions are provided in Table 1.

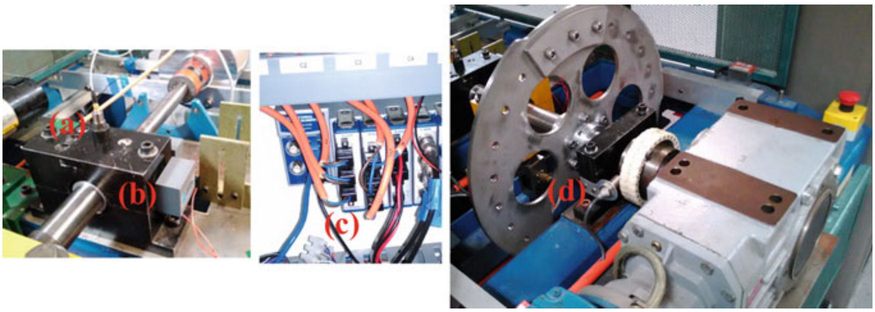

Fig. 1 Instrumented WT drive train simulator at QUT

Table 1 Test specifications

Imbalance type	Imbalance mass (gram(s))	Shaft speed (rpm)
Healthy	0	6, 10, 16, 70
Imb1	586	6, 10, 16, 70
Imb2	890	6, 10, 16, 70
Imb3	1339	6, 10, 16, 70

4 Results and Discussions

4.1 Vibrations

A zoom of the vibration spectra of the *Healthy* and *Imb3* state are shown in Fig. 2 for all the different shaft speeds. No clear peak is identifiable at the 1xRev order, suggesting that this methodology may not be effective and reliable within the operating range of a WT.

The expected imbalance modulation of the gearmesh has its major impact in the neighbourhood of the 333.3 Nx harmonics. This gear meshing order is a consequence of the two stages gearbox ratio 10.1:1 with a first stage pinion of 33 teeth. Figure 3a, b show the spectrum of the vibration signal after order tracking (using the tachometer) in this frequency range. It is clear that for low speeds—Fig. 3a, 6 rpm—the gearmesh itself has a lower-than-noise power, while for higher speeds—Fig. 3b, 70 rpm—it is clearly visible with a rich pattern in case of imbalance.

The amplitude of the 1xRev component of the extracted speed modulation (Hilbert method) is reported in Fig. 3c for different imbalances and speeds. The low sensitivity for low shaft speeds is probably due to the linear dependency of the generator torque on speed, and the consequent low gear meshing forces. The high dependency of this technique on the amplitude of the gearmesh is not the only problem, since the 1xRev modulations of the gearmesh are often consequence of other phenomena such as tooth damages.

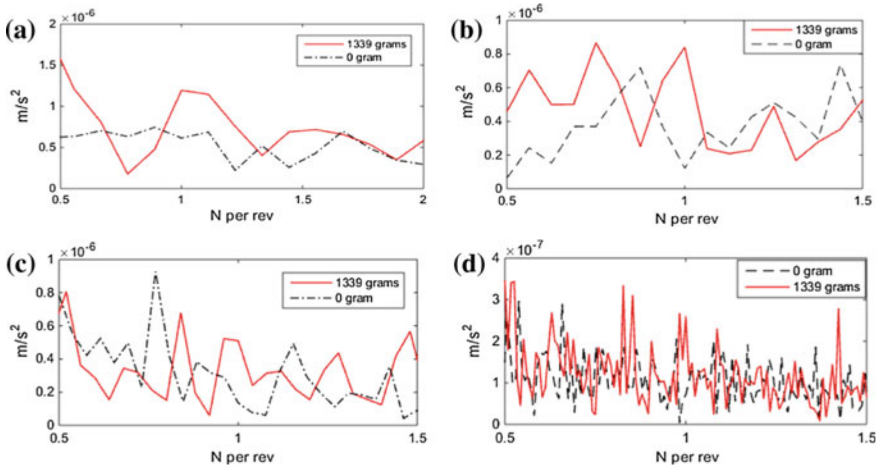

Fig. 2 Magnitude of 1xRev acceleration: comparison between vibration spectra of *Healthy* and *Imb3* (max imbalance) at **a** 6 rpm, **b** 10 rpm, **c** 16 rpm, **d** 70 rpm

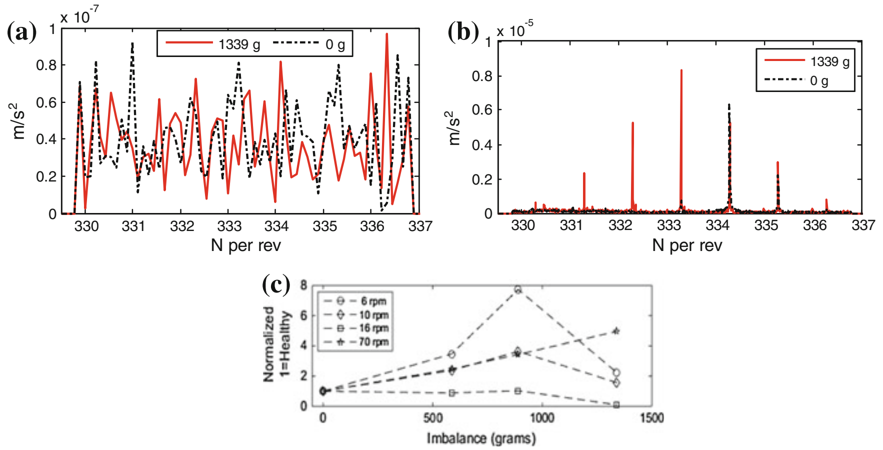

Fig. 3 **a** OT spectrum for *Healthy* and *Imb3* case at 6 rpm, **b** OT spectrum for *Healthy* and *Imb3* case at 70 rpm, **c** magnitude of 1xRev harmonics for different imbalances and shaft speeds

4.2 Acoustic Emissions

The power spectral density (Fig. 4a) of the AE shows two distinct response regions (below and above 26 kHz), somehow in agreement with the velocity- and pressure-sensitivity of the sensor (P.A. Corporation 2010). The analysis is therefore performed separately, demodulating the content in the bands 100 Hz–26 kHz and 26–100 kHz. The results of the demodulation of the lower AE band are reported in Fig. 4b, c, respectively representing rotating speeds of 6 and 70 rpm.

The measurements seem sensitive to imbalance at both speeds. Figure 4d, e shows the results of the demodulation of the higher AE frequency band for the same rotating speeds. In this case, for high shaft speed the result seems inconsistent. These results, together with the other speeds and imbalance levels are summarised in Fig. 4f, g. The low AE frequency band has a similar performance to the vibration signal of Fig. 3c, as the sensor is actually working in its "vibration" range, while in the "real" AE high frequency range the demodulation is effective only for very low shaft speeds. The reasons for this behaviour are still to be investigated, but the high dependency of these performances on shaft speed does not allow validating AE as reliable imbalance quantification sensors.

4.3 Electrical Measurements

Figure 5a, b show the order tracked (angular domain) current signals for *Healthy* and *Imb2* cases. In the same diagrams the envelope is also reported in red, and it is

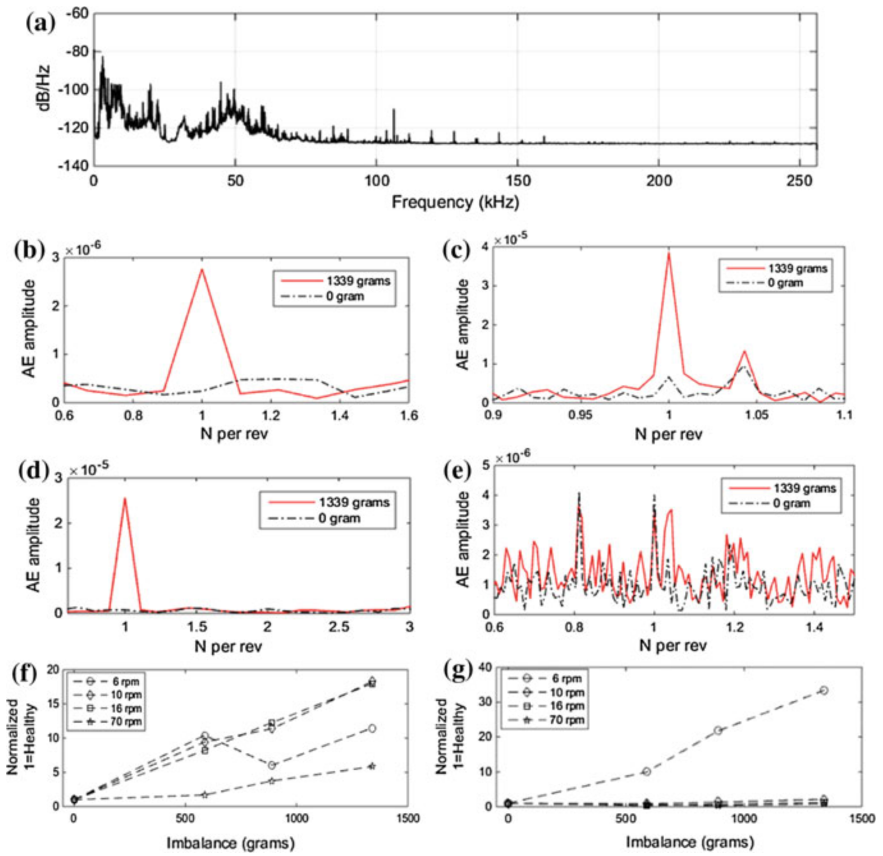

Fig. 4 AE analysis: **a** power spectral density 70 rpm—*Imb3*, **b** spectrum of demodulated band 100 Hz–26 kHz at 6 rpm, **c** spectrum of demodulated band 100 Hz–26 kHz at 70 rpm, **d** spectrum of demodulated band 26–100 kHz at 6 rpm, **e** spectrum of demodulated band 26–100 kHz at 70 rpm, **f** 1xRev modulation peak amplitude (100 Hz–26 kHz), and **g** 1xRev modulation peak amplitude (26–100 kHz)

expected to be proportional to the speed variation (proportionality factor related to magnetic flux). Figure 5c, d show the spectrum of the corresponding envelopes with clear 1xRev peaks. Figure 5e finally summarises the dependency of the 1xRev envelope spectrum amplitude on imbalance. It is evident that the 1xRev magnitude is fairly linear with imbalance for all shaft speeds. This linearity is theoretically justified by the linear dependence of the gravitational pull on imbalance. The sensitivity to imbalance is kept for all speeds, making current measurements the most reliable of the measurements seen so far.

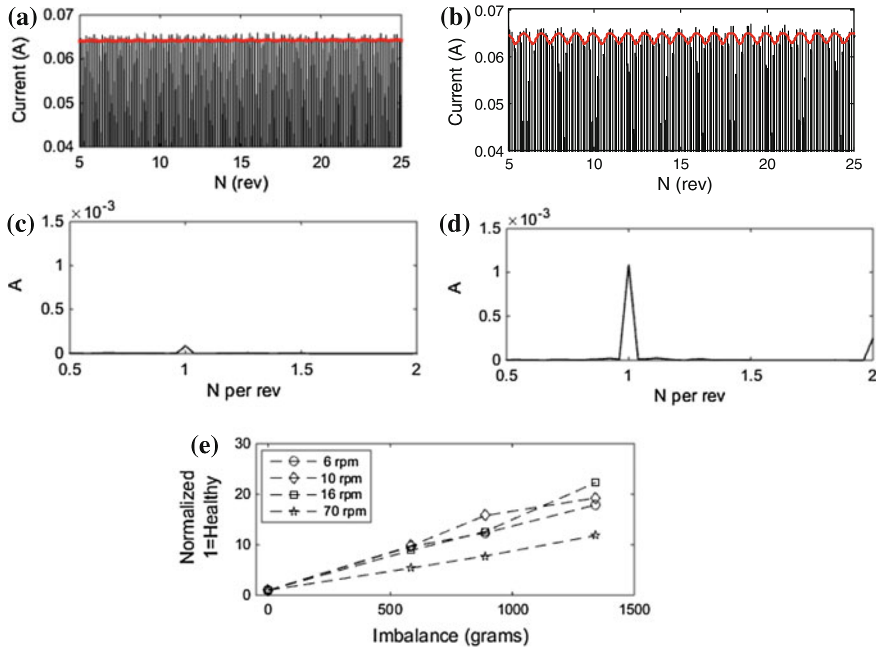

Fig. 5 Current signal analysis: **a** envelope of order tracked current signal for *Healthy* case at 16 rpm; **b** envelope of order tracked current signal for *Imb2* case at 16 rpm; **c** 1xRev harmonics of the envelope for *Healthy* case at 16 rpm; **d c** 1xRev harmonics of the envelope for *Imb2* case at 16 rpm; **e** magnitude of 1xRev harmonics for different levels of imbalance at different shaft speeds

5 Conclusions

In this work, three commonly existing sensor technologies have been investigated for their capability of imbalance detection. The results showed that electrical signals are the most reliable in the detection and future projection of imbalance levels with monotonic and almost-linear amplitude versus imbalance curves, highly sensitive to fault at within the entire range of WT speeds. Vibration measurements show sensitivity to imbalance at high rotating speeds, but a precise measurement and quantification of imbalance at the low speed characteristic of WTs is hindered by both the magnitude of centrifugal excitations and the response of the accelerometer. AE measurements were found, as expected, the least sensitive to imbalance, showing scarce detection capabilities and inconsistent trends. This advantage is coupled with the superior cost-effectiveness of electric measurement-based imbalance detection, which exploits a measurement setup already installed for control purposes (in comparison with vibration and AE additional sensors which would need to be installed for diagnostic purposes only in proximity of the input bearing). In conclusion, electrical signal appears to be the most reliable and cost-efficient solution for detection, quantification and trending of rotor imbalance in large scale WTs. Further investigations need to be done for the exact quantification of imbalance using current signal and to identify the influence of control systems.

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Circulate Your Idling Assets

Anna-Maria Talonpoika, Timo Kärri and Miia Pirttilä

Abstract This paper aims to study how financial working capital affects profitability. Financial working capital can be defined as current assets and liabilities that are not tied in operational working capital and it therefore presents the liquidity situation of the company. The research in this paper has been conducted using simulation with flexible asset management (FAM) model. The simulations indicate that profitability can be improved by decreasing the cycle time of financial working capital. The effect of the reduction can be intensified by increasing earnings or average depreciation time or decreasing relative amount of fixed assets or the cycle time of operational working capital. The results imply that profitability can be improved with strategic decisions on fixed and current assets. The paper also encourages to use models such as FAM model in the strategic decision making.

1 Introduction

Financial working capital consists from current assets and liabilities that are not tied into operations instead it presents the amount of cash needed to finance operational working capital but it also indicates the liquidity situation of the company. Liquidity is one of the four main necessities in survival of a company. The other necessities are profitability, growth and solvency (Petersen and Plenborg 2012). Liquidity can be improved with powerful working capital management (e.g. Raheman and Nasr 2007; Schilling 1996) and liberate working capital management can even cause a liquidity crisis to the company (Chiou et al. 2006). de Souza

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Guimarães and Nossa (2010) although argue that long cycle times of operational and financial working capital would increase liquidity which is opposite to the general view of the academia.

Aggressive liquidity management usually implies higher level of profitability (Wang 2002). The aggressive strategies indicate a reduction of liquidity for the favour of profitability. Arslan-Ayadin et al. (2014) on the other hand argue that good liquidity ensures high profitability in crisis situations which was for example suffered couple years ago. Deloof (2003) has established a negative relationship between operational working capital and profitability which has been confirmed in several studies (Knauer and Wöhrmann 2013). Companies have after that started to minimize their operational working capital in order to improve their profitability (Yazdanfar and Öhman 2014). de Medeiros (2005) has established a connection between operational and financial working capital. Reduction of operational working capital would increase financial working capital since they jointly form the net working capital which would indicate that liquidity presented through financial working capital would be improved.

Flexible asset management can be used to improve profitability and it is seen as a success factor for a company (Gupta et al. 2011; Lin et al. 2007). Flexible asset management concerns both fixed assets and working capital although the academic emphasis has been on fixed assets (Komonen 2010; Ojanen et al. 2012). Hatinen et al. (2012) have discovered that working capital management affect faster than actions of fixed assets and therefore the working capital management should be an essential part of flexible asset management. Aggressive working capital management allows investments to fixed assets even when the company is financially constrained (Ding et al. 2013).

The aim of this paper is to study how financial working capital affects profitability. Profitability is not affected only by one single variable and therefore this study also includes other variables. The included variables are part of flexible asset management model developed by Marttonen et al. (2013), which is also used as a simulation model in this study. The paper also validates the flexible asset management model which is earlier used mainly in the industrial maintenance setting. This paper is divided into four sections. The next section will present the research design of this paper. The data analysis and results of the simulations are introduced in the third section. The discussion of the results and conclusions can be found in the fourth section.

2 Research Design

Simulation has been used as a research method in this study. The simulation model used in this study is flexible asset management (FAM) model developed by Marttonen et al. (2013). The model has been previously used to study flexible asset management in the industrial maintenance setting. The data used in this study consists of 98 different companies listed in Nasdaq OMX Helsinki (Helsinki Stock Exchange) during the time period of 2008–2012. The total amount of observations is therefore 490 (5 × 98). The data has been collected from the financial statements of the companies. Data includes companies from all other industries except the financial industry. Financial companies were not included in the dataset because their financial structure is different and working capital cannot be calculated similarly for those companies.

Flexible asset management model has nine parameters including return on investment (ROI). The parameters can be divided into three sets: working capital parameters, fixed assets parameters and profitability parameters. Working capital parameters can be further divided into financial and operational working capital parameters. The flexible asset management model is presented in Eq. 1 (Marttonen et al. 2013).

$$ROI = \frac{EBITDA\% - \left(FA\% \times \frac{1}{B-1}\right)}{\frac{CCC+FFC}{365} + FA\%} \tag{1}$$

Financial flow cycle (FFC) is used to measure financial working capital. Financial flow cycle can be calculated as other current assets (OCA) less other current liabilities (OCL). Other current assets include all other current assets except inventories and trade receivables whereas other current liabilities include all other current liabilities excluding trade payables. Operational working capital is measured using cash conversion cycle (CCC). CCC is calculated using the method introduced by Shin and Soenen (1998). Inventories and accounts receivables less accounts payables are divided by net sales and multiplied with 365 to receive the cycle times. Fixed assets are measured using the fixed assets percentage (FA%), which proportions fixed assets to net sales. The average depreciation period (B) measures fixed assets as well as provides information on the investments of the company. Average depreciation period is calculated by dividing fixed assets with depreciations and adding one year. Profitability is measured using earnings before interests, taxes, depreciations and amortizations scaled by sales (EBITDA%).

The simulation was conducted using flexible asset management model and mean values of the data. The simulation was done in two phases. The first phase included defining the parameter levels. The parameters were given three values: average value, 80 % of the average value and 120 % of the average value. Only one of the parameters was alternated in one simulation round and the other parameters of the model remained in the average values. Secondly financial flow cycle was given values between −100 and 100 days. The lower limit of the value was selected based on the descriptive statistics and the upper limit was selected to be symmetrical with the lower one. Return on investment was calculated for all of these values.

3 Data Analysis

Flexible asset management model (see Eq. 1) presents the logic how financial and operational working capital is related to profitability. The model can be examined mathematically which indicates that profitability measured by return on investment increases if the numerator increases or the denominator decreases based on basic mathematical rules. The numerator includes variables affecting profitability and fixed assets. The denominator reports fixed assets and the cycle time of current assets. The equation implies that return on investments will be improve if earnings increase and the relative amount of fixed assets is decreased and the average depreciation time increases. The cycle time of current assets, financial and operational working capital, should also decline.

The simulation demonstrates the findings of the mathematical analysis. Figure 1 presents how the individual variables affect profitability when the cycle time of financial working capital is altered. The profitability increases when the cycle time of financial working capital is reduced which indicates that companies have to minimize the amount of cash and other current assets and lean towards current liabilities in order to finance their daily operations. The individual variables affect differently to the relationship between profitability and the cycle time of financial working capital when they are fixed at specified levels. Twenty percent change will have the greatest effect in earnings and in the relative amount of fixed assets. A change in the cycle time of operational working capital on the other hand does not affect return on investment equally.

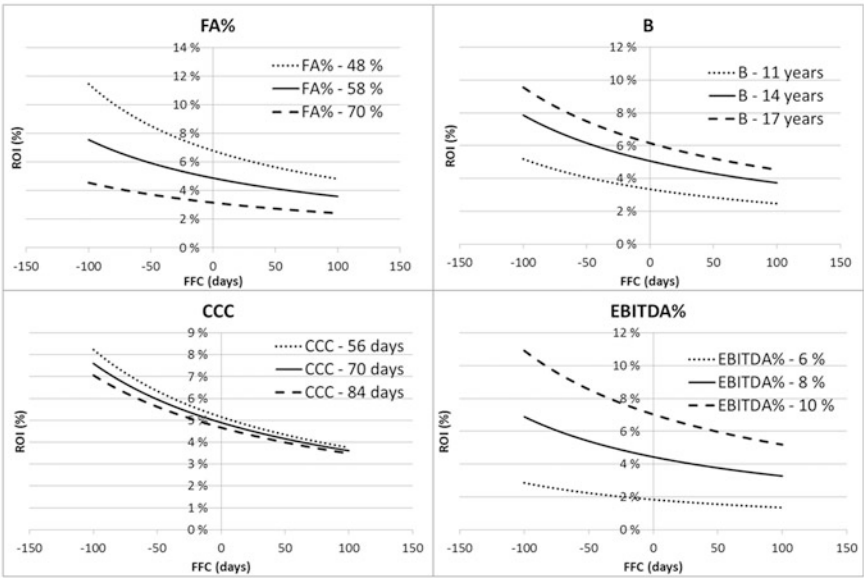

Fig. 1 The relationship between FFC and ROI

Smaller amount of fixed assets will result higher profitability which was also the result of the mathematical examination. The interesting finding is that the improvement in profitability when cycle time of financial working capital is reduced is more notable when the level of fixed assets is lower. The slope of the curve is doubled if the relative amount of fixed assets is reduced with 20 %. Increase in the level of relative amount of fixed assets will result the slope to approach zero which indicates that the relative amount of fixed assets does not affect that much to the relationship between profitability and the cycle time of financial working capital. The longer the average depreciation period is the better the profitability will be. The slope of the curve does not change when the level of the average depreciation period is altered. There is on the other hand a clear difference in the scale when the different levels are compared. A short average depreciation period reduces the profitability more than a long cycle time of financial working capital.

Profitability will be improved if the cycle times of financial and operational working capital will be reduced. The decrease or increase of the cycle time of operational working capital will not dramatically change the profitability if the cycle time of financial working capital is kept stable. It can although be noted that the different levels of the cycle time of operational working capital will have more impact on profitability if the cycle time of financial working capital is reduced dramatically. The slope of the curve is rather prominent which indicates that the company should aim at decreasing the cycle time of financial working capital even if the changes in cycle time of operational working capital could not be achieved.

Earnings before interests, taxes, depreciations and amortizations have a clear impact on return on investment. The increase or a decrease of the level of earnings will have an equal impact in the scale on the connection between the cycle time of financial working capital and return on investment. High earnings will evidently result higher return on investment. Radical reduction of the cycle time of financial working capital will have a greater improvement in return on investment. The slope of the curve is doubled when the earnings percentage is increased with two percentage units.

4 Discussion and Conclusions

The aim of a company is to be profitable but it is also vital to have good liquidity. The results of this study indicate that profitability could be increased by minimizing the cycle time of financial working capital. The minimizing basically requires companies to invest their cash into more profitable investments and more over to use current liabilities more efficiently. Fixed assets were a major variable affecting return on investment. Relative amount of fixed assets presents the investment policy of the company proportioned to net sales and large relative amount indicates that the company has made extensive investments compared to their net sales. Good profitability would require decreases of fixed assets since the reduction of the cycle time of financial working capital is not enough solely. There are dramatic difference in the relative amount of fixed assets across industries and the reduction of fixed assets is much more difficult for capital intensive industries. Operational working capital on the other hand did not had a striking effect on return on investment but a minor effect can still be seen. The reductions in cycle time of operational working capital in relation to profitability have been studied a lot and companies have started to have more attention to operational working capital. Inventories are cut down and operation is streamlined which of course improves operational working capital but also directly profitability. Increased earnings will result better profitability. Earnings percentage have been decreasing especially in the manufacturing companies since the cost structures have changed. The costs are consuming large portions of the net sales which will then result a lower level of earnings. Reducing costs is therefore the first step in increasing earnings and profitability.

This study indicated that financial working capital has a negative connection to profitability measured with return on investment. Profitability will increase when the cycle time of financial working capital is reduced. The intensity of the connection is affected by other variables of the flexible asset management model used in the simulation. Relative amount of fixed assets has the largest effect on the connection between financial working capital and profitability. The study also showed that flexible asset management model can be used to simulate large and fairly generic datasets since it has been earlier used mainly in the maintenance setting. This paper gives managers insights to balancing between liquidity and profitability. The results of this paper present how profitability can be improved with minor adjustments to current and fixed assets. The study also encourages managers to use simulation models in the decision making. Managers can simulate the planned actions and see whether the actions should be executed. The models, e.g. flexible asset management model, can be used in company, industry and network levels to see the greater effects.

Simulation method is the largest limitation in this study. The data used in the simulation is real data from companies but the simulation itself is based on a model which does not present actual real life events only simulate and predict them. This limitation could be solved with a time series analysis or another type of simulation. Time series analysis could be used to check how financial working capital and profitability behave when they change over time. Future research could also study the relationship between interest rates and financial working capital because this study only included data from a low interest rate period and the authors believe that it has affected the results. The simulation could be extended by simulating all components simultaneously.

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Advanced RCM Industry Case—Modeling and Advanced Analytics (ELMAS) for Improved Availability and Cost-Efficiency

Miikka Tammi, Ville Vuorela and Timo Lehtinen

Abstract Today there are several well-proven analysis methods available for reliability and maintenance management. Most of them are however developed for analyzing safety-critical applications. Within basic industry the focus is typically on cost management and traditional analysis methods are often presumed as too laborious. This seminar paper is based on an ELMAS reliability analysis performed for a production-critical molding crane in metals industry at SSAB Raahe factory in Finland. The main objective was to identify risks and optimize maintenance actions in a cost-effective manner. Another objective was to develop a systematic procedure for managing cost risks of production-critical process parts. The analysis combines the main benefits of fault tree analysis (FTA), failure mode and effect analysis (FMEA) and reliability centered maintenance (RCM) to form a systematic method for performing versatile analysis and corrective action planning.

1 Introduction

Managing reliability, availability and maintainability is an integral part of risk management. It focuses on technical issues that may lead to system unavailability. Modern technical systems often consist of numerous complex subsystems and components that operate in mutual interaction enabling the system to fulfill its operative requirements (Rausand and Høyland 2004). In order to support and to maintain this task a systematic method for identification, assessment and control of the technical risks is required.

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Several qualitative and quantitative methods suitable for reliability management have been developed during the last few decades. Some of them focus on identification of risks and faults, some on describing cause-consequence logic in an easily understandable way and some also on risk assessment. These methods have all been widely used for decades and they have all earned their place among the most effective risk analysis methods.

The problem is that these methods are often too heavy for the needs of basic industry. In addition they are not always suitable for analyzing complex applications or problems. When the target is not safety-critical there is a need for more efficient and flexible methods that are easier to use. Within basic industry the focus is usually on cost management. Often the aim is to identify bottlenecks in production, root causes of unavailability, to analyze improvement potentials, to plan various improvements and compare different scenarios and investment options.

ELMAS (Event Logic Modeling and Analysis Software) is a tool developed by Ramentor Oy for risk identification, event logic modeling, simulation and analysis. ELMAS contains both quantitative and qualitative analysis methods and combines the benefits of well-known analysis methods to form a uniform functional entity within a single user interface. The stochastic simulation engine of ELMAS is able to analyze also very large and complex models (Ramentor Oy 2015) (Fig. 1).

This seminar paper is based on an ELMAS reliability analysis of a production-critical molding crane in SSAB Raahe factory in Finland. The main objective was to identify risks and improve maintenance in a cost-effective manner. Another objective was to develop a systematic procedure for managing cost risks of production-critical process parts. The analysis combines fault tree analysis (FTA), failure mode and effects analysis (FMEA) and reliability centered maintenance (RCM) to form an efficient method for cost and reliability-aware analysis and improvement in a more streamlined manner than the traditional RCM-analysis (Roberts et al. 1981; Moubray 1997).

Fig. 1 Molding crane no: 123

2 ELMAS Reliability Analysis

The ELMAS reliability analysis of the molding crane consisted of the following steps:

1. Modeling device hierarchy and analyzing failure history
2. Modeling function hierarchy and cause-consequence logic
3. Current state risk analysis
4. Action planning and effect simulation

2.1 Modeling Device Hierarchy and Analyzing Failure History

The modeling of the molding crane was started by describing the device hierarchy of the crane. In the hierarchical model the molding crane was described by its subsystems and part groups. The hierarchical model was constructed by utilizing the IDs and names used in the local computerized maintenance management system (CMMS).

The created device hierarchy model is a visual presentation of the studied object showing also the different entities involved in the study. With the model it is easier for the project group to grasp the studied entity and the delimitations set for the analysis. In addition the device hierarchy can be utilized for analyzing the event history data accrued to the CMMS. The data to be transferred to the device hierarchy model can include failure history and preventive maintenance events. This makes it possible to analyze the entire event history and trends. Studying the failure history also helps in failure mode identification.

2.2 Modeling Function Hierarchy and Cause-Consequence Logic

In the next step the modeling was continued by including the molding crane functions and event chains capable of potentially stopping these functions. The functions (*PF#/SF#*) and functional failures (*FF#*) included in the function hierarchy are shown in Fig. 2.

In function hierarchy the device entities and their failure modes are placed under each functional failure describing the reasons why the particular functional entity of the crane may fail. The cause-consequence chains describing the failure logic may be very complex thus creating a need for versatile logical gate types. In practical applications there is also often need for repair and probability gates. Figure 3 shows the failure-related cause-consequence chains of auxiliary trolley travelling electrical drives.

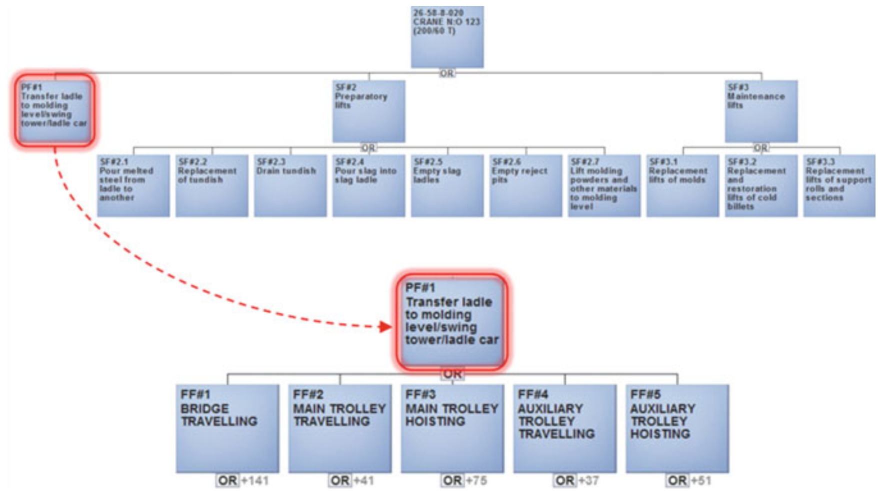

Fig. 2 Functions of a molding crane

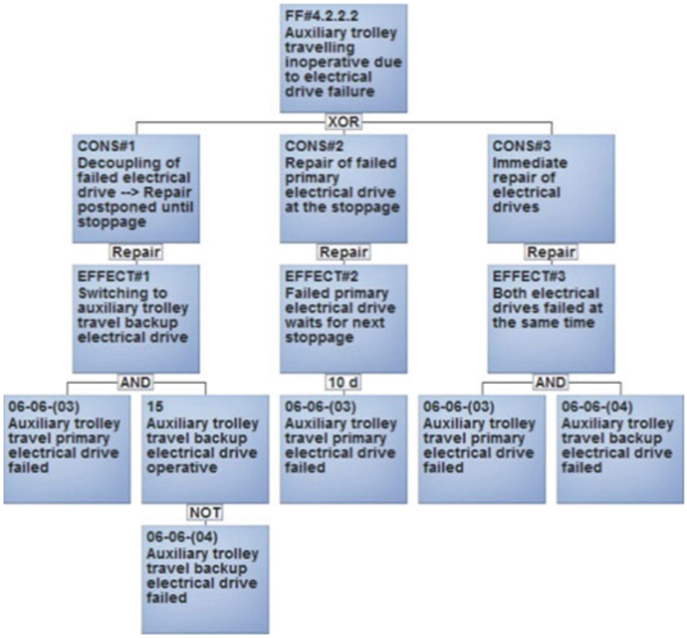

Fig. 3 Failure logic for electrical drives in the auxiliary trolley travelling

2.3 Current State Risk Analysis

The function hierarchy model containing the device entities and failures forms a basis for the current state risk analysis of the system. In the first step of the risk analysis each device failure was assessed by the characteristic failure behavior and failure effects. The failure and its effects were further reviewed in more detail by the failure rate, restoration time, and resource and spare part costs. In addition a mean cost for loss of production per hour was defined for the molding crane. With mechanical failures the age of the device was taken into account if there was evidence of age dependency in the failure behavior. The input data was primarily collected through expert estimations. The failure history, results of previous analyses and reliability libraries were utilized to support the expert estimations. For assessing the event probabilities the mean, at least, at most-method was used (Fig. 4).

In the second step of the risk analysis the functional failure logic with failure rates, recovery times and cost data was analyzed using the stochastic simulation tool of ELMAS. Through simulation the risks and improvement potentials of the molding crane were discovered in terms of reliability and costs for the whole system, functional levels and single failure modes. Figure 5 shows the unavailability time and failure count distribution for the functional failures disallowing the main function of the crane during a ten-year-long period of interest.

The graph shows that the main and auxiliary trolley hoisting entities are the most important entities in terms of unavailability time and failure count. For these two entities the accumulated unavailability time (23 % + 28 %) and failures (29 % + 21 %) account for roughly a half of the total unavailability time and number of failures. In terms of just failure count (23 %) the bridge travelling is one of the most important entities but due to short restoration times the unavailability time caused by it for the entire crane is just one tenth of the total amount. On the other hand the auxiliary trolley travelling fails less frequently (11 %) but due to long restoration times it causes ca. one fifth (19 %) of the total unavailability time of the crane.

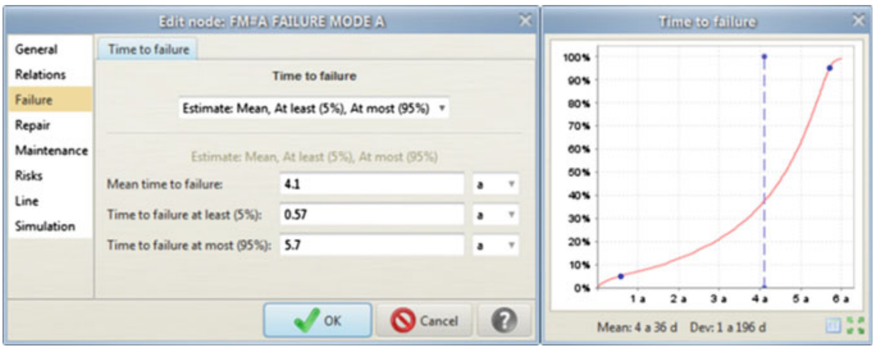

Fig. 4 Failure estimation in ELMAS with the mean, at least, at most-method

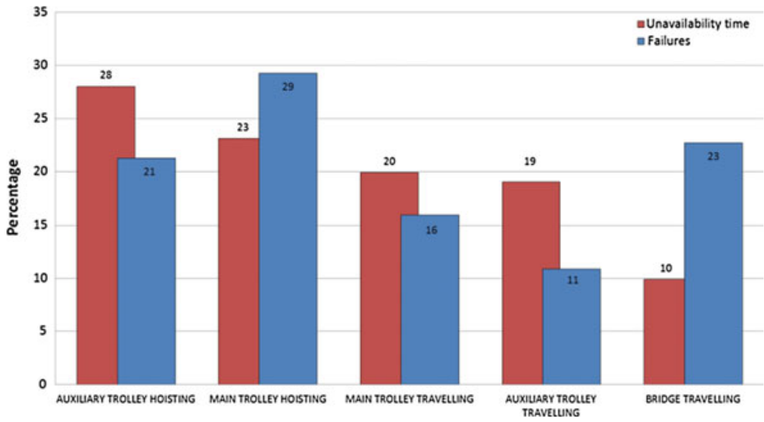

Fig. 5 Distribution of unavailability times and failure count of the molding crane caused by functional failures

2.4 Action Planning and Effect Simulation

In the next step of the analysis there was a search for applicable and efficient actions to prevent failure modes or to reduce their consequences. This was done for the failure modes found to be the most significant in the current state risk analysis. Before the actual action planning the most significant failure modes were assessed in more detail in terms of local safety impact, potential concerning consequence reduction, and the causes, detection and nature of the failures.

Only the most significant failure modes in terms of costs were studied further. This way the usage of resources by the project group was optimized. Based on these studies an applicable action or combination of actions was defined for each of the most significant failure modes to prevent them and reduce their consequences by utilizing RCM decision logic (IEC 60300-3-11 1999). During this definition process different actions were considered based on their applicability to either remove or to detect the causes of the failure before these causes lead into an unexpected failure event.

The effect of the defined actions to the whole system became evident by simulating the action plan and comparing the results to the current state risk analysis. Figure 6 shows the division of the crane cost risk between different cost factors. The red bars indicate the current state risk analysis results and the blue bars indicate results with the new action plan. All results are shown relative to the overall cost risk of the current state analysis.

The action plan proposed by the project group enabled reduction of ca. one fourth (22.7 %) of the overall cost risk of the molding crane during the ten-year period of interest. In terms of production loss the cost risk coming from unplanned stoppages is dropped by ca. one fourth (82.2 % − 58.9 % = 23.3 %) compared to the current state risk analysis. Performing the actions does increase the preventive

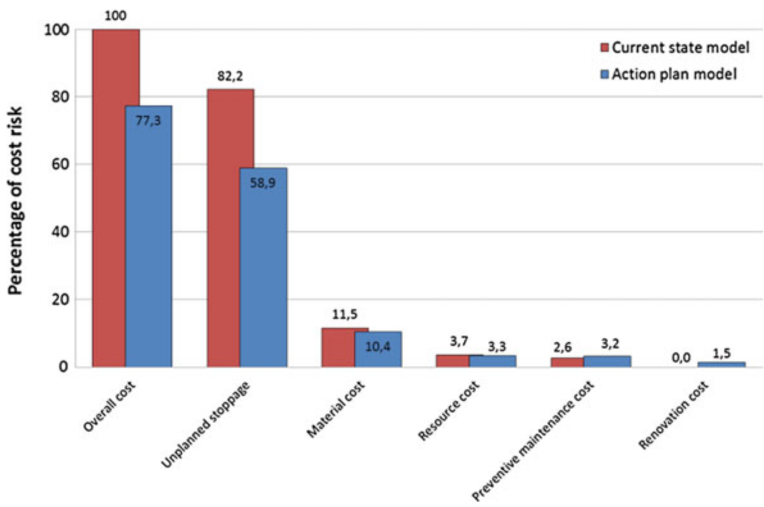

Fig. 6 Crane cost risk factors

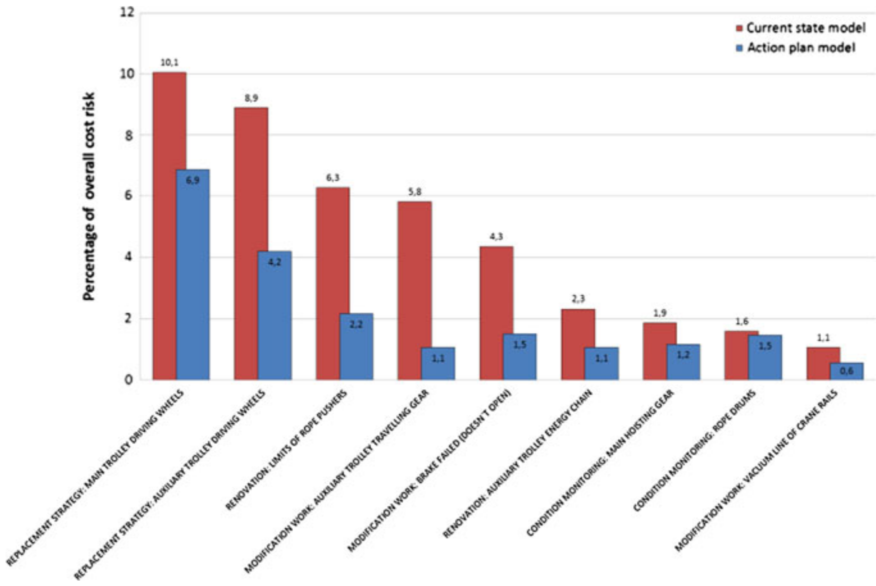

Fig. 7 Cost effects of actions

maintenance costs slightly (0.6 %). The actions also involved some crane parts where a renovation was seen to be the best option to improve performance. The renovation costs caused the overall cost risk rise ca. 1.5 %.

The most important individual action recommendations in terms of costs are shown in Fig. 7. The savings achieved by driving wheel replacements amounts to a

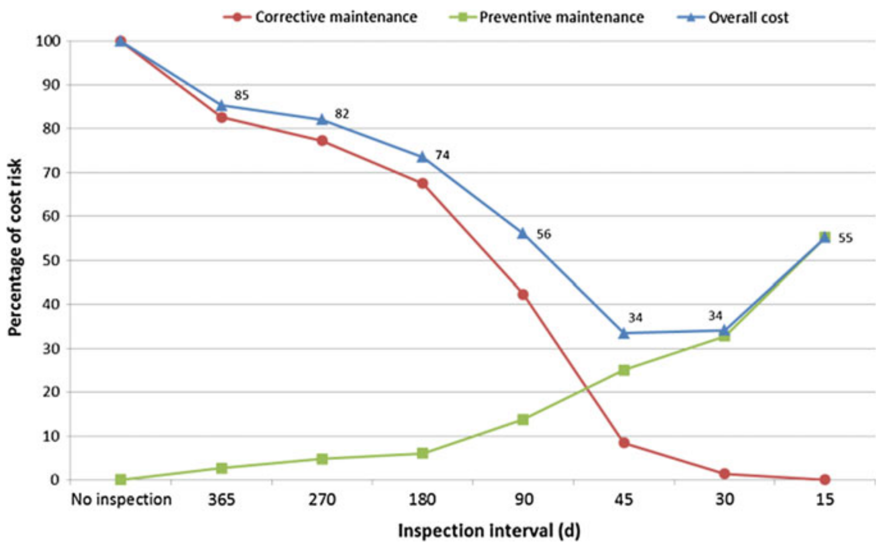

Fig. 8 Effect of inspection interval to the main hoisting gear cost risk factors

total of 7.9 % of the overall cost risk. This replacement strategy makes it possible to save more than 40 % of the cost risk caused by the driving wheels. The replacement strategy includes an agreed plan of operation where a certain trigger event causes the actions defined in the replacement strategy to take place.

Renovating the limits of the rope pushers and the energy transfer chain was found to be feasible in terms of costs. The renovation actions make it possible to reduce the cost risk of the crane by more than 5 %. The most important modification work focused on indicators of gear failure in the auxiliary trolley travelling machinery, protection of brake pushers and performance of vacuum line on the crane rails. It was estimated to be possible to achieve ca. 8 % overall cost reduction for the crane by these modification actions. It is worth pointing out that the cost savings relating to improvement effects of such renovation and modification actions involve an extra share of uncertainty. Comparing several effect scenarios helps with the decision making process. At best the effect on reliability and overall costs is positive even in the most pessimistic scenarios.

The effect of inspection interval to the cost factors is shown in Fig. 8. The graph is formed for main hoisting gear vibration measurements, but an equal inspection interval analysis is suitable for efficient studying of other inspection actions as well. The graph shows how the preventive maintenance costs, calculated by simulation, rise as the inspection interval is reduced and the unexpected failure repair costs also reduce. The minimum for the overall costs is achieved by using an inspection interval of 30–45 days. All in all the overall costs can be dropped to one third by using the optimal inspection interval relating to the time period when early warning symptoms can be detected.

3 Analysis Process and Decision Making

Risk management is a continuous process aimed at identifying, assessing and controlling characteristic risks of some system. It is typical for system risks to evolve during time, system aging and process modifications. For this reason it is important to update the analysis for example every two years for continuous improvement. Model update includes importing new event history and reviewing the ability of the action plan to maintain system operation in a cost-effective way in the light of the new history data. If the review reveals new failure modes or some previously made estimates need updating, it is time to renew the reliability analysis with new information. Updating the reliability models and analyses regularly gives time to react to changes in the system or process well in advance.

The input data used in the analyses naturally contains some uncertainty. The results obtained by ELMAS reliability analysis do not represent absolute truth, but rather serve as a prediction that has been achieved by using the best available information on unavailability and cost risk related issues. It is necessary to acknowledge this uncertainty, but not let that step in the way of optimized decision making. Especially the most significant decisions should always be based on the most accurate and comprehensive information available. This is exactly what the proposed procedure and ELMAS reliability analysis is all about: Refining data into information to support both operative and strategic decision-making.

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Change from Machines to Production Systems—An Approach and Qualitative Methods for the Assessment of System Safety and System Availability Risks

Risto Tiusanen

Abstract The change from single machines to automated machine systems transforms the design and engineering problems from machine design and manufacturing issues into system design, systems engineering and system integration ones. The developed approach integrates key elements from systems engineering, machinery safety and industrial safety engineering practices. Evaluation of the usefulness of the overall approach and risk analysis methods has been done following the qualitative case-study research methods. The results of the study show that the three-level approach to risk assessment is applicable for automated machine systems and the selected methods are applicable for system-level hazard identification and risk analysis. The approach and the methods have been adopted in case companies. The results can be utilized among machine manufacturers, system suppliers, end users of the machinery systems, and safety experts.

1 Introduction

Machine manufacturers are changing their business strategies from equipment supplier's role to system supplier's role. The need for change from single production units, machines and equipment, towards large scale automated production systems can be seen in several industrial branches such as manufacturing industry, constructing industry and mining industry utilising mobile work machinery. Increasing needs for better productivity, demands for cost reduction and higher process and product quality is driving the production management towards process control instead of improving the management of separate machine operations. Automation has repeatedly seen one of the key solutions to enable this development.

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From machine manufacturer's point of view single industrial machines and automated machine systems differ greatly considering their whole life cycle. Industrial machines are products that are placed on the market, but automated machine systems are unique customer specific projects. The systems are built and commissioned at the work site in the final production environment. From both of these perspectives, such automated machine systems can be compared with process-automation applications. The change from single machines to automated machine systems transforms the design and engineering problems from machine design and manufacturing issues into system design, systems engineering and system integration ones (Tiusanen 2014).

The change towards automated complex machine systems takes risk management considerations to a new, system risk level. According to Leveson (2011a), new digital technology increases the complexity of the systems and introduces new potential causal factors. In complex systems, accidents occur on account of the interaction of perfectly functioning components. New safety threats due to system complexity in automated machinery systems are seen in complex human–machine interactions, complex system operations and maintenance situations, systematic or random system failures in control systems, and system interfaces within the operation environment at the work sites. According to Sammarco (2005) and Leveson (2011a), current accident models and safety-engineering techniques do not cover all of the new technological and operational aspects. Experiences from various sectors of industry confirm these concerns. Among others Rasmussen (1997), Leveson (2011b) and Rausand (2011) have pointed out that the system complexity, increased amount of software, automated functions, and automatic operation bring out new safety issues and design problems for system designers and safety engineers.

This development implies that proactive analysis and control of system hazards is growing increasingly important. The case with new technology applications is even more demanding as comprehensive data is not available for modelling, simulations and qualitative analysis to help support risk estimation, evaluation and assessment in the early conceptual phases of the system lifecycle. Moreover, risk analysis methods based on a systems approach become essential when identifying and analysing potential dependability and safety issues from technical and operational perspectives. From the systems engineering view there is lack of knowledge and experience of approaches and practical risk assessment methods applicable for system availability, maintainability and safety issues in early conceptual design phases.

2 System Risk Management

In this paper the term 'System risk' is associated with risks that are related to the whole production system and its operating environment. It is not related to single component, device or functionality of a machine. The success of system risk

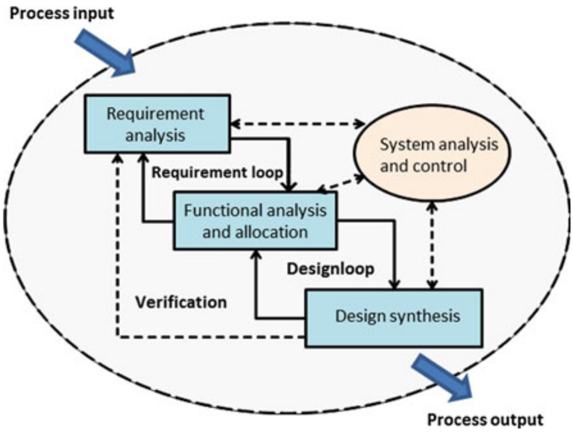

Fig. 1 A simplified flowchart of the systems engineering problem solving process (DoD DAU 2001)

management, especially in large and networked projects, depends heavily on the management framework that provides the organizational foundation and practical arrangements for the application of the enterprise risk management process at all organizational levels (ISO 31000 2009). The framework is needed to enable and assist risk management work at different levels and different roles in the wind farm project organization. From a systems-engineering management perspective, the risk-management process is a continuous process to identify, analyse, treat, and monitor risks related to the acquisition, development, maintenance, or operation of a system (ISO IEC 15288 2008). The general risk-assessment process is specified in more detail in the specific risk-assessment process standard ISO IEC 16085 (2006). The integration of risk-management activities into the systems-engineering process application in each phase in the system life cycle is described e.g. in ISO IEC 26702 (2007) and DoD DAU (2001) (Fig. 1). In the systems-engineering approach, risk management covers both project risk-management and product risk-management issues.

A practical three-level approach for system-level safety-risk assessment for automated mobile work-machine systems has been developed in VTT. The developed approach applies the top-down approach adopted from the systems engineering guidelines and integrates key elements from system safety, machinery safety and industrial safety engineering practices. The three assessment levels are the overall system level including the operating environment, system operation level and system function level. The approach and experiences of the use of qualitative methods utilised in case projects are presented in details in Tiusanen (2014).

System risk assessment follows the whole system lifecycle, identifying strengths and weaknesses in the development, operation and maintenance of the system. In this system level perspective the time frame in system risk analysis and assessment is also longer. Different phases in system development have different needs and these must be understood to execute efficient risk management that supports decision making and project management. For example, ISO 31010 (2009) states that in the concept and definition phase of the product lifecycle risk assessment can be used to decide whether to proceed the development project or not. Basic methodologies that are recommended in and in practice well proven for risk analysis of complex machinery systems are among others: Checklists and Brainstorming methods, Scenario Analysis, Structured WHAT–IF studies, Preliminary Hazard Analysis (PHA), HAZOP studies, FMECA and LCC analysis (IEC ISO 31010 2009; SFS EN ISO 12100 2010).

3 Case Studies on Risk Assessment Methods

In this paper we introduce and discuss results from two case studies on the evaluation of usefulness of risk assessment methods. Both cases are related to early life cycle phases of an automated mobile work machine system. The cases represent different industrial sectors and automation technologies: underground ore transportation and container handling in a port terminal.

The automated ore-transportation system in question was unique—the first of its kind in the underground mining industry. The target system uses autonomously operating dump trucks that transport ore from the transfer points (loading points) to the crusher pin (dump point). The main subsystems in this complex application are a production planning system, a mission-control system and operator stations at the surface control-room level, and automated dump trucks and the local safety system in the underground production area. A wireless communication system connects the machines to a mine-wide high-speed communication system. The autonomous dump trucks are loaded with manually operated LHDs at the transfer points (Burger 2006).

The other case system was related to the development of a semi-automatic container terminal utilising automatic crane systems for containers' stacking and handling. The target system was an automatic stacking crane (ASC) system that handles containers in one block with three automatic cranes. The complexity of the system can be understood by its multi-machine nature and the control systems and data transmission systems needed for automatic operation. In this application two identical 'inner cranes' use the same tracks, while one 'outer crane' uses a separate track. The outer crane is able to pass both inner cranes (Tiusanen 2014).

3.1 Study Design

The usefulness of the three-level risk assessment approach in automated mobile work-machine applications is examined through evaluation of benefits of the results and impacts of the risk-assessment work in light of the risk-assessment results achieved in the projects. The risk-analysis and risk-estimation methods were analysed through examination of the pros and cons of the selected methods and work practices in the projects. The evaluation based on project material, documented experiences and observations were supplemented afterwards with expert interviews. The case studies and the evaluation method are presented in more details in Tiusanen (2014). In case 1 the usefulness of qualitative risk analysis and risk-estimation methods (Preliminary Hazard Analysis (PHA), HAZOP study and risk matrix) in system design phase were examined. In case 2 the usefulness of the PHA, Operating Hazard Analysis (OHA) and risk matrix methods in conceptual design and in system design phases were examined.

PHA is commonly conducted early in the system life cycle, when there is little information available and it forms the framework for other risk analyses that may be performed. The output of the PHA is then used for the development of system safety requirements (IEC ISO 31010 2009; Vincoli 2006).

OHA, sometimes called operating and support hazard analysis (OSHA) is used to analyse hazards associated with the operation and maintenance of the system. It considers especially hazards resulting from tasks, activities, or operating system functions as the system is operated or maintained in its intended operating environment. The approach in OHA is similar to PHA to identify hazards, but the categorising function in the analysis is an operational event. OHA focuses on human factors, procedures and human-machine interfaces, not only on technical failures or human errors (Vincoli 2006; Stephenson 1991).

HAZOP study is a detailed problem identification process, carried out by an expert team. HAZOP study focuses on the identification of potential deviations from the design intent, examination of their possible causes and assessment of their consequences (IEC 61882 2001, p. 13). Redmill et al. (1999) declares that HAZOP technique can be employed at all stages in a system's life cycle and be applied to operational systems just as well as system designs. HAZOP is a structured team-work-based technique that is effective for analysing new systems and novel technologies and particularly powerful for exploring interactions between parts of a system.

Risk matrix, also called a consequence—probability matrix, is used to rank risks on the basis of the level of risk. Risk matrices are commonly used as a screening tool together with hazard identification methods when many risks have been identified, for example to define which risks need further or more detailed analysis, which risks need treatment first, or which need to be referred to a higher level of management.

3.2 Main Results

According to the industrial partners' comments and the author's observations in the mining automation case the analysis method utilising brainstorming sessions and team discussions was easy to learn and suitable for hazard identification and analysis for an automated mobile work machine system in its conceptual design phase. In the container handling automation case the PHA method, utilising brainstorming sessions for hazard identification and creation of accident scenarios in combination with team discussions for specifying causes and consequences, worked out well. The hazards identified in the conceptual design phase and the conceptual safety solutions were used later as a baseline in customer–site–specific OHA. The system supplier stated that the scope of the risk analysis should be broadened to cover also system installation, building, and testing phases on the site.

Use-case descriptions covering various human–human and human–technology interactions were defined for the specified system operations in OHA. In the container handling case the OHA report including worksheets was considered a useful and practicable work document, describing the system operations and functions at such a level that all system designers, with diverse technological backgrounds, can take part in the analysis and discussion. Comparing OHA with HAZOP study for upper system level risk analysis aimed at analysis of system operations, one finds that OHA provides support for the creation of new views of operation situations and human factors. The approach of HAZOP study is limited to the designed, intended use of the system, and in this sense OHA is a PHA-type hazard-identification and analysis method.

The results show that the risk estimation methods and risk-evaluation practices utilising risk matrices need to be developed to be more appropriate for the specific needs of risk assessment activities at the various levels of systems engineering and in the individual phases in the system life cycle. It was also noted that deficiencies in the risk analysis methods applied at the time caused problems near the end of the risk assessment process in both cases. It was difficult to perceive and decide upon the appropriate level of the safety measures. The case-study results emphasise that the interpretation and explanation of the implications of the final risk-level results should be developed such that they give better support to the decision-making in risk evaluation and trade studies in requirement, functional, and design analyses in systems-engineering processes.

Systematic analysis of system operations and system functions via PHA, OHA, and HAZOP studies in both cases studies brought out a great deal of information that was not directly related to safety but did have links to system availability, system usability, or system reliability. Applying a bottom-up analysis method in reliability engineering later in the life cycle may not bring out these issues, because the objectives and analysis method are not aligned with each other. To allow systematic utilisation of this valuable information, the companies could establish and maintain an overall RAMS (Reliability, Availability, Maintainability and Safety) management process that brings system-availability and system safety information together. The integration of RAMS risk management issues to the systems engineering process model is outlined in Fig. 2.

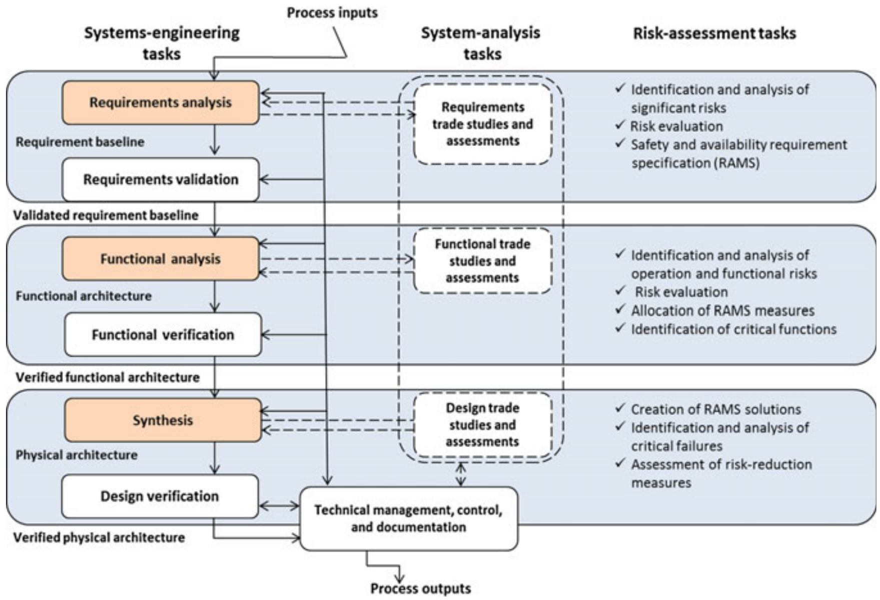

Fig. 2 An outline of the risk-assessment tasks allocated to the various phases in the systems-engineering process and associated system-analysis activities

4 Discussion and Conclusions

The system suppliers in both cases have adopted the system approach for risk assessment and implemented it in new automation system projects. The companies stated that the integration of risk assessment approach into the systems engineering process provide applicable, systematically reasoned and traceable information for risk conscious decision making in the context of automated machinery applications. The case-study results emphasise that risk assessment in unique automated machine applications should be understood as a top-down process wherein upper-work-site-level assessment results represent input and requirements for the next level, ensuring that the system-safety and system availability requirements and risk-reduction solutions are based on the actual site-specific factors involved, not merely on theoretical worst-case scenarios. The results are in line with Leveson (2011a) who also states that hazard analyses, which have long been used in industries that use dangerous processes and for other hazardous systems, can identify the causes of accidents that have never occurred before. In unique, new technology systems, analysis should begin with identification of all potential hazardous events and situations and then involve assessment of whether they are possible or not. If the consequences are very serious (e.g., fatal), the hazards in question should be eliminated even if it is not possible to determine their likelihood.

These findings are also in line with the results of recent studies of system availability and of system reliability issues in complex mobile machinery in early stages of design. Ahonen et al. (2012) state that in R&D projects intended for development of applications of entirely new technology, it is essential to carry out overall system-level availability-related risk analysis in the conceptual design phase. The availability-risk assessment in the conceptual phase should be based on system functions, not on system architecture or system components.

It can be concluded that the qualitative risk analysis methods such as PHA, OHA and HAZOP study are applicable for system-level risk identification and analysis. The case study results confirm that, when the risk analyses and risk evaluations are systematically linked to the overall systems engineering problem-solving process, the system-level elements that create risks at various levels of the system can be identified at the right time and the risk reduction measures can be assigned to the appropriate level of the organisation for evaluation.

Although recommended in international risk management standards, risk matrices should be used with caution. Four types of problems linked to risk matrices have been identified: poor resolution, errors, sub-optimal resource allocation, and ambiguous inputs and outputs. The results support the opinion stated by Cox (2008) that risk management decisions cannot be based only on rating of risks' frequency and severity factors. The judgement inherent in risk ranking should be carefully explained (Cox 2008). The decision-makers must understand what the results mean. Site-specific information should be used as much as possible in risk analyses, risk estimation, and risk evaluation, to enable appropriate reasoning based on the actual work-site conditions, practices, and limitations.

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Incorporating Data Warehouse Technology into Asset Information Management Systems for Large Assets

Amy J.C. Trappey, Charles V. Trappey, Lin Ma and Acer C.C. Chang

Abstract Large sized engineering assets such as power transformers are critical parts of the power supply networks. Therefore, focusing on early fault diagnosis to maintain large transformers in good condition is an important operational task to the power companies. In order to manage and fully utilize the big data generated from the large number of transformers, this paper incorporates data warehouse technology to a fault diagnosis system for the entire transformer fleet. The research includes two major parts. First, a data warehouse (DW) is designed for the large assets information management. Then, the DW-based intelligent fault diagnosis system is developed and implemented. The DW stores the complete transformers' data and then different data cubes are defined according to various applications. The fault diagnosis system for power transformers consists of the condition monitoring module, failure diagnosis module, and intelligent decision supports module. The research methodology and prototype system are verified with real data from a series of 161 kV transformers in operations.

Keywords Engineering asset management · Fault diagnosis · Transformer · Data warehouse · Data mining

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1 Introduction

The conditions of power transformers influence the stable operations of entire power supplies. Preventing power transformers from unexpected shut-down become an important part in engineering asset management (EAM). In early stage of power transformer asset management, power transformer engineers sample and send oil from the transformer to the laboratory for testing. The tests measure the amounts of dissolved gases (DG) in oil samples. Through several international dissolved gas analysis (DGA) guidelines, based on the DG readings and heuristic rules, the potential problems of transformers and give suggestions for maintenance and repairs are identified. Unfortunately, the amount of the gases may increase rapidly in between samplings. Thus, it is essential to develop a sensor-based remote data collection, directly linking to the fault diagnosis system, to alert asset managers of the potential faults in real-time.

Nowadays, many power companies are installing remote terminal units (RTUs) with sensor equipment on power transformers to monitor real time data (e.g., oil dissolved gases, temperatures, and other parameters). RTU systems collect huge amounts of data from an increasing number of transformers constantly. With the increasing volume and complexity of transformers' operational parameters and data, a basic database management system (DBMS) is too simple to manage multidimensional big data in real time. Thus, the data warehouse technique is incorporated not only to store data but also to process multidimensional data for efficient and flexible applications. The integrated web-based transformer asset management system includes applications, such as intelligent decision support module, real-time condition monitoring module, and data visualization module. In this research, the modules of the DW and its fault diagnosis prototype modules are developed and implemented using the Microsoft SQL Server Business Intelligence and the ASP.NET for C#. The prototype system with the DW and application framework is verified with real condition data collected from a set of 161 kV transformers operated by Taiwan's power suppliers.

2 Literature Review

This paper presents the development of a transformer asset information system. The main research goal is to increase the efficiency and flexibility of big data processing by using data warehouse technology and integrating intelligent method to diagnose potential faults of transformers. In this section, we focus on reviewing transformer fault diagnostic literature and the introduction of data warehouse technology.

2.1 Transformer Fault Diagnostic Methods

Dissolved gas-in-oil analysis (DGA) is one of the most reliable approaches for detecting early faults of transformers, which is widely used in many power companies. Main principle of DGA is to check the condition of insulating materials and insulating oil of power transformers operating under high temperature. Dissolved gases, such as O_2, CO, CO_2, H_2, H_2O, CH_4, C_2H_6, C_2H_4, and C_2H_2, are monitored and measured as DGA readings for detecting potential faults. There are many methods in DGA to identify the potential faults of transformers. Trappey and Chang (2013) integrate five sets of international DGA rules, i.e., Doernenburg ratio, Rogers ratio, Duval's triangle, the dominant gases, and the phase analysis, into an intelligent diagnostic e-report system to improve the consistency of transformer faulty diagnoses. Although DGA is one of the most reliable and proven techniques to detect incipient faults in transformers, these heuristic and non-mathematical approaches, are based on commonly accepted rules of thumb and may provide intuitive and inconsistent diagnostic results. To overcome the potential inconsistency in diagnoses, artificial intelligence approaches such as back-propagation neural network (BPANN), have been used to predict incipient faults in transformers. Zakaria et al. (2012) integrated BPANN and DGA techniques to classify seven types of transformer conditions based on three combustible gas ratios (C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6). These gas ratios are based on IEC 60599 (2007) standard and are defined as inputs to the BPANN prognostic system. The output layer is composed of seven transformer condition types (partial discharge, discharge of low energy, discharge of high energy, three types of thermal faults, and normal). Annapoorani and Umamaheswari (2012) discuss all possible failure types and identify six key dissolved gases (i.e., H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO_2) which cause these faults. Two kinds of data input to the neural network's training parameters (input and output layers). Both literatures (Zakaria et al., Annapoorani and Umamaheswari) show good performance for the prediction of faults in power transformers fault diagnostic systems.

2.2 Data Warehouse Techniques

The "data warehouse" (DW) was first defined as a tool for maintaining subject-oriented, integrated, time-variant, and non-volatile data to support decision making. A DW integrates data from different data bases and data sources through consistent filtering criteria, record data at each time point, and normalize the structure of database for the same subject to support data processing and information analysis (Inmon 2005). Today, there are a few existing DW solutions in the commercial applications, e.g., Oracle Database, IBM Red Brick and Microsoft SQL

Table 1 Difference between OLAP and OLTP

OLAP	OLTP
Current and historical data	Current data
Multidimensional data structure	Complex data structures
To help with planning, problem solving, and decision support	To control and run fundamental query tasks

Server Business Intelligence. The concept of DW is different from a traditional database. The latter is mainly to conduct online transaction processing (OLTP) and the former is to efficiently and flexibly handle online analytical processing (OLAP). OLAP provides a summary of complete data set (past, current, and future/planned) in multi-dimensional formats. Different details of data can be queried through “drilling-down” and “rolling-up” techniques in DW. Differences between OLAP and OLTP are showed in Table 1 as reported by Thomsen et al. (1999).

Data warehouse is composed of one to many data cubes. Each data cube is designed for different purposes (subject-oriented) of monitoring, visualization, and analytic applications. Data cubes are the main objects in OLAP, a technology that provides fast query data in a data warehouse. A data cube is usually constructed from a subset of a data warehouse and is organized into a multidimensional structure. Data cube is designed by fact tables and dimension tables. A fact table typically has two types of columns: foreign keys from dimension tables and fact column contain numeric data. The primary key of a fact table is a composite key that is made up of all of fact table’s foreign keys. Fact tables contain the content about the subject of the data cube. A dimension table is a structure usually composed of one or more hierarchies for conducting OLAP analysis to fact table. The primary keys of each dimension table are a part of the composite primary key of the fact table.

The most common data cube structures are star schemas and snowflake schemas. The star schema uses the fact table to link dimensional tables to implement the relationships among data. The snowflake schema not only links dimensional tables with the fact table but also with other dimensional tables. Figure 1 shows the cube structures of star schema and snowflake schema (Microsoft 2015).

In the Microsoft SQL Server Business Intelligence data warehouse system, MDX is a standard query language used to retrieve data for OLAP analysis from the data cube. After data warehouse development, when users run an analytical application using a pre-defined data cube, it is necessary to apply MDX for full queries and for calculations. The MDX editor is included in the SQL Server Management Studio (Microsoft 2015) for creating MDX codes.

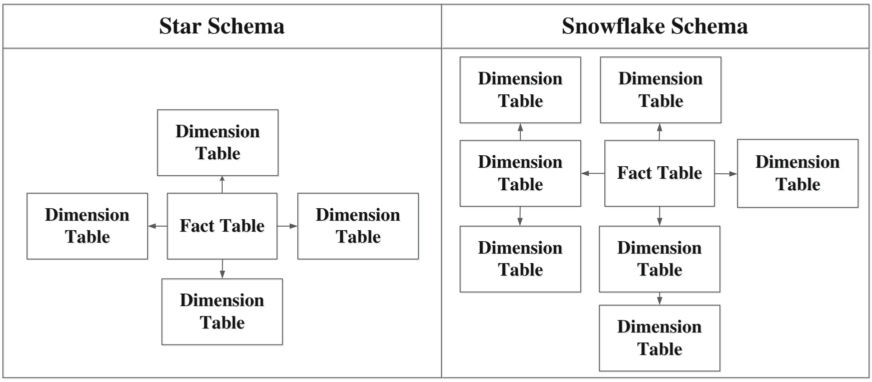

Fig. 1 Examples of data cube structures in star schema and snowflake schema

3 Methodology

This paper presented integrated engineering asset management system by adopting DW technology. Figure 2 shows the framework and the entire operational process of the integrated engineering asset management system for transformers' fault diagnoses. First, the existing sensors acquired data from operational transformers in every five incremental minutes. Then, data are consolidated into the central DW. Transformer maintenance crudes use the online system to constantly monitor and detect potential faults of remote transformers. The system uses OLAP approach to input data to run different fault diagnose modules. The system transmits the diagnosis results consistently to the users via web-based user interfaces. Afterward, the asset managers and crudes can take actions to maintain and/or repair transformers according to the diagnostic results.

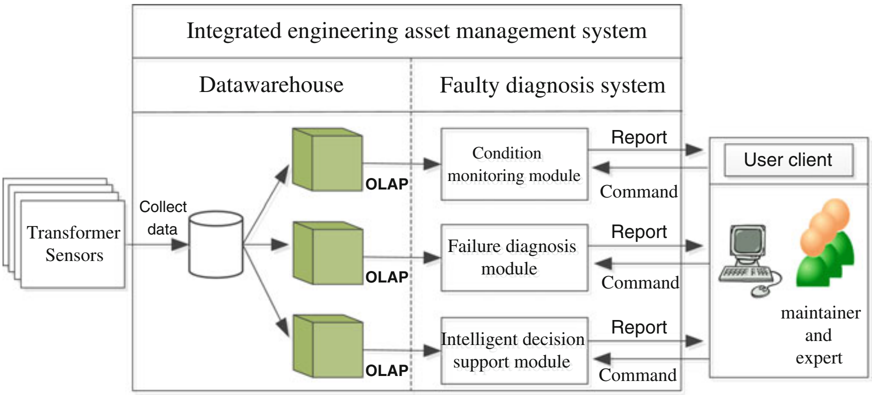

Fig. 2 The framework of integrated engineering asset management system for transformers fault diagnoses

The prototype system framework, as shown in Fig. 2, is divided into two main parts, which are the DW and the fault diagnosis system providing modules of condition monitoring, diagnostic heuristic rules, and intelligent (BPANN) decision supports. The details of the modules are described in the fallowing sub-sessions.

4 Data Warehouse for Large Asset Information Management

The data warehouse stores whole historical and real time data about transformers (basic information, parameters, and dissolved gases) and then utilizes these data to design different data cubes according to various applications of this system. There are three data cubes in the data warehouse system. They are "Oil dissolved gases" data cube, "Condition monitoring" data cube, and "Others parameters" data cube. In the "Condition monitoring" data cube, factor table is [Transformer_Monitor] and the dimension tables are [Transformer_Profile], [Transformer_VoltageType], [Year], [Month], [Date], [Hour], and [Minute]. Their primary keys are ID, VoltageType, Year, Month, Date, Hour and Minute. In the "Oil dissolved gases" data cube, the factor table is [Transformer_Gas] and the dimension tables are [Transformer_Profile], [Year], [Month], [Date], [Hour], and [Minute]. The primary keys of them are ID, Year, Month, Date, Hour and Minute. In the "Others parameters" data cube, the factor table is [Transformer_Others] and the dimension tables are [Transformer_Profile], [Year], [Month], [Date], [Hour], and [Minute]. Their primary keys are ID, Year, Month, Date, Hour, and Minute. Figures 3, 4 and 5 illustrate the structures of three data cubes.

In a data warehouse system, each data cube has several dimensions. We can use these dimensions to roll-up and drill-down the data cube. In this research, the most important dimension is time for each data cube. Because time play an crucial role in building annual reports, monthly reports, and daily reports respectively. Time dimension is divided into year, month, date, hour and minute in this system. This method let users observe historical data in an intelligent way. System shows the line chart in each year, month, and date. So, users can know which months or dates or hours are dangerous through these historical data. In the [Transformer_Profile] data table, ID is the primary key. Every single ID represents unique equipment and each of them has their criteria about each monitoring data. When the value is below the "min" value indicating "safe," between "max" and "min" indicating "notice," and greater than "max" indicating "danger." There are exceptions. For example, the voltage has to be between "max" and "min" values; otherwise, "danger" indicator will appear.

After finishing data warehouse development, users can apply OLAP technique to query interesting data in the data cubes of data warehouse easily. But, if users want to use web interfaces to query data from data cubes, MDX codes are to be created to query data from the data warehouse.

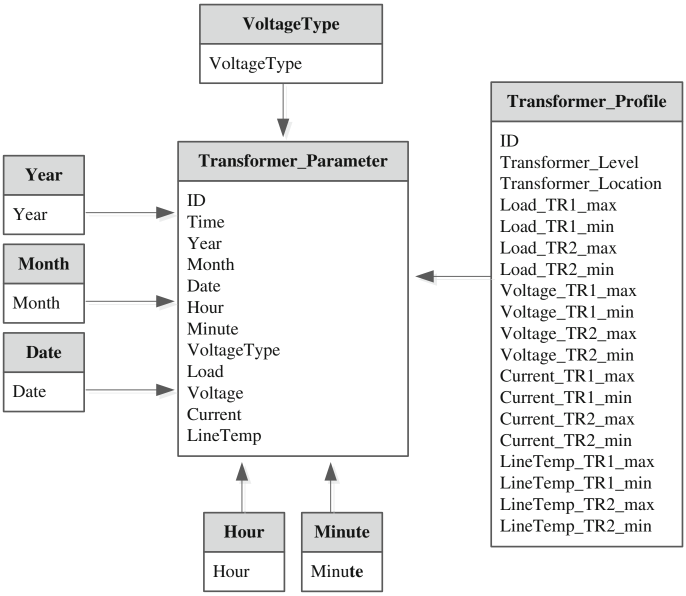

Fig. 3 The structure of "Condition monitoring" data cube

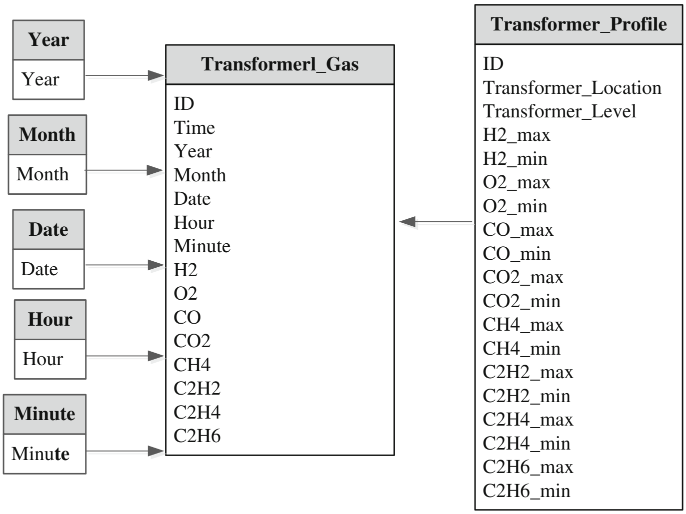

Fig. 4 The structure of "Oil dissolved gases" data cube

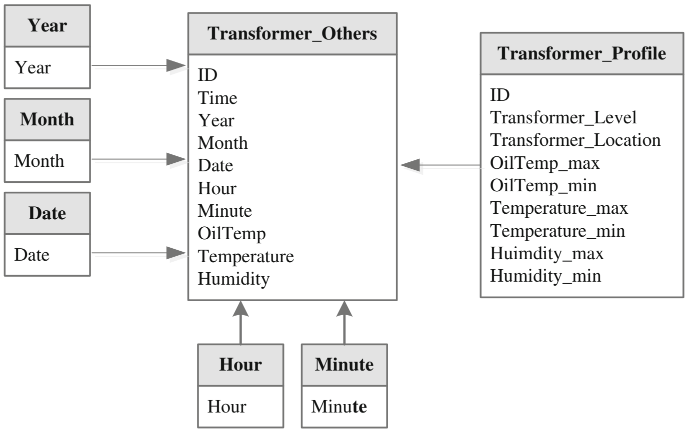

Fig. 5 The structure of "Others parameters" data cube

4.1 Decision Support Module for Fault Prognosis

There are three modules in integrated engineering asset management system. They are condition monitoring module, failure diagnosis module, and intelligent decision support module. Condition monitoring module applies the "Condition monitoring" data cube as defined in the previous section. There are two functions in condition monitoring module. In real-time condition monitor function, system will show the latest data, based on each parameter's warning zone (defined in the transformer's profile), with the indication of the transformer's safety status in real-time. On the other hand, the historic condition monitoring function provides multi-dimensional reports of statistical trends according to the users' specifications using OLAP technique. Data warehouse can flexibly build annual reports, monthly reports, daily reports, or hourly reports for each parameter. Through these reports and visualization graphs, users can effectively monitor transformer conditions (e.g., line temperature, load, voltage, current, and oil dissolved gas levels) and historical trends in specified intervals.

The intelligent decision support module uses BPANN to predict the faults of transformers. The inputting parameters for BPANN fault prediction are organized in a cube with five parameters (CO_2, C_2H_4, C_2H_6, CH_4 and CO) according to the previous research (Trappey et al. 2015). In this module, the input data cube is the "Oil dissolved gases." Via the OLAP technique, the system will filter other gases out from the "Oil dissolved gases" data cube as BPANN module inputs. Users can select equipment they are interested in analysing to run prognosis in any given time using data queried and retrieved from the data cube. In the failure diagnosis module, the DGA rules are run with the data cube inputs. Each rule needs different oil dissolved gases as input parameters. The data queries from the cubes are also conducted based on the DGA rules using OLAP technique.

4.2 System Demonstration

This prototype system's data warehouse is implemented using SQL Server Business Intelligence System. The example of actual data warehouse structure is shown in Table 2. The example is about the historical voltage data of transformer, whose equipment ID is #08020. The data record full January 2013 voltage readings. The column (vertical)-axis is in dates and the horizontal-axis is in hours and minutes. Before connecting data warehouse to web pages, it is necessary to test MDX code in SQL. At the same time, to show the benefit of data warehouse, we compare the query results between MDX and SQL codes.

Table 3 shows the query result by using MDX code in SQL Server.

Table 4 shows the similar query using the traditional SQL code. In a data warehouse, dimensions in vertical-axis and horizontal-axis can be flexibly changed according to MDX commands. Any parameters' data trends can be drawn into annual, monthly, daily or hourly reports. On the other hand, in traditional SQL commands, data are shown in fixed patterns. Thus, data warehouse can present data in more flexible ways than the traditional SQL database using SQL queries.

Figure 6 shows six daily voltage data curves between 1:00 and 2:00 in January 1st, 2013. The data of the daily line chart are acquired from the data warehouse using MDX query codes as shown in Table 3. The MDX query result includes

Table 2 The actual data warehouse in SQL server business intelligence

ID	Voltage type		Year		Month		
08020	LVTR1		2013		01		
Date	Time						
	00:14	00:19	00:24	…	01:14	01:19	01:24
01	23,273.7	23,263.9	23,273.7	…	23,293.2	23,322.4	23,332.1
02	23,166.5	23,176.2	23,205.5	…	23,283.4	23,254.2	23,283.4
03	22,981.3	23,010.5	22,932.6	…	23,059.3	23,078.8	23,088.5
04	23,117.7	23,166.5	23,176.2	…	23,332.1	23,332.1	23,371.1

Table 3 The query result using MDX code (i.e., the voltage record)

ID	08020	08020	08020	…	08020	08020	08020
Year	2013	2013	2013	…	2013	2013	2013
Month	01	01	01	…	01	01	01
Date	Time						
	00:14	00:19	00:24	…	00:14	00:19	00:24
01	23,273.7	23,263.9	23,273.7	…	23,293.2	23,322.4	23,332.1
02	23,166.5	23,176.2	23,205.5	…	23,283.4	23,254.2	23,283.4
03	22,981.3	23,010.5	22,932.6	…	23,059.3	23,078.8	23,088.5
04	23,117.7	23,166.5	23,176.2	…	23,332.1	23,332.1	23,371.1

Table 4 The query result using traditional SQL code (i.e., the same voltage record)

ID	Year	Month	Date	Hour	Minute	Voltage
08020	2013	01	01	00	14	23,273.7
08020	2013	01	01	00	19	23,263.9
08020	2013	01	01	00	24	23,273.7
…	…	…	…	…	…	…
08020	2013	01	01	01	14	23,293.2
08020	2013	01	01	01	19	23,322.4

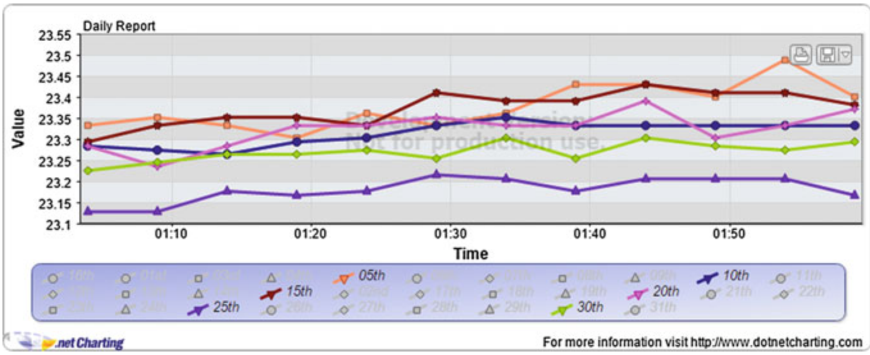

Fig. 6 The comparison of six daily voltage curves

multiple dates (6 days) in the same hour frame. Therefore, the visualization graph can show the multiple daily curves simultaneously for comparison. Figure 7 shows another comparison of six monthly (November, December, January, June, July, and August) temperature trends. Through the flexible MDX query and report, the line temperatures of transformers in different months are closely monitored.

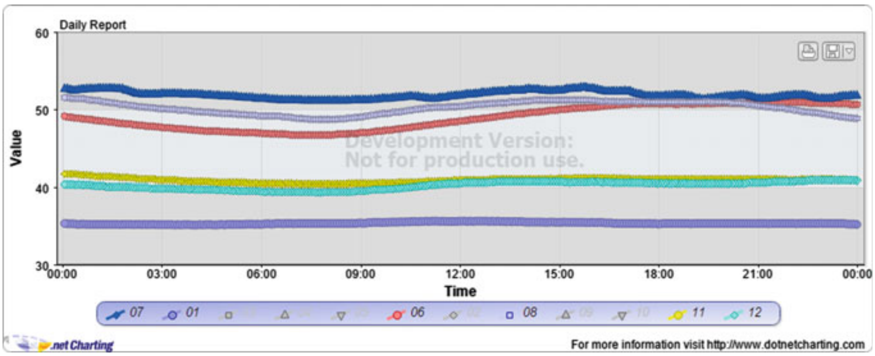

Fig. 7 Six monthly line temperature curves (plotted with daily averages)

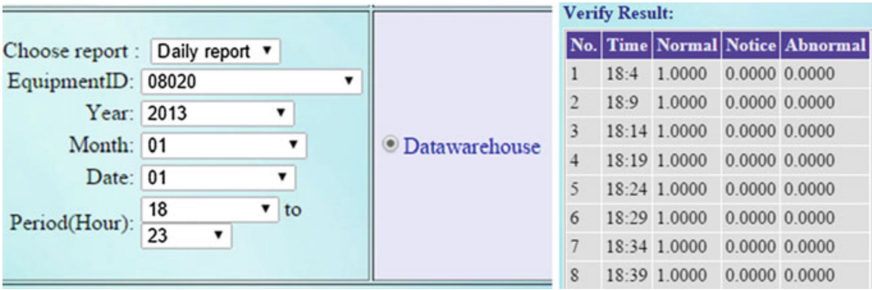

Fig. 8 User interface of intelligent decision support module

Figure 8 shows user interface of intelligent decision support module. First, select time period and choose equipment ID for running BPANN diagnosis. Then, the results are shown corresponding to the time period. There could be three types of results (normal, notice, and abnormal). Both times and diagnostic results are shown as the right-side table of "Verify Result" in Fig. 8.

5 Conclusion

This paper proposes an information management system for large transformer asset management. The main research focuses on DW design, development, and its integrated applications to the integrated engineering asset management, which includes condition monitoring and fault diagnosis modules. Through data warehouse technology, system can process large volume of data efficiently and flexibly for a variety of data visualizations and applications. The OLAP technology provides multi-dimensional reporting and visualization capabilities, which help asset managers monitor dynamic information and conditions of large assets with remote sensors (e.g., transformers). The integrated DW technology and decision support modules allow remote monitoring and integrated management of large assets clusters to ensure the healthy conditions and reliable operations of assets and infrastructure, which are critical to the energy sector or other sectors relying heavily on large assets.

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Spare Part Stock Modeling and Cost Optimization

Joel Turpela and Timo Lehtinen

Abstract Modeling and planning the spare part item stock is a quite complex, but utmost rewarding task regarding the operational excellence of a manufacturing industry company. The challenge with the design is derived from multi-variable optimization tasks, including e.g. consumption rate of an item, division of stocking costs, and potential shortage costs. This applies especially in case of new spare part item with no history data for defining the consumption rate. The extra reward from a systematic spare part stock design process with the simulation based method is the ability to test stocking scenarios (optimized own stock vs stock outsourcing) and to obtain summary reports of different stocking cost type distributions (e.g. net interests costs, stock upkeep costs, order costs and shortage costs). In practice, the design process often focuses on finding optimal stocking parameters for hundreds or thousands of stock items that belong to the same criticality class. The optimization is either done to fulfill service rate requirement or for direct cost optimization purposes. The whole process helps to refine gathered history data and expert knowledge to true understanding, and with the systematic method to identify key indicators for the optimal spare part stock (min. risks, max. availability, min. costs). A Finnish advanced analytics expert company, called Ramentor Oy, together with the research institute (Tampere University of Technology) and several industry partners, has developed a systematic methodology combined with a pragmatic software tool that guides through the stock design and optimization process. The tool, called StockOptim, also provides interface to operative IT systems (ERP, CMMS, EAM) and to modern data analytics tools (e.g. ELMAS) for managing the precedent process modeling, data collection, criticality and risk analyses tasks. StockOptim simulates spare part stock events, calculates stocking costs and stock items shortage data (e.g. mean shortage time or mean shortage costs). The software is also able to find approximation for the items optimal stocking parameters (reorder

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point and order amount). The simulation based approach is flexible, also for adding new details or extensions, and not as exposed to distorting and restricting assumptions as analytic-numeric methods.

1 Introduction

Spare part logistics and optimization, thus, modeling and planning the spare part items inventory, has a fundamental role in the development of both reliable and cost-efficient service business over multiple locations.

In the research, the subject of spare part stock control and management has long history of various projects over past decades. E.g. in the literature overview of spare parts inventories by Kennedy et al. (2002), the reported methods were found to be very case specific, which is limiting the overall usability of the methods on general spare part stock optimization case. In order to create more generic approach, Ramentor Oy, together with the research (Tampere University of Technology) and several industry partners, developed a systematic methodology combined with a pragmatic software tool, called StockOptim.

The kernel of the StockOptim tool is presented on the Fig. 1. The actors on the tool are one stock, one stock item, one or more suppliers, and one or more stock item consumers.

The key modules are stock balance simulation (later referred as SB simulation) and cost calculation. Both modules are based on the research work of Hagmark and Pernu (2006). Attributes for the SB simulation are: customers' consumption, lead-time attributes (e.g. supply time and order preparation time) and spare part stock control parameters (re-order point, order quantity and pre-order time). Stock control parameters are later referred as stocking strategy on text. The modeling of customers' spare part consumption is divided in two different categories depending on how long in advance the stock has information of upcoming consumption event. These categories are named as unscheduled and scheduled consumption on the tool.

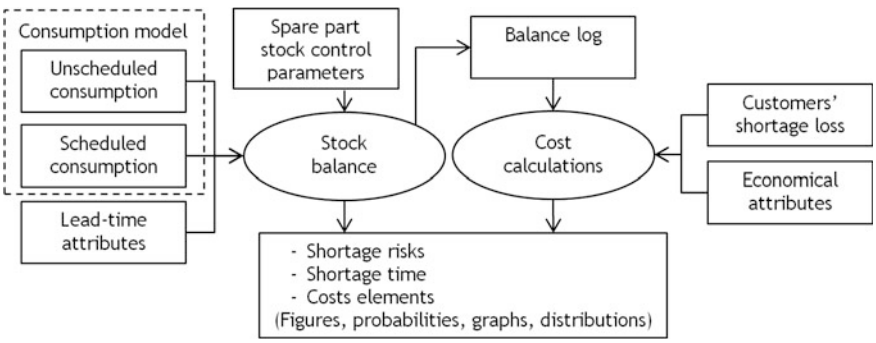


Fig. 1 The kernel of StockOptim method

Spare part consumption model can be defined from different sources:

- Spare part stock history events (pick-up times, pickup amounts, lead-times)
- Direct expert knowledge (pick-ups per year and probabilities of consumption amounts)
- Simulating k/n-clusters spare part consumption in certain stress level (Hagmark and Pernu 2006).
- Simulating spare part consumption of event logic model of process

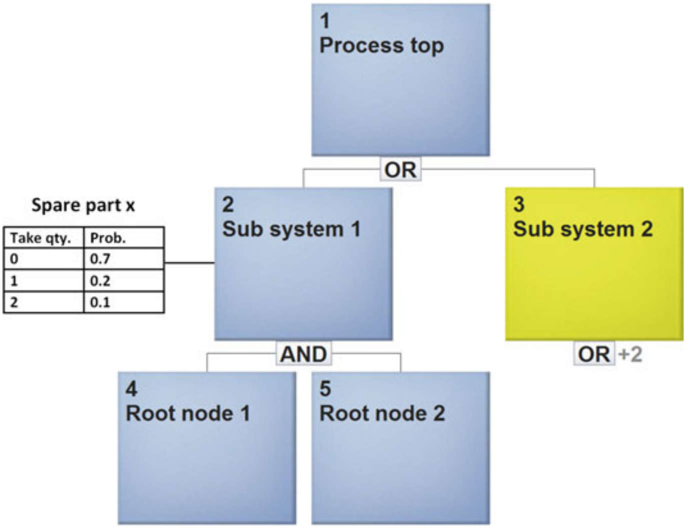
SB simulation module generates a time ordered stock event log with information of consumer location and current stock balance. The log is the base for stock key performance indicator (KPI) calculations and for stock shortage calculations (its possible sort out of spare part shortage events from the log as the stock balance drops below zero). Calculated stock shortage data contains time distributions, shortage occurrence probabilities and stock service rate values. Detailed shortage data calculation is one of the main benefits of the SB simulation. In the costs calculation module, simulated log data is combined with the monetary input values (e.g. net interests' costs, stock upkeep costs, order costs) and stock shortage costs to calculate various profit/loss elements and total cost for the stock item over the planning period (period of time where consumption and costs are examined).

The objective in spare part stock design is to ensure sufficient supply of parts to customers with minimum overall costs. What is sufficient, depends on customer's definition on criticality (consequences if the spare part is not available). The StockOptim tool includes the optimization algorithm that finds approximation (Whitley 2001) of the fittest (the most cost effective) stocking strategy. In a case the spare part shortage cost cannot be defined, it's possible to use the stock service level constraint as the optimization target level (Taijbakhsh 2010).

2 Spare Part Consumption Model

Spare part consumption model is a key attribute for the SB simulation. As mentioned before, possible data sources for the model are: history data, expert knowledge, k/n-cluster durability simulation and the event logic model (Fig. 2).

The StockOptim tool's consumption model is divided to unscheduled and scheduled categories depending on how long beforehand spare part stock have information of upcoming consumption event (stock has enough time to react). Scheduled consumption is defined by customer visit time inside the planning period and pickup quantity by the visit. SB simulation's method to react on the scheduled consumption is to order special supply of spare parts n days (pre-order time) before actual consumption event. All items in that special order are used on the upcoming scheduled consumption event. Unscheduled consumption is defined by customer visit time distribution, probabilities of consumption quantities, consumption periodicity and unevenness in the planning period. Method to react on the unscheduled



Take qty.	Prob.
0	0.7
1	0.2
2	0.1

Fig. 2 Event logic model with spare part consumption data

consumption implements continuous-review (Q, R) inventory policy, where new order (fixed quantity) is placed if stock balance reaches the reorder point (R).

Planning the stocking strategy for an item that does not have any consumption history events, or if consumption is dramatically changed due to new facility investments, require expert data (e.g. part reliability estimate, customer location MTTF) based methods to construct a consumption model. One method is to simulate consumption with a k/n-cluster that is a group of part locations with certain stress levels (Hagmark and Pernu 2006). To define cluster, nine attributes are used: stress level of the parts, failure logic redundancies, operation and maintenance strategies, etc. This method works well if planning task contains only few stock items but may be hard to scale up for larger item numbers. An alternative way is to add spare part data to event logic model of the system (Fig. 2). The model contains detailed information of timing, causes and consequences of failure events and by advanced analysis methods is possible to calculate spare part consumption model. This article focuses explaining this method as part of spare part stock planning. An event in the event logic model can mean the change of anything or any situation. In addition to relations between events, it is possible to model other event-related features like spare part consumption. The model can be done as part of a system analysis (e.g. LCC, criticality classification, risk management) and used later as base for the spare part consumption model. Figure 2 presents an event logic model with spare part consumption quantities and quantity probabilities data. When model events are simulated and "Sub system 1" goes to failure mode ("Root node 1" and "Root node 2" are both in failure mode) there are 0.7 probability that failure can be repaired without any spare parts, 0.2 probability that one spare part x is needed and 0.1 probability that 2 spare parts are needed. Ramentor Oy has ELMAS (Event

Logic Modeling and Analysis Software) tool that is capable to model, analyse and create a report of complex systems or production processes.

There are several advantages to use event logic model as data source for the spare part consumption model:

- Support of very complex spare part consumption logics
- The event logic model can be used in wide variety of analysis (spare part consumption model is one minor use case)
- The event logic model usually contains information of spare part criticality and spare part shortage costs.

3 Spare Part Stock Balance and Costs Elements

According Kennedy et al. (2002) key issues to be solved are: when to place order, order size and choice of balancing between reducing stocking costs and increasing spare part availability. To calculate spare part stock operational costs for certain stocking strategy, StockOptim tool combines a stock event log with various economical attributes. The log contains of customer visit events and spare part supply events and is created with stochastic simulation in SB simulation module.

The key attributes in simulating spare part stock balance, are customers' consumption, lead-time and stocking strategy (Fig. 1). The StockOptim method models spare part lead-time with order preparation time (time that sending order to supplier takes) and supply time of one or more suppliers. Supplier is defined by supply time distribution (mean and standard deviation), probability to use supplier (one stock item can have multiple suppliers) and supply costs.

Figure 3 represents one year's section of the simulated stock balance log. Used stocking strategy in simulation was: reorder point = 2, order quantity = 10, pre-order time = 20 days. At time of about 220 (days) spare part stock encounters a shortage period (stock balance drops below zero) when spare part demand surpasses

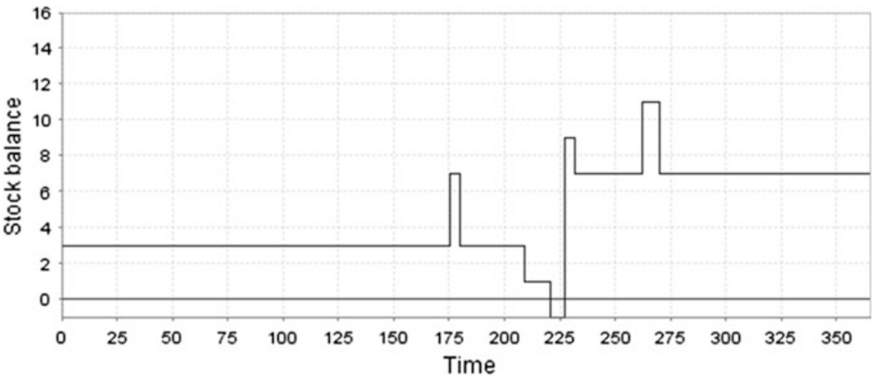


Fig. 3 One section of simulated stock balance

available items in stock. Unscheduled consumption events occur yearly at time 180 days and 270 days. Supply orders for them are done 20 days before actual event and simulated balance shows peaks at those points.

Spare part stocking cost elements can be calculated by combining supplier costs, economical inputs and customer's shortage costs to the simulated balance log (Fig. 1). Economical inputs in the tool are: item purchase price, cost of making order line, value of lost item, item holding cost, value decline and annual percentage rate. Customer's shortage costs are defined by shortage event cost and time dependent costs for different shortage sizes (size of negative balance).

Results from costs calculation module are figures (mean, standard deviation and distributions) for ordering, delivery, upkeep, value decline, waste, interest and customers' shortage costs. The cost calculation module keeps cost areas separated and enables to sum combination of selected areas. Results enables option to test cost effects of various stocking strategies e.g. spare part stock outsourcing vs. owned spare part stock near customer site.

4 Spare Part Stock Optimization

Finding optimal stocking strategy is multivariable optimization task. The goal is to find balance between reducing stocking costs and ensuring spare part availability to the customer locations. The problem is a common topic in the research and number of models exists in literature (Al-Rifai and Rosetti 2007). In the StockOptim, the optimization method is a genetic algorithm. It does not guarantee to find the absolute optimum (Whitley 2001), but the approximation of the fittest stocking strategy.

Spare parts stock optimization with the event logic model is a process (Fig. 4) where expert data is documented and refined to knowledge. The logic model is

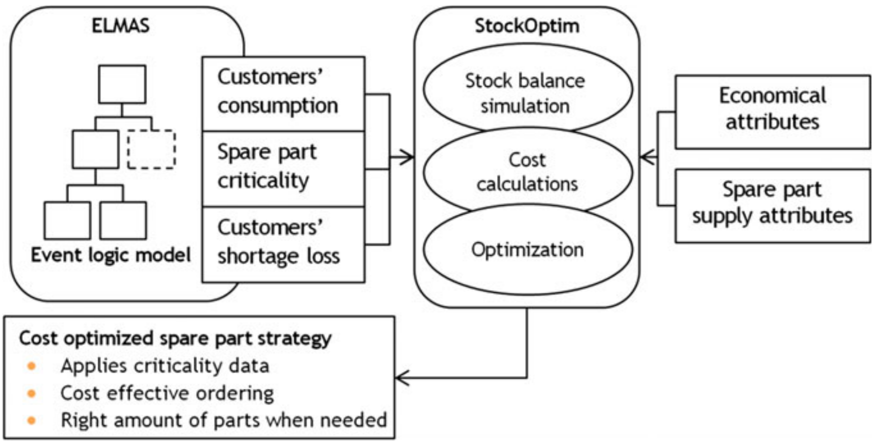


Fig. 4 Spare part stock optimization process

usually created as part of system analysis (e.g. risk analysis). Ramentor Oy has developed advanced analysis methods to calculate spare part consumption, customer locations criticality and approximation of the spare part shortage costs from the event logic model. Spare part criticality data is essential attribute especially if shortage costs data is not available. The optimization algorithm searches the fittest stocking strategy that fulfils required service level with stock items criticality.

The result of spare part stock optimization process is a list of stock items with optimized cost of stocking strategy and data on the service rate for the stock and its separate items. Optimized availability for the critical spare parts increases the reliability of the whole manufacturing and/or service process. The result data also contains various economical values for the items. This detailed information enables risk management in operations, improved cost-efficiency in stock management, and above all productive dialogue and informed decision making for all the responsible parties, with both CAPEX and OPEX related business development point of view covered.

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Industrial Fleet Services: Introduction and Application Case

Simone Turrin and Mohamed-Zied Ouertani

Abstract Traditional industrial service offerings are mainly designed to service a single device or a single system of devices. The current trend in new industrial service development is the so-called fleet services. Fleet services are meant to service a finite set of homogeneous and heterogeneous devices and systems (over different production plants, locations, regions, etc.). This paper first illustrates the relevance of fleet services in a business-to-business environment and their importance for both service provider and customer. The second part of this paper focuses on fleet monitoring as an application case of fleet services. The idea behind fleet monitoring is the ability to provide a customer with monitoring capabilities of its industrial equipment mainly in terms of fleet composition, fleet reliability, fleet availability and fleet maintainability. The key performance indicators developed for the proposed fleet monitoring solutions are introduced and discussed in the last part of the paper.

1 Introduction

Business-to-business services relating to physical asset management play an increasingly important role in industry. Industries are indeed more and more focusing on their core business while outsourcing non-value creating activities. Their challenges become more difficult as they own or operate a high number of assets or what is now being coined as “fleet of assets”. Managing the entire fleet of asset is what industries are currently thriving for. The fleet management problem, in its simplest form involves managing fleets of assets to meet customer requests as they evolve over time. The management of information related to a global asset fleet becomes therefore one of the main success factors of industrial service development

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in addition to the generic success factors when managing single assets as reported in earlier studies (Jooste and Vlok 2014).

Although the fleet management benefits seem trivial to the reader, few studies presented real cases on how fleet management can support the service provider and consumer in keeping up with competitive pressure. This paper aims at shedding light on the potential of focusing on fleet of assets instead of single asset. A use case will be presented on fleet monitoring and the related KPIs to make sure customers and service providers are extracting value from such an offering. The remaining of this paper is structured as follows. Section 2 describes what is meant by fleet management and fleet services as well as the benefit of fleet services for customers and service providers. Section 3 reports on the specific case of fleet monitoring from a power and automation service provider. Section 4 provides a set of KPIs a service provider could use to make sure both the service provider and the service consumer gain benefit and co-create value. Finally, Sect. 5 concludes the paper and proposes future prospects.

2 Fleet Services

While asset management is well defined in literature and industrial practices as "*the coordinated activity of an organization to realize value from assets*" (ISO 55001 2014), fleet management is at its infancy and not well defined. This paper considers fleet management as the *systematic and coordinated* ***practices*** *through which an organization optimally and sustainably manages its* ***fleet*** *of assets, the associated* ***performance***, ***risks*** *and* ***expenditures*** *over their* ***life cycles*** *for the purpose of achieving its organizational strategic plan.* This definition serves as a basis of developing a fleet management system and is adopted from the BSI-PAS55.

This definition currently focuses mainly on the value of fleet management to asset users. For an organization managing a high number of devices, equipment and plant, it is crucial to have a holistic view on that fleet. Fleet management allows for better resources management, reduced maintenance costs, optimized scheduled downtimes and preventive maintenance. This will lead to higher overall equipment effectiveness and efficiency.

On the other hand, it is equally important to highlight the benefit of servicing a fleet of assets instead of single jobs for a service provider. First, a service provider will be able to better dispatch the service technician for the respective service jobs. This will lead to cost reduction. Second, the more the service provider has a visibility on the fleet, the higher will be the quality of the delivered service. Indeed, the knowledge built from the fleet is higher than the sum of knowledge gained from single asset servicing. Third, customers often do not want to deal with more than 3 service providers making fleet management a key component to gain competitive advantage. This will lead to higher customer retention. Finally, the learning from the fleet could be then fed back to the research and development department for product and service improvement and innovation.

3 Fleet Monitoring

Among different possible industrial fleet service solutions, fleet monitoring is considered in this paper as an application case. The main purpose of fleet monitoring is supporting the fleet management by providing the fleet management organization with monitoring capabilities of relevant fleet properties. Ideally, a fleet monitoring solution should not only track and visualize the historical and current values of the relevant fleet properties but also predict their future trends. In the following part of this section a possible configuration for an added value fleet monitoring solutions is suggested and discussed.

Table 1 shows a list of the properties that are relevant for fleet monitoring. Monitoring the *fleet composition* in terms of number, list and main characteristics (asset family, asset type, asset manufacturer, asset age, application, etc.) of any fleet component is the cornerstone of any fleet monitoring solution. This provides the fleet management organization with a so called asset register which is the reference of any further fleet monitoring capability. In addition, monitoring the historical and current installed value of the fleet (as sum of the monetary value of each fleet component) gives a valuable insight into the current status and the development of the capital asset. For fleet of vehicles or ships (or fleet of devices installed in vehicles or ships), the *fleet location* in terms of position of each fleet component is

Table 1 Exemplary list of fleet properties that are relevant for fleet monitoring

Fleet monitoring of …	
Categories	Properties
Fleet composition	Number of fleet components
	List of fleet components
	Installed value of fleet components
Fleet location	
Fleet utilization	Status of fleet components
	Usage profile of fleet components
	Operating conditions of fleet components
Fleet reliability	Number of failures
	Fleet health index
	Fleet probability of failure
Fleet availability	Fleet uptime
	Fleet downtime
	Fleet MTTR/MTTF/MTBF/etc.
Fleet risk	Fleet criticality
Fleet maintainability	List of fleet maintenance activities
	Spare parts
	Maintenance skills and competences
	Maintenance budget

also a valuable fleet property to be monitored. This is true, for example, in the case when the capability of maintaining the fleet depends on its current location. Monitoring the *fleet utilization* in terms of status, usage profile and operation condition helps the fleet manager to identify sub-fleets characterized by a particular high or low capacity utilization. This may lead to the identification and definition of best practices and weak spots in the fleet utilization that can be used for a better exploitation of each fleet component. Due to the direct impact on the business and on human and environment safety aspect, the monitoring of fleet properties related to the reliability, availability and maintainability of a fleet of assets is of particular interest. Monitoring the *fleet reliability* is strictly related to tracking and forecasting the health condition and the remaining useful life of the fleet and its individual components, mainly in terms of probability of failures or health index. *Fleet availability* considers also all the additional aspects related to maintenance (corrective, preventive and predictive), repair, replacement or retrofit having an influence on critical factors like the fleet uptime, the fleet downtime and the fleet MTBF (mean time between failures). Finally, by monitoring the *fleet maintainability* an indication about the capabilities of the fleet management organization to maintain properly the fleet are expressed in terms of maintenance activities, spare parts, skills, competences and maintenance budget. Again, it is worthy to mention that the highest value to the fleet management organization is provided not only by tracking the historical values or monitoring the current value of the fleet properties but by predicting their future trends.

Due to the richness of information that the suggested fleet monitoring solution provides to the fleet management organization, fleet monitoring can be considered to all effects an added value software-based service supporting and facilitating any efficient and cost effective fleet management strategy. For the point of view of a fleet service provider, a fleet monitoring solution with predictive capabilities can be considered as a trigger of traditional industrial maintenance activities (preventive and predictive). Furthermore, fleet monitoring can be considered as an enabler of advanced fleet services, such as fleet benchmarking, fleet availability as a service, or fleet extended warranties, by highlighting the value and the need for such service offerings or by tracking and monitoring their efficient delivery and implementation into the fleet management strategy.

Monitoring the fleet properties reported in Table 1 requires the definition and implementation of significant fleet KPIs (key performance indicators) particularly with respect to fleet reliability and availability. These fleet KPIs are necessary to express numerically all the relevant fleet properties and are the main components of a fleet monitoring dashboard. In addition, fleet KPIs are required anytime a service provider needs to quantify the value proposition of any fleet service. In the following section, the most important fleet KPIs with respect to fleet reliability and availability are defined and shortly discussed.

4 Fleet KPIs

Based on the generally accepted definition of KPI (Parmenter 2010), we defined here *fleet KPIs as a set of measures focusing on those aspects of fleet performance that are most critical for the current and future success of the organization, i.e. for the fleet management*. In the following fleet KPIs focusing on fleet reliability and fleet availability are defined and discussed. Being related to potential asset failures and asset downtime, these fleet KPIs are, in the authors' opinion, the most critical for the daily business of the fleet operator as well as, in the case of hazardous applications and industries, for the environmental and human safety.

4.1 Fleet Reliability

Starting from the definition of asset reliability (Yang 2007) "as the probability that an asset performs its intended function without failure under specified conditions for a specified period of time", *fleet reliability* is defined here *as the probability that a fleet (i.e. all fleet components) perform its intended function without failure under specified conditions for a specified period of time*. In other words, the one-year fleet reliability corresponds to the probability that all fleet devices will perform properly, i.e. without any asset failure, within the next one year. Assuming that a fleet consists of a series of n not identical and independent assets with reliability function $R(t)_i$, for $i = 1, \ldots, n$, the fleet reliability $R(t)_{fleet}$ is given by:

$$R(t)_{fleet} = \prod_{i=1}^{n} R(t)_i \tag{1}$$

The reliability function $R(t)$ is interpreted as the population fraction surviving time t (Yang 2007) and can be written as:

$$R(t) = Pr(T > t) = \int_t^{\infty} f(t)dt \tag{2}$$

where $f(t)$ is the probability density function of the asset and indicates the failure distribution of the asset over the entire time range. In Fig. 1 the reliability function $R(t)$ for an asset with time to failure exponentially distributed and mean parameter μ equal to 30 years is plotted. In the same figure, the fleet reliability function $R(t)_{fleet}$ for a fleet of 10 identical and independent assets (each asset with time to failure exponentially distributed and mean parameter μ equal to 30 years) is plotted.

Since a fleet usually consists of assets with different ages (i.e. new and old assets), the calculation of conditional probability must be considered in the determination of the current asset reliability $R(t)_i$. The conditional probability can be

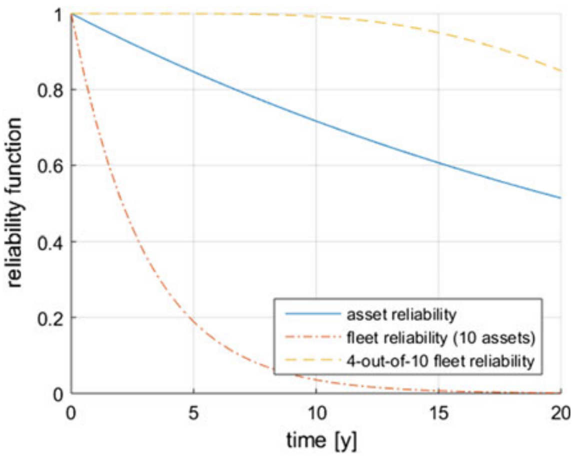

Fig. 1 Asset reliability, fleet reliability and 4-out-of-10 fleet reliability for a fleet consisting of 10 independent and identical assets. The time to failure of each asset is exponentially distributed with mean parameter μ equal to 30 years

calculated if the reliability of the asset is known in terms of statistical distribution function (in this case, the age of the asset is also required) or by applying advance predictive analytics based on asset condition monitoring data. The definition of fleet reliability here introduced is very much depending on the actual size of the fleet and refers to the probability that the whole fleet, i.e. each and any fleet component, will perform properly within a defined time window. To overcome such limitations, the k-out-of-n fleet reliability is proposed in the following.

4.2 k-Out-of-n Fleet Reliability

The *k-out-of-n fleet reliability* is defined in this paper as the *probability that k devices out of a fleet of n devices (with k ≤ n) perform their intended functions without failure under specified conditions for a specified period of time*. By calculating the k-out-of-n fleet reliability the following relevant questions can successfully be answered:

- What is the probability that 10 assets in the fleet will fail within the next one year?
- If the fleet maintenance team can repair 100 assets a year, what is the probability that the fleet maintenance team will be able to maintain properly the fleet for the next one year?
- If the fleet manager planned 50 spare devices for the fleet for the next one years, would they be enough?

Since the analytical formulation and solution of the k-out-of-n fleet reliability is not feasible for large values of *k* and *n*, the authors have developed a numerical method based on Monte Carlo simulation. The description of the method and the corresponding results are not reported in this paper. The mathematical formulation for the 2-out-of-3 fleet reliability is reported in ReliaWiki (2015). In Fig. 1 the 4-out-of-10 fleet reliability for a fleet of 10 identical and independent assets with time to failure exponentially distributed and mean parameter μ equal to 30 years is plotted.

4.3 Number of Failures

The *number of failures* is a fleet KPI strictly related to the fleet reliability. It is defined as the *total number of failures within a fleet for a specified period of time*. Of particular importance is the prediction of the trend of the total number of failures for a future time period. In fact, this would support the fleet maintenance organization in forecasting the number of maintenance activities (with the corresponding required tools and skills) or the spare parts required for the future.

4.4 Fleet Availability

According to NASA (2005), *fleet availability* is defined as *the ratio of time a fleet is functional to the total time it is required or expected to function*. Assuming that a fleet consists of a series of n not identical and independent assets with availability $A(t)_i$ for $i = 1, \ldots, n$, the fleet availability $A(t)_{fleet}$ is given by:

$$A(t)_{fleet} = \frac{1}{n} \cdot \sum_{i=1}^{n} A(t)_i = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{uptime(t)_i}{max\,uptime(t)_i} \quad (3)$$

4.5 Other Fleet KPIs

Fleet KPIs related to reliability figures such as fleet MTTF (mean time to failure), MTTR (mean time to repair), MTBF (mean time between failures) as well as to fleet criticality and risk have been defined and developed by the authors but not presented in this paper.

5 Conclusions

In the first part of this paper, a definition of fleet management and the benefits of servicing a fleet of assets instead of servicing single assets for a service provider as well as for an asset management organization have been extensively described.

From the side of a service provider, this fleet perspective would increase customer retention, provide a competitive advantage over small and local service provider and enable innovative added value fleet service solutions that will not be possible or rentable if looking at servicing a single asset. For the fleet management organization, the fleet perspective would provide a holistic view of the fleet and a comprehensive management solution over different lines, plants, locations. Furthermore, it would limit the number of contractual relationship and risk sharing with service providers. Finally, fleet services would lead to the reduction of cost and price in servicing a single device within the fleet. As an application case of industrial fleet service, fleet monitoring was discussed by listing all the relevant fleet properties that a comprehensive fleet monitoring solutions should be able to track and monitor. In order to numerically express these fleet properties, fleet KPIs have been defined and developed. A subset of fleet KPIs related to fleet reliability and availability have been presented in this paper.

From the point of view of a service provider, in the authors' opinion, on the way to providing the customer with the best possible fleet services and fleet monitoring solutions additional research activities are still required. These activities are mainly related to data integration, cleansing and consolidation, advanced predictive and prescriptive data analytics as well as to data visualization and decision supporting for fleet management. Furthermore, a comprehensive fleet perspective may be exploited to develop innovative business models and added value service products.

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Equipment and Process Condition Monitoring for Asset Management in Small Modular Nuclear Reactors

Belle R. Upadhyaya, Jamie B. Coble and J. Wesley Hines

Abstract Small modular reactors (SMRs) belong to the category of nuclear power generating plants in the range 25–200 MW-electric. SMRs have in-vessel space constraints and limited number of reactor vessel penetrations. This warrants indirect approaches for certain measurements such as, for example, the coolant flow rate in the vessel. On-line monitoring of equipment and process condition is necessary to plan maintenance, equipment repair/replacement, and alternative operational strategy. The design of these systems for extended fuel cycles, to minimize forced outages, and to provide safe and reliable power generation require long-term asset management strategy. This is achieved by developing and implementing methods for equipment and process condition monitoring, diagnostics, and prognostics using plant dynamics, measurements, and operational knowledge of these integral systems.

1 Introduction

New designs of light water-cooled small modular nuclear reactor (SMR) plants are being developed by several vendors. Examples of these SMR designs include NuScale Power (45 MWe), mPower reactor (180 MWe), Westinghouse-SMR (220 MWe) in the United States; and the construction of the CAREM-25 reactor designed and developed by CNEA, Argentina. These reactors are designed for an extended fuel cycle (up to 4 years) with the goal of uninterrupted operation, and often with a fully replaceable reactor core. In order to achieve this long-term asset management and for safe, reliable, and economic operation of SMRs, it is

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imperative that on-line monitoring of equipment and process condition be incorporated during the design phase of the plant systems. The objective of research is to develop methods for condition monitoring of systems and devices without interfering with plant operation, and to apply this knowledge to prognostics and critical asset management.

Because of the integral nature of the design, SMRs have in-vessel space constraints. This warrants indirect approaches for certain safety-related measurements; for example, the coolant flow rate in the vessel. One approach for flow monitoring is to calculate the power drawn by electric motors that circulate the water in the vessel. It was shown that the pump flow rate is a function of the pump shaft power. Thus a calibration of flow rate versus motor power is possible, and can be used for detecting changes in the desired flow rate (Upadhyaya et al. 2014). Physics models of the reactor systems were developed and used for generating data with anomalies such as sensor faults, motor faults causing varying pump discharge, controller faults, and anomalies in the process parameters such as heat transfer coefficients and control rod reactivity insertion.

Experimental studies, along with data processing tools and physics models (Upadhyaya et al. 2014) were used as part of the research and development at the University of Tennessee. The experiments performed in a flow control loop show that there is a strong relationship among pump motor power, discharge pressure, and flow rate and can be used to monitor the condition of sensors, actuators, and process anomalies. The fault detection and isolation algorithms are then used to identify the general path model that is needed for prognostics and the estimation of remaining useful life (RUL) of the equipment being tracked. The monitoring and prognostics methods (Coble et al. 2012) can strengthen the argument for remote deployment of SMRs and the utilization of these power generating units in small electric grid environment and in locations with limited infrastructure.

The paper outlines methods developed for condition monitoring and prognosis that lead to long-term management of plant assets during the nuclear fuel cycle, and extension to the entire plant life. The primary focus of this paper is the development of condition monitoring and prognostic techniques for application to management of critical assets in integral nuclear power reactors. Because of the limited manuscript length, the reader is encouraged to refer to the details of the techniques in the references.

2 Condition Monitoring of SMR Components

2.1 Introduction

One of the early designs of an integral light water reactor was the IRIS (International Reactor Innovative and Safe) system, developed under a collaborative effort by Westinghouse Electric Company (Carelli et al. 2004). A schematic of the

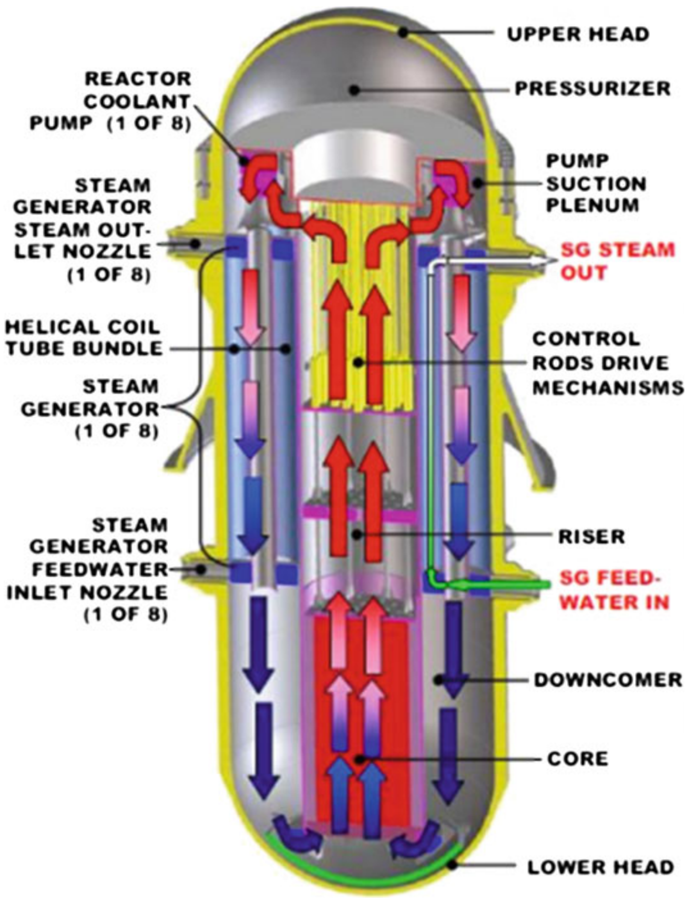

Fig. 1 Schematic of the IRIS system (Carelli et al. 2004)

IRIS primary system is shown in Fig. 1. The primary water is pumped from the upper plenum down through the annular space between the reactor vessel and the shielding, where eight helical coil steam generators (HCSG) are located. The primary water flows up through the reactor core, the riser section, and to the upper plenum.

The secondary water flows through the HCSG tubing, and the steam generator produces super-heated steam.

The goal is to monitor the primary coolant flow rate which is regulated by the pumps located in the vessel upper plenum.

2.2 Relationship Between Coolant Flow Rate and Pump Motor Electric Power

When the pump is driven by an induction motor, the power drawn by the motor changes as a function of the load (or pump flow rate). It is known that the pump hydraulic power is given by

$$Pump\, Hydraulic\, Power\, (\mathrm{kW}) = \frac{(Q\, H\, SG)\, 9.81}{3600} \tag{1}$$

where Q is the flow rate (m^3/h), H is the pump head (m) at the given flow rate Q, and SG is the specific gravity of the fluid at the pumped temperature. In general, the pump hydraulic power is a nonlinear function of flow rate, Q. Note that the power delivered to the pump shaft differs from the motor power by a factor of its mechanical efficiency. Several experiments were performed on a flow test loop to develop the relationship between motor power and pump flow rate.

The pump speed was varied using a frequency controller that changes the frequency of the three-phase power supply as desired. Figure 2 shows a plot of the water flow rate as a function of calculated motor power. The relationship between these two parameters is well defined and can be used to estimate the coolant flow rate as a function of motor power. In general, the relationship between the two parameters is nonlinear; the RMS power increases as the flow rate increases.

Degradation of stationary components such as heat exchangers and steam generators include tube fouling, stress corrosion cracking, pitting, and vibration related mechanical fretting. An application is presented in Sect. 3.

2.3 Data-Based Approaches for Condition Monitoring

In a large-scale system, with several hundred measurements from sensors located at different sub-systems, condition monitoring of process, instrumentation, and

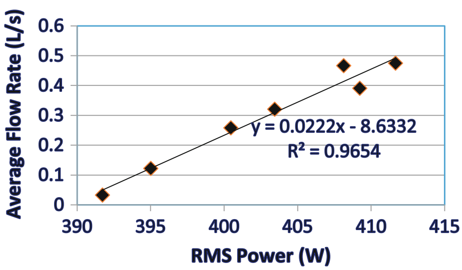

Fig. 2 Relationship between motor RMS power and pump discharge rate in an experimental flow control loop (Upadhyaya et al. 2014)

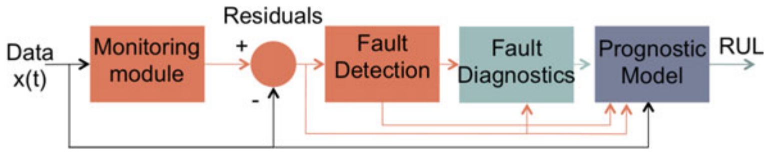

Fig. 3 Equipment health monitoring system

equipment is performed using data-based techniques. In this approach, measurements specific to a subsystem, are being used for developing empirical models. These models describe the interrelationship among a set of variables. An example of a simple nonlinear relationship has the form

$$Y = f(X_1, X_2, \ldots, X_n) \tag{2}$$

Where the variables Y is estimated as a function of a set of variables $\{X_1, X_2, \ldots, X_n\}$ that influences the dynamics of $Y(t)$. The parameters of the model in Eq. (2) are estimated using a set of plant measurements over a normal operation regime for training the model. During the plant monitoring phase the variable $Y(t)$ is estimated using the current measurements of $\{X_1, X_2, \ldots, X_n\}$. The residual between the measured and estimated values of $Y(t)$ are monitored over a time interval and a decision about a possible anomaly is made based on the degree of deviation of the residuals from their normal values. The residual at any discrete time instant, k, is defined as

$$R(k) = Y_{meas}(k) - Y_{est}(k) \tag{3}$$

Figure 3 is block diagram of the overall equipment health monitoring system, with the various blocks indicating the signal processing algorithms used for analysis.

A two-step fault detection and isolation approach has been developed based on an elimination/similarity (ES) data comparison algorithm. This equipment monitoring algorithm first eliminates fault symptoms which do not qualitatively match the current fault. Then, from the remaining subset of faults, the closest match is determined through a simple distance calculation.

3 Equipment Prognostics and Asset Management

3.1 Introduction

Prognosis deals with trending certain signatures that reflect the condition of a piece of equipment during its lifetime. A large plant may have several critical components (machinery, actuators, sensors, etc.) that require continuous surveillance. Figure 4

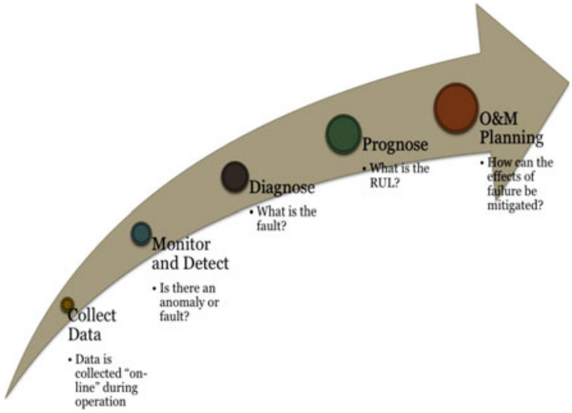

Fig. 4 Steps towards component prognostics and asset management, indicating increasing complexity of analysis (Hines et al. 2008)

shows the steps in achieving a successful prognostics and asset management approach (Hines et al. 2008). It is clear from this schematic that the level of difficulty in achieving each of these objectives increases, with added resources for planning operation and maintenance to minimize and avoid the effects of system anomalies. Techniques have been developed to estimate the remaining useful life (RUL) of both active and passive components under various operating conditions and environmental effects (Hines and Coble 2011). This parameter provides an indication of the operability of the component(s) being monitored so that timely actions may be taken, such as maintenance/calibration, repair, and replacement.

3.2 *Examples of Condition Monitoring and Prognostics*

A successful development of condition monitoring and prognostics approach requires several tools. Among these are data-based and physics-based modelling, tracking faults through statistical analysis, establishing and updating prognostics models, and uncertainty analysis of estimated parameters, such as the remaining useful life (Hines and Coble 2011).

Several examples of prognostics of active and passive components include (Coble et al. 2012): Electric motors, pumps, valve actuators, control rod drive mechanisms, industrial fans, blowers, turbines, sensors, heat exchangers and steam generators, pressure vessels, transformers, and electric cables.

3.3 *Application to Vibration in a Heat Exchanger System*

A 7.5 horsepower motor was used to run a pump for circulating water in an industrial heat exchanger system. The motor vibration was monitored using

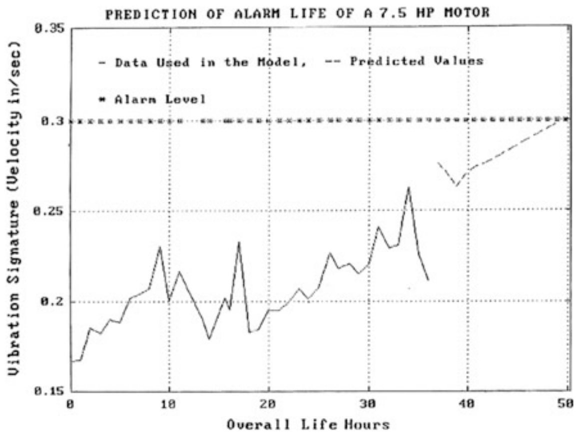

Fig. 5 Motor vibration signature trend showing alarm level

accelerometers mounted on the motor bearing. Figure 5 shows the trend in the vibration signature. Figure 5 shows the vibration signature for a time period of 36 h.

These data were used to develop a general path model of degradation. The prediction of future values of the vibration signature were made using this model and the remaining life to reach the alarm level was estimated as ≈50 h from the start of observation. This estimate was conservative, but showed the correct trend in the motor degradation.

4 Concluding Remarks

Remote monitoring of small modular reactors and analysis of plant measurements are needed to ensure continuous and safe operability of systems. Techniques have been developed for online monitoring, fault diagnostics, and prognostics of various components. The results of applications to plant operational data and dynamic model simulation have demonstrated the capability of implementing these approaches for asset management of existing power plants and next generation nuclear plants. Certain technology gaps remain and need further development during the design phase of small modular reactors and advanced nuclear reactors.

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ESP and the Question Advanced Sensor Technology: A Transcendentalist Analysis

Ikechukwu Kingsley Uzoma

Abstract Sensor technologies are all encompassing and critical to this digital era. It has helped man to remotely gain active control over valued asset and otherwise, not constraint to time and space. The dynamics and efficiency of the technologies as invented by man no doubt has brought simplicity to the quest for continuous unraveling of mysteries posed by nature whilst man transcends the non-given(ness) of nature from the mere given. Acknowledging science as an enterprise set-out to unravel mysteries, and technology implying a sort of development; extra sensory perception (ESP) as discussed herewith evaluates the fundamentals of sensor technologies with cognizance of cybernetics, whilst bringing to lime-light the limitations of machines of today, demonstrating its sole reliance on programmed sense perception, devoid of rationality. It is an epistemological analysis of possible synthesis of two main faculties of knowledge viz. empiricism and rationalism. This intellectual voyage pinpoints the fact that advanced sensor technologies are what they are today and would be in future because of what its author of existence (man) has made it to be, and thereby validates the maxim of Protagoras the Greek philosopher, that "man is the measure of all things". The task herewith is to unscramble engineering asset management from lenses of metaphysics of engineering where advanced sensor technology is the object of inquiry.

1 Introduction

Sensor technology is one of the unique apparatus crafted out to enhance efficiency and promote sustainability of asset. Given that asset management (AM) according to the (U.S. Environmental Protection Agency 2007) is the Systematic integration of advanced and sustainable management techniques into a management paradigm or way of thinking, with primary focus on the long-term lifecycle of the asset and its sustained performance. McElroy R.S defines asset management as a 'systematic

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process of maintaining, operating and upgrading physical assets cost-effectively' (Joe Amadi-Echendu 2007). Thus, the focus on effective asset management is argued to require an asset decision making framework that incorporates both organizational structures and information technology aligned with financial and budgetary deliberations.

2 Asset Management (AM) Expository

As defined earlier, AM is the combination of management, finance, economy, engineering and other practices applied to physical assets, with the objective of providing the required level of service in the most cost-effective manner (SI-ZHEN 2008). AM system must meet the goals of an organisation in both financial and physical parts, in order to improve the values of the organization, and better returns to shareholders.

On the other hand, physical asset management (PAM), is the practice of managing the whole life cycle (design, construction, commissioning, operating, maintaining, repairing, modifying, replacing and decommissioning/disposal) of physical assets such as structures, production and service plant, power, water and waste treatment facilities, distribution networks, transport systems, buildings, and etcetera (ISM 2014). Some scholars had pointed out that an EAM requires an asset registry (inventory of assets and their attributes) combined with a computerized maintenance management system (CMMS). The versatility and functionality of a Geographic Information System (GIS) allows for the control and management of all assets and land-focused activities. In this regard, all public assets are interconnected and share proximity, and this connectivity is possible via GIS deployment. Thus, GIS-centric public asset management standardizes data, and allows interoperability, providing users with the capability to reuse, coordinate, and share information in an efficient and effective manner by making the GIS geo-database the asset registry (SI-ZHEN 2008).

For instance, in the United States, the de facto EAM standard is the Environmental Systems Research Institute (ESRI) GIS for utilities and municipalities. The GIS platform combined with the overall public asset management umbrella of both physical "hard" and "soft" assets helps remove the traditional silos of structured municipal functions that serve the citizens. While the hard assets are the typical physical/infrastructure assets, the soft asset of a municipality includes permits, license, code enforcement, right-of-ways and other land-focused work activities (Haslam 2011).

This definition of "public asset management" was coined and defined by Brian L. Haslam, President and CEO of a leading International ESRI GIS-centric computerized maintenance management system company located in Utah whose software is certified by the National Association of GIS-Centric Solutions (NAGCS). GIS-centric public asset management is a system design approach for managing public assets that leverages the investment local governments continue to make in GIS and provides a common framework for sharing useful data from disparate systems. Permits, licenses, code enforcement, road worthiness, and other land-focused work activities are examples of land-focused public assets managed by municipal governments.

3 Extrasensory Perception (ESP)

The arguments of medieval philosophers and beyond on the process of knowledge acquisition viz. Empiricism-sense experienced based knowledge and Rationalism-reason based knowledge which underpins epistemology (the science of knowledge) was to some extent synthesized among scholars especially on the ground of complementary role both faculties plays in the process of knowing. Hence, our knowledge of things around us is better explained under reliance of reason and sense experience, and this in the Kantian analysis amounts to synthetic a priori judgment. Immanuel Kant (1724–1804) established this philosophical position as transcendentalism.

Ordinarily, extrasensory perception should be valid in the domain of science and technology so to speak and as such, appeared to be the mystery behind what is crowned advanced sensor technology. Though ESP refers to the knowledge of external objects or events without the aid of the senses, but scholars like William James (1842–1910) and Joseph Banks Rhine (1895–1980) made frantic efforts to have it established as a scientific body of knowledge especially from the lenses of psychology. But as fate would have it, the desired breakthrough is still being sharpened by scholars till date.

Viewed from another lens, ESP is the philosophy of perception that is concerned with the nature of perceptual experience and the condition of perceptual objects. It lays claim on how perceptual experience relates to appearances and beliefs about the world. Though ESP theories could lead to skepticism but it equally transcends its scope, and thereby sniffing into the domain of sensor technology where human reason and faculties of sensation appears slow in action while computer apparatus-a handiwork of man takes the lead. It is at this backdrop that we speak of cybernetics.

ESP conceived as the ability to gain information about an object, person, location or physical event through means other than the known senses, entails the act(s) of telekinesis, psychokinesis, telepathy, clairvoyance and Clair-audience. It formed the background for advanced sensor technology. Ontologically, these concepts are better described as astral senses which by implication are different from physical sense but correspond with one another, as telepathic impressions are drawn. On the other hand, clairvoyance as an incident of astral voyage is man’s faculties that enable him to sense vibrations not responded to by ordinary physical sense. Each physical sense has a correspondent astral sense, whilst astral sense enables man to receive ideas not readily available to the sense or normal level reasoning faculty.

As made possible via telepathy, simple clairvoyance and space clairvoyance equals the power to see things from afar, and this is what is made manifest in sensor technologies of today. Man's ability of precognition-(the ability to perceive or predict future events, retro-cognition-the ability to see past events, and remote viewing-the perception of contemporary events happening outside of the range of normal perception), codified as telepathy, further characterized the wonders of sensor technologies.

Hence, telepathy simply put, is the transference of thoughts or feelings between two or more subjects through parapsychology. Conversely, parapsychology captures the scenario where i.e. objects "A" gains from object "B", the information that was shielded from their traditional senses by distance, time, or physical barriers.

4 Cybernetics

Cybernetics according to Oxford Advanced Learners Dictionary (Online) is the scientific study of communication and control, especially concerned with comparing human and animal brains with machines and electronic devices. Similarly, Norbert Wiener (1948) defined cybernetics as the "scientific study of control and communication in the animal and the machine". The word cybernetics came from the Greek κυβερνητική (kybernetike), meaning "governance", i.e., all that are pertinent to κυβερνάω (kybernao), and the latter meaning "to steer, navigate or govern".

Contemporary cybernetics began as an interdisciplinary study connecting the fields of control systems, electrical network theory, mechanical engineering, logic modeling, evolutionary biology, neuroscience, anthropology, and psychology in the 1940s, often attributed to the Macy Conferences says (Pangaro 2013). During the second half of the 20th century cybernetics evolved in ways that distinguish first-order cybernetics (about observed systems) from second-order cybernetics (about observing systems). More recently there is talk about third-order cybernetics (a synthesis of the first and second-order). Thus, the epistemology of sensor technology portrays that actions of robotics are predetermined, conditioned and that cognitive systems have both an inside and outside representation while intelligence revolves round observed conversations and manipulation of information's.

4.1 Sensor Technology/Remote Viewing

Remote viewing (RV) is another name for telepathy or clairvoyance, and refers to the supposed psychic ability to perceive places, persons, and actions that are not within the range of the sense. It is a form of psychic ability very common among people and rooted in the mind. Typically the entity engaged in the viewing task is expected to give information about an object, event, person or location that is hidden from physical view.

ESP is the basis of what sensor technologies are exhibiting as made manifest via hardware and software programmings. It's all about the modus operandi of science, and the apparently programmed pseudo-metaphysics of human intelligence. A knowledge gateway driven by man's instinct and creatively designed to rapidly ignite communication directly from one object to another without depending on speeches, writings, or symbols. The philosophy behind sensor technology therefore, is to give man active control over his valued asset, not constraint with time and space. It is a tool devised by man to aid the penetration, mastering and conquering of nature in a bid to understand the mysteries of our day-to-day live, and also to explore the universe in a more pleasurable manner.

4.2 Artificial Intelligence

Not natural, not intrinsically part and parcel of man or other animal biological architecture, better described the word artificial intelligence which is equated to super robots. This assertion is further validated by the first artificial intelligence conference that occurred at Dartmouth College in New Hampshire in 1956, in which researchers were inspired to undertake projects that emulated human behavior in the areas of reasoning, language comprehension, and communications. Artificial Intelligence (AI), according to Microsoft Encyclopedia, is the study and engineering of intelligent machines capable of performing the same kinds of functions that characterize human thought. The concept of AI dates to antiquity, but the advent of digital computers in the 20th century brought AI into the realm of possibility.

It is an intelligence that in actual fact appears not only faster in thought process but equally smarter in action than human intelligence. No matter how relative this assertion may appear to some schools of thought especially the skeptics, the point remains that even at its programmable intelligence mechanism, sensor technologies or robotics were invented for higher productivity, proficiency and efficiency.

4.3 Robot/Robotic

Oxford Advanced Learner Dictionary (online) conceived robot to mean "a machine that is made to look like a human and that can do some things that a human can do", and equally a machine that can perform a complicated series of tasks automatically. This 21st century features a great degree of advanced sensor mechanisms possessed by robots with the capability of doing and achieving with ease, the task that seems difficult and monotonous to human being.

Some robots are designed architecturally in human forms, and irrespective of their functions, pseudo-humans better described their nature. In the year 2000, the 4-foot-tall ASIMO humanoid robot designed by Japanese engineers at the Honda

Fig. 1 Hospital assistant robot

Motor Company, appeared in public for the first time, demonstrating its capability of walking and running like a human, climbing stairs and getting at objects. The name ASIMO stands for Advanced Step in Innovative Mobility.

Figure 1 above shows a hospital helpmate robot that independently navigates through hospital corridors, delivering meal trays, paperwork, and supplies. The

Fig. 2 Humanoid robot ASIMO majestically walks down stairs

robot employs multiple sensors to safely navigate and work in close proximity to people.

Conversely, any robot designed to move in an unstructured or unknown environment will require multiple sensors and controls, such as ultrasonic or infrared sensors, to avoid obstacles. Robots, such as the National Aeronautics and Space Administration (NASA) planetary rovers, require a multitude of sensors and powerful onboard computers to process the complex information that allows them mobility. This is particularly true for robots designed to work in close proximity with human beings, such as robots that assist persons with disabilities and robots that deliver meals in a hospital. Safety must be integral to the design of human service robots (Fig. 2).

5 Advanced Sensor Technology Applied to AM

Nowadays advanced sensor technologies are increasingly deployed across diverse sector of the global economy to enhance the optimal use of industrial machines, massive assembling of automobiles and other mechanical and electronic gadgets manufacturing, almost with zero fault records and even more economical as against human workforce. Modern sensor technologies have the capability to schedule maintenance task on assets, perform the task of fault detection, diagnosis, reporting and fixing.

Advanced sensor technologies, therefore are crafted out to enhance man's quest of conquering and mastering of nature in the logic of development. It is man's invention for the purpose of building reliable assets, reducing the cost of labour, operations and maintenance and at the same time actively monitoring asset(s) health status for continuous safety and security.

In a nutshell, the point here is that deployment of sensor technologies across industries as applicable based on their environments and individual needs are central to asset management framework. In "Speculations Concerning the First ultra-intelligent Machine" (1965), I. J. Good wrote:

> Let an ultra-intelligent machine be defined as a machine that can far surpass all the intellectual activities of any man however clever. Since the design of machines is one of these intellectual activities, an ultra-intelligent machine could design even better machines. Thus the first ultra-intelligent machine is the last invention that man need ever make.

Above all, a critical evaluation of AM framework where policy is at the apex of its triad hierarchy depicts that both government, and other institutions utilizing sensor technologies, first conceived it as a policy, then deployed it as a strategy and had task assigned to it as plans (Fig. 3).

Thus, sensor technologies are efficacious all through AM lifecycle, and as such remained a lifeline for continuous safety and security of assets whilst minimizing if not eradicating system breakdown or production halt. Practically, it is a knowledge based tactics in AM practice, depicting a scenario where human wisdom is

Fig. 3 AM framework

ontologically and mathematically ceded to machines (artificial intelligent) for a better, smarter and rapid performance in task execution, devoid of complaints, arguments and sense of revolt against perceived hard labour and office victimization. In fact there is no room for a sense of business ethics.

5.1 Synthesis

In the epistemological school, a fusion of reason and sensory based knowledge equals better understanding of reality. It was at this juncture that the Kant (1724–1804) gave credit to his theory of synthetic-a priori judgment. In a nutshell, technology as derived from the Greek words tekhnē, which refers to an art or craft, and logia, meaning an area of study is the general term for the processes by which human beings fashion tools and machines to increase their control and understanding of the material environment (Merritt 2008). Hence, technology is to complement human effort in our day-to-day activities but there is also this anxiety that in the nearest future, sensor technologies would take the place of man and thereby rendering many jobless.

6 Man as the Creator (God) of Robots

It does not matter how bitter this may sound to theist, with all apology to God my creator; the breakthroughs that continue to grace the field of science and technology and at the same time engineering societal development, cannot be credited to God but rather to man, especially those in the noble discovery career of science and technology. These believe is in consonance with the maxim of the Greek philosopher Protagoras (480–411 BC) of Abdera, “man is the measure of all things” of things that are that they are and of things that are not that they are not.

Hence sensor technologies are man’s creation for the advancement of the society we dwell, and the exploration of other planets i.e. space that were not readily given to man by nature. Today, much advancement has been recorded in the field of cyberspace, and of which we now speak of a supra-sensible world (digital society) where almost all our daily activities are now interconnected to. As entities devoid of reason but reach in memory and smart in action, activities of sensor technologies are calculated, specified and as such they lack the capacity to neither change their world nor act contrary to their programmed nature.

6.1 Limitations of Sensor Technologies

The assumption that nothing in this world is perfect, and most especially the handiwork of man, further implies that every scientific conjecture are valid for a period of time and therefore not absolute. Philosophers like Aristotle (384–322 BC) would have us believe beyond reasonable doubt that aside from God who is a perfect being-“pure act that needs no potency”, all other entities are imperfect and subject to the principles of “act and potency”-always in a state of becoming. In this sense a problem detecting and reporting robot of today has the potentiality of being a problem fixing robot tomorrow. Contrarily, in as much as man who is a semblance of God is imperfect, his handiworks cannot be said to be absolutely perfect in all ramifications. Hence the limitations of sensor technologies include but not limited to;

- Absolute reliance on the principles of perception
- Absolute reliance on electricity or alternative source of current
- Lack of reasoning faculty
- Zero respect to both business and geological ethics
- Function and lifespan is dependent on man to program
- In ability to recreate, master and conquer its own world

Thus, problems associated to sensor technologies are not solely self solving, as man’s input is required and as such rationalism is imported to complement sensitivity in a system diagnosed problem. And even if a supra or doctor-robot is launched tomorrow with the task of curing ailment associated to its robotic-community, yet the task of signing off, and a job well-don endorsement still depends on man to program. Hence, sensor technologies and the digital world as made manifest via cyber society and the outer space, are not independent of man.

7 Conclusion

Bearing in mind that technology achieves power through domination and control (Francis 1974), it then goes to say that existence has become more independently plausible, by objectifying and controlling the relationship of man to nature, and beyond. Viewed from the apparatus of the philosophy of engineering, technology is the rational ordering of processes for deliberate aims, fusing each relevant relationship into its programmed design, and thus subjecting that relationship to pre-determined control.

It is my submissions at this juncture that further breakthroughs in the realm of philosophy of mind and psychology will aid more refined and simplistic accomplishments in the area of sensor technology, and this no doubt, characterized the principles of innovations.

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Simulation Models Supporting Multiple Assets Along the Product Life Cycle

Henri Vainio, Jussi Aaltonen, Kari T. Koskinen and Miia Martinsuo

Abstract Modelling and simulation are commonly used in modern engineering work. However, the models are often created to solve individual problems and the possibilities they offer for multiple different users are not considered. Better planning and a higher level of awareness of the existence and the capabilities of the models would enable them to be used throughout the organization and all along a product's life cycle for a wide variety of tasks. This would give much more return on the investment made in their creation. In this article some of the theoretical and strategic concepts affecting the modelling of a lifting device are discussed. To demonstrate the versatility of the model, three cases of using the model in supporting different assets in different phases of the product's life cycle and by different types of users are shown. The conclusions are the demonstrated ability of the well planned model to be used in supporting varied engineering assets and the need to make the models available for all who might benefit from them.

1 Introduction

In the modern industrial setting, modelling and simulation are common tools for many tasks. The versatility of the technology, the improved speed of testing and cost effectiveness are among the reasons for its use (Robinson 2014, p. 9–16). The M&S technologies of today allow for the creation of multi-purpose models that can be used for a wide variety of tasks along a product's life cycle by different parts of the organization. The use of M&S becomes more crucial as the amount of design and operational data grows exponentially. The emerging internet of things with its hordes of sensors increases the amount of that data even more and gives rise to many new uses of simulation and modelling. In order to fully utilize the models and to gain maximum benefits for the resources invested in their creation, the modelling project should be planned with this in mind. Knowledge about the existence and the

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abilities of the models should be made available within an organisation. This article demonstrates the ability of a single simulation model to support several engineering assets by explaining the creation of such a model and then presenting several cases of its use.

2 Background

Much research and development has been done on complex co-simulation environments, especially ones integrating the models used in the design phases of the product life cycle (Dassault 2015; Ansys 2015). While there is little research done on the matter of actual model usage, in practice it has become evident that one of the main issues restricting the full potential of mathematical models is their compartmentalized use. Models are built by different departments to solve their own engineering problems and the awareness of the existence of these models is often not a matter of official internal corporate communications, but of word of mouth. Generally, models remain tools created by specialists to complete their own tasks, and often these tools are not shared with others who might even use them to solve entirely different kinds of problems. The lack of awareness on a company level and the lack of access to the models are reasons for this. There might also be a lack of skills to use the models. These issues greatly weaken the potential of modelling and simulation and lead to overlapping simulation projects and to models being forgotten. In other words, resources are wasted. There is a general lack of understanding the multi-disciplinary, cross-departmental potential of well-built models. Resistance to change is also a contributing factor (Nykänen et al. 2013).

Models are needed to convey complex information to different parts of the organisation and to people with vastly different backgrounds and training (Nykänen et al. 2013). The industrial internet and service business applications would greatly benefit from model based solutions, given the amount of data becoming available for model based processing. The models themselves should support these solutions and be widely available to give the best results. The existence, abilities, limitations and requirements of the models as well as the skills required to use them and the way to contact people who have those skills, should be made available throughout the company.

3 The Multi-purpose Model with an Example of Creating One

In order to examine the needed theoretical and planning aspects of building a versatile multi-purpose model, the creation of one is presented. The object of the modelling is a lifting device, which features a rope, a hoist and a number of moving units. The modelling and simulation were done using OpenModelica, a Modelica based open source modelling and simulation environment (OpenModelica 2015). The exact nature of the device and the exact results of the simulations are intentionally left unclear, as the project involved a real commercial product.

The model built in this example is a dynamic model, able to simulate the electrical and mechanical behaviours of the device over time. The input values include control commands and the physical properties of the object the device lifts. The output values are forces, accelerations, currents and voltages. While this type of a model is not able support every need or asset and other types of models are required as well, the model can nonetheless be applied for a variety of tasks by many different users. To achieve this, modelling projects should be planned with a number of possible interest groups in mind.

The goal of the example model is to be able to support multiple engineering assets along the product life cycle of the device. Since this is a theoretical demonstration, no actual interest groups were consulted, but the choice of modelling strategies was made to give versatility to the model. The model was built using physical modelling, which means that the component level submodels communicate with each other through the transmission of forces and electric current, similar to the way the components would interact in reality. The level of detail was kept high enough to make the model analytical, giving the possibility to examine action chains from one physical phenomenon to another, within the model's operational range. Physical modelling also enables the independent development of component level submodels. The submodels need only to accept as inputs and create as outputs the values of forces or other phenomena the component would act with its surroundings in reality. Accelerations and such are calculated based on these interactions and the parameters of the device. With this model structure in mind, the modelling was done in a top-down fashion, first creating a basic framework of the entire lifting device with extremely simple component level submodels. The submodels were then developed one by one to achieve the needed accuracy, verifying the functionality of the complete model with each new submodel before moving on to develop the next.

The submodels given most depth were a beam experiencing vertical loads, the rope and the electric motors. The beam was modelled using the equations of a beam stressed by a point force and a beam stressed by a force field. Unit conversions were done to the submodel to extract numerical values from the input signals and to convert the output signals into SI-units in order to adhere to the physical modelling strategy. The rope was similarly modelled as the equation of stretch and the equation of a spring, both equations using the length of the unwound rope as one of the parameters; again with added unit converters. The quite detailed electric motor model was provided with OpenModelica. Other components, such as the wheels and control system, were left on a less detailed level, this configuration allowing for the envisioned applications of the model. Should new needs arise, new, more detailed submodels could be added to allow for the examination of other phenomena. Different users can create or commission more accurate submodels to meet their needs.

The model along with the needed submodel combinations should be validated and verified with proper sensitivity analyses and comparisons to actual measurements where possible. Due to the nature of this project, the verification of the model was left quite light and the model acts only as an example. With some adjustment, it could serve as a real tool, but at its current state it remains a theoretical test. The abilities of the model to reflect reality should be kept in mind at all times. The results only apply within the operational ranges of the model and these depend on the accuracy of its submodels. The examination of some phenomenon might need a very accurate model of a certain subsystem, but a lesser level of accuracy for other sub-system models may suffice. In that case, only the accurate submodel might yield usable data.

4 Example Cases: A Single Model Supporting Multiple Assets

In the product design phase, the designer can use the model for determining the parameters of a component, in this example choosing the type of hoisting motor for a known maximum lifted weight. By simply inserting the parameters in the model and running a few simulations, the designer gains information about the needed motor size. This is the simplest design use case; it could be enhanced with automatic parameterization and semantic parameter databases and such. In Fig. 1 two different motors are tested, with torque, speed and power examined.

Based on the simulation results shown in Fig. 1 the choice of the motor can be done. This would be a part of an iterative design cycle, as the choice of the hoisting motor creates demands for example for the gearbox, mechanical structure, the controlling electronics, the brakes and the power supply, which all in turn have an effect on the choice of the motor as well.

In marketing, the same model can be used in creating data to support the sales argument. The simulation parameters can quite easily be chosen to correspond to the potential customer's situation and the results can be used to demonstrate the benefits the technology being offered would create. Cases with and without an automated control system and the effects its use has on the physical components, in this case the beam, are shown in Fig. 2.

The results in Fig. 2 show the smaller amount of stress experienced by the beam when the device is being used with the automated control features. These results could then be refined to show the financial benefits of the automated control system to a potential buyer.

Predictive maintenance planning for a known work cycle can be performed using the model. A rope damage counter is added to count the number of times the rope stretches over a critical value during the work cycle. Different work cycles can be tested for optimization purposes and real-time updates of the maintenance

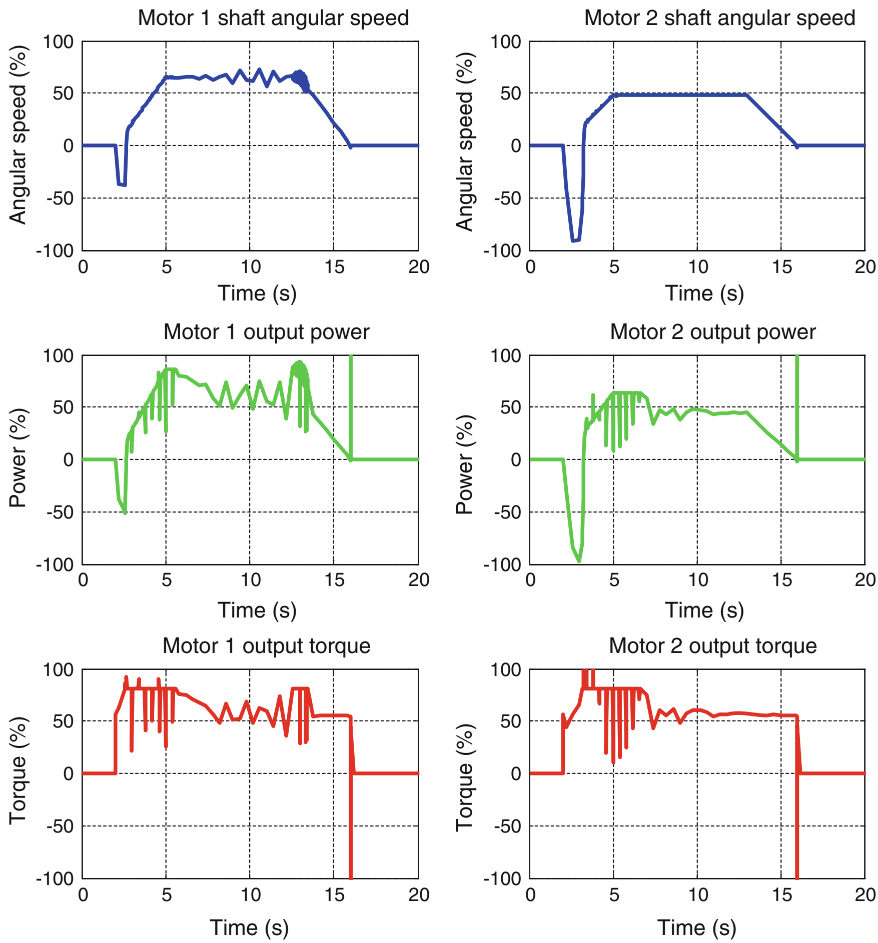

Fig. 1 A simple work cycle simulated using two different motors

schedule can be performed. The work cycle and the rope damage results are shown in Fig. 3.

The results shown in the Fig. 3 allow for estimation of the remaining operational life of the rope and enable the scheduling of the quite costly and time consuming rope replacement operation well in advance. If the results are updated to take into account changes in the ways the device is used in the real world, this schedule can be dynamically updated. In reality a more accurate way of estimating the rope life would be used, the stretch under load is not the most eroding of the phenomena a lifting device rope experiences, but the principle of safe life estimation remains the same.

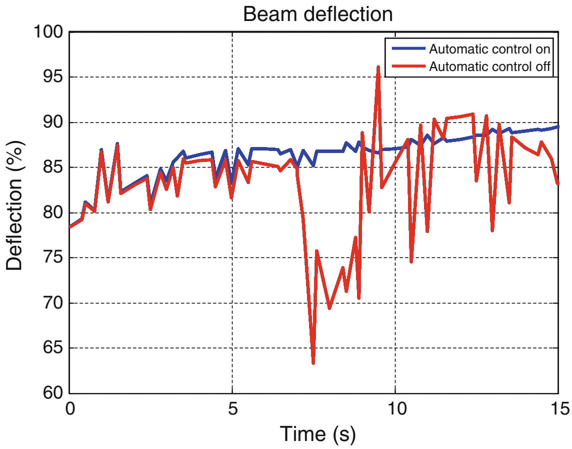

Fig. 2 Comparing the effects of automatic control functions on a structural beam

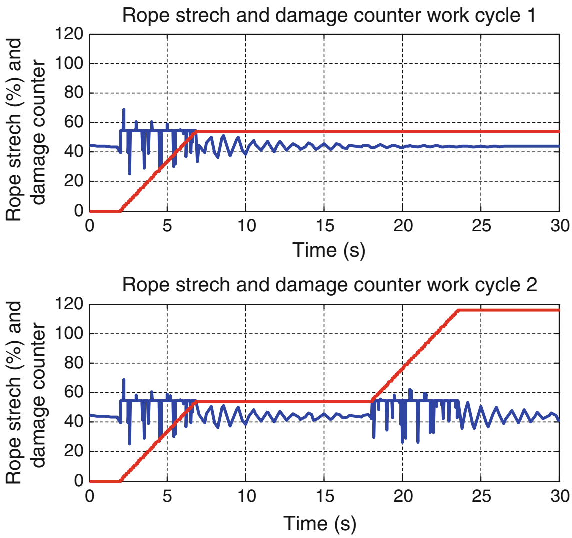

Fig. 3 Comparing the effects of two work cycles on the rope damage

The model could also be used for other applications. Real time simulation would enable its use in training both users and maintenance personnel. Maintenance could compare simulated values and measurements from a defective device to find faults. Recorded control and command values could be used as parameters for the simulations in order to gain an understanding on what kinds of stresses the actual use of the device causes.

5 Conclusions

A simulation model can support multiple engineering assets along the product life cycle, if it is created with such objectives in mind. The modelling strategies should be chosen to reflect this. Even if the models fall in the category of single use and are not maintained actively, they may still be of use to several people. The information regarding to the existence, abilities, and limitations of models within a company should be made easily available and promoted. If possible, simulation services within an organization should be offered to people lacking the skills to use the models themselves. These steps would ensure the resources invested into modelling projects giving better returns. They are just the first steps on a path towards integrated simulation environments, virtual machine laboratories, semantic data-architectures and engineering intelligence concepts, a rather easy and relatively cost effective way to begin the journey of managing the massive amounts of data created by modern industrial systems. After all, the rise of the industrial internet and service business concepts are going to force companies to do something with that data, and the tools to handle the situation should not be scattered and hidden.

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Designing Performance Measures for Asset Management Systems in Asset-Intensive Manufacturing Companies: A Case Study

Jiaqiang Wang, Zhongkai Chen and Ajith Parlikad

Abstract This paper proposes a structural and procedural framework for developing performance measures for engineering asset management systems with an in-depth case study of an international glass manufacturer. The structural framework was built by adapting the Balanced Scorecard method to leading engineering asset management standards. Further, the procedural framework describes how to develop the performance measures systematically, and provides practical guidelines facilitate design process. Asset managers at different levels were brought together to use the proposed structural framework to an build asset management strategy map by linking and mapping all critical objectives in the defined perspectives. Subsequently performance measures are identified for each objective in the asset management strategy map. Finally all selected performance measures are critically reviewed with existing performance measures and qualitative feedback was collected from a senior participant. The results showed that the proposed structural and procedural framework are effective and efficient in helping asset-intensive organisations build their performance measurement systems for asset management.

1 Introduction

Engineering asset management systems (EAMS) are designed and implemented by asset intensive manufacturing organisations to serve their overall business strategy. Therefore asset intensive manufacturing companies heavily rely on their EAMS to

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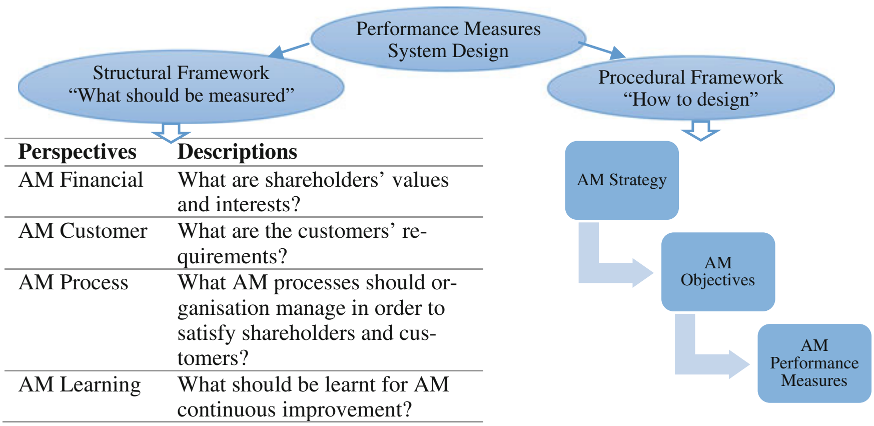
gain core competitive advantages (Woodhouse 2009; Amadi-Echendu et al. 2007; El-Akruti et al. 2013). A performance measurement system (PMS), is a set of individual performance measures (PMs) essential and useful for ensuring the effectiveness and efficiency of EAMS. Designing and applying effective performance measures has been regarded as a challenging and critical issue for asset owning organisations. It is necessary for internal operation management such as process management and incentive designs (Woodhouse 2009), additionally it is required by third party regulators (i.e. government agencies in safety, service and environment), and furthermore it is also recommended and highlighted by several leading industrial standards such as ISO55000 and PAS55 (IAM 2015).

Although there is rapidly growing interests, engineering asset management (EAM) is still in its early stage. Particularly performance measurement research for EAM is very limited. From a practical point of view, industrial organisations rarely apply structured methods to design performance measures and this results in their EAM performance measures evolved to address only a particular part of EAMS. A number of AM excellency frameworks or AM maturity models are accepted and applied by asset-intensive organisations (IAM 2015). These are very useful tools to generally understand how professional the assessed company was in terms of managing their engineering assets. However, these models do not help understand the relationship between organisations actual performance and their maturity model scores (Attwater et al. 2014).

Balanced scorecard by Kaplan and Norton is presently the most widely used performance measurement design approach (Folan and Browne 2005), and it provides effective guidelines to identify strategy-aligned performance measures. However, it only contains generic frameworks aiming for business strategy of whole organisation. Hence it is not most suitable under the specific context of organisations' EAM, for example, EAM is heavily relied on the successful management of various asset risks such as asset safety and reliability. A notable study by Arthur et al. (2014) designed their own top-down strategy map for developing performance measures based on balanced scorecard approach. However, this innovative approach did not address the integrative complexity of EAMS, requiring performance measures design cross perspective. Existing literature also placed extra emphasis on maintenance performance measures rather than the whole concept of systematic EAM, Simoes et al. (2010) conducted a comprehensive review of 345 different measures in use for maintenance management performance. That research provided indications for how to design performance measures but only focused on part of the EAMS. Therefore a refined approach which combines leading thoughts of both EAM and balanced scorecard is necessary. The paper proposed frameworks built on both structural literature review and interviews with experienced asset management practitioners in industry for practical perspectives. Furthermore, the proposed frameworks were tested and refined with an in-depth case study.

2 Proposed Frameworks

There are two fundamental tasks in designing performance measures: (i) understand relevant strategy, and (ii) select aligned AM performance measures (Neely et al. 2005). It is commonly agreed in the literature that at least a structural framework and a procedural framework (Fig. 1) are required for designing performance measurement systems (Folan and Browne 2005). The first framework is a structural framework explaining four perspectives or dimensions for identifying performance measures: asset management financial, asset management customer, asset management processes and asset management learning. All perspectives add risk control elements, which are highlighted in most EAM literature. Additionally AM planning, AM implementing, AM monitoring and AM review "plan-do-check-act" framework from ISO55000 are applied for AM process perspective. And this is necessary given the complexity nature of "asset management process" perspective in the structural framework. The second framework describes a step-by-step "strategy-objective-performance measures" process for designing performance measures for EAMS, and it also contains guidelines for facilitation the design process in the workshop.



Perspectives	Descriptions
AM Financial	What are shareholders' values and interests?
AM Customer	What are the customers' requirements?
AM Process	What AM processes should organisation manage in order to satisfy shareholders and customers?
AM Learning	What should be learnt for AM continuous improvement?

Fig. 1 Frameworks for designing performance measures

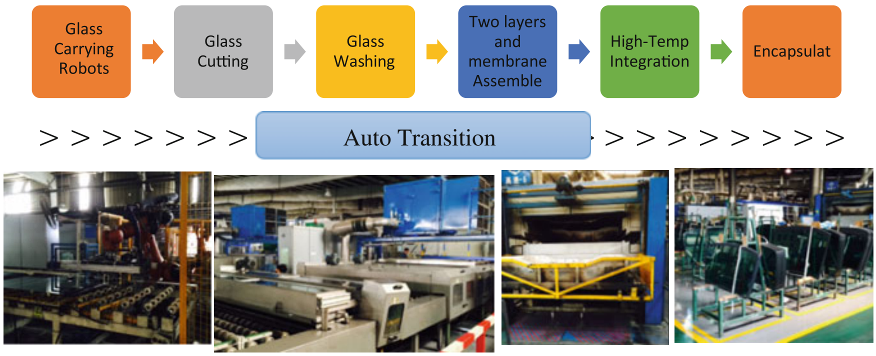


Fig. 2 Glass Inc. production line simplified illustration

3 Case Study

3.1 Background

Glass Inc.[1] is based in China and it has more than 25 years' experience in wide-screen and special glass manufacturing. It has established asset management practice and asset management systems. As nationally and internationally leading organisation in glass manufacturing, it has been accredited by ISO9000 and TS16949 and it is aware of the newly introduced ISO55000. All Glass Inc. production lines (Fig. 2) apply six sigma principles and 5S management practice, therefore Glass Inc. is a representative example to reflect existing industrial practice. Several interviews with asset management practitioners and an action research workshop were conducted for this case study. The interviews aimed at understanding the asset management context of the company. Next the workshop invited asset managers to apply the proposed frameworks to select performance measures from scratch. The aim of this case study was targeted testing the proposed frameworks:

- What are the essential dimensions/perspectives for measuring the activities' results? What are the critical objectives in each perspectives and what are the relationships between objectives?
- What are the steps for designing performance measures for their EAMS, and how to order and implement them?

[1]The name of the company has been changed to protect confidentiality.

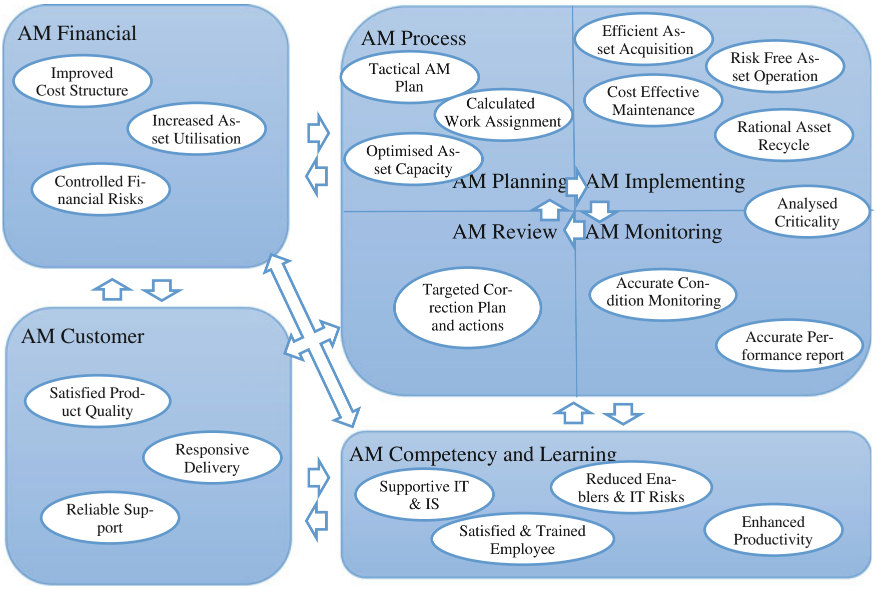


Fig. 3 Glass Inc. asset management strategy map

3.2 Results from Case Study

Interviews with asset managers revealed that Glass Inc. does not have a well defined holistic approach to design performance measures for its EAMS and all its performance measures are evolved separately. For example: safety and quality performance measures are simply issued by requirements from regulators and customers. Using a workshop, we constructed asset management strategy map (Fig. 3) by mapping and linking critical objectives in four perspectives: AM customer, AM financial, AM process and AM learning.

Subsequently, all participants developed performance measures (Table 1) for each objective and critical objective relationships in the asset management strategy map.

3.3 Comparisons and Feedback

By comparing the performance measures developed by the proposed frameworks with existing performance measures, there are a number of significant improvements. Firstly the proposed frameworks showed a whole picture of asset management so that participants were able to uncover missing areas in performance measurement. For example: there is no performance measures to assess the asset

Table 1 Objectives and issued performance measures

Objectives	Performance measures and descriptions
Improved cost structure	Reduction of cost per unit compared to last year
Increased asset utilisation	Overall equipment effectiveness
Controlled financial risks	Return on investment, daily operation cost, maintenance cost
Satisfied product quality	Quality through test pass ratio, customer return quantity due to quality issue
Responsive delivery	Delivery on time rate
Reliable support	Safety stock
Tactical AM plan	Budget precision rate, capacity gap quantity, planned/unplanned working hours, material in stock days
Optimised asset capacity	Spare/short asset hours
Calculated work assignment	Short of labour hours, spare labour hours
Efficient asset acquisition	Installation on time rate, number of error caused in installation, acquisition cost
Risk free operation	Number of incident, loss caused by incident, unexpected shutdown time, reliability rate,
Cost effective maintenance	Mean time to repair, average maintenance cost
Rational asset recycle	Number of reusable units, resale value, time to recycle
Analysed asset criticality	Maintenance cost for critical (non-critical) assets/loss caused by critical (non-critical) assets
Accurate condition monitoring	Number of faulty positive/negative monitoring
Accurate performance report	Number of performance report errors
Targeted correction plan and actions	Number of initialised/completed improvement projects
Supportive IT & IS	Bespoke IT development time, IT system coverage
Satisfied & trained staff	AM staff turnover ratio, satisfaction ratio, training test pass ratio
Reduced enablers & IT risks	Number/loss of incident caused by staff/IT
Enhanced worker productivity	Worker productivity compared to last year

management plan other than over budget ratio, no performance indicators for measuring criticality management in place as well as asset recycle activities. In addition, some leading indicators have been introduced to assist existing performance measures, for example: Glass Inc. applied "penalty charged by government for pollution" as a measure, and it is agreed to introduce leading indicator "untreated waste" to prevent the penalty. Furthermore, qualitative feedback collected from case study participants also strongly supported the usability and feasibility of the proposed frameworks.

4 Discussions and Conclusions

Folan and Browne (2005) summarised ideal recommendations for both structural and procedural framework, additionally Cocca and Alberti (2010) concluded a set of "good performance measurement system characteristics". The proposed frameworks have been tested in the reported case study in a way complied with these surveyed design criteria. Such as, design with different level of asset managers and design from different perspectives. Performance measurement as an essentially additional and internal element to EAM maturity models, which are conducted by external entities, ensures the effectiveness and efficiency of the ultimate engineering asset performance. Furthermore, strategy aligned performance measures provide reliable data source for future work directions such as quantifying the benefits of asset management (Roda et al. 2015). For asset-intensive manufacturing or production companies, the engineering asset performance directly determines their business performance. Therefore engineering asset management performance measures are important leading indicators of overall business key performance indicators. A common problem with capital-intensive manufacturing organisations is that only maintenance performance measures have been highlighted while other areas (e.g. asset management plan and criticality analysis) of engineering asset management are considered little. This paper proposed and empirically studied a structural framework and a procedural framework for designing performance measures especially for engineering asset management systems in heavy manufacturing industry. These frameworks have been tested and refined by a case study in an international leading vehicle glass manufacturer. The results and feedback from the case study proved great refinement and improvement of proposed frameworks from existing performance measures for collaborated organisation. Therefore the proposed frameworks are feasible and useful in identifying asset management strategy aligned performance measures. The results also indicated that there may be a generic set of performance measures which could potentially work as specific industrial sector guidelines or standardisation. The main future work to test the frameworks using more asset-intensive production organisations particularly for less mature companies. Furthermore, there are many upper level work can be exploited, for example: asset management incentives and target setting based on performance measurement systems.

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Towards Quantification of Asset Management Optimality

Ype Wijnia

Abstract Asset Management as a field of science is relatively new, starting only in the late 60s/early 70s as terotechnology. In its existence it developed from tools and concepts to improve profitability towards a more holistic and integral management system orientation, formalized by ISO55k. Asset management is highly quantitative, in systematically comparing cost, performance and risk of decision options to find the best balance. Yet, no absolute measure exists for determining asset optimality. It is also hard to find any quantification at all justifying the implementation of asset management or even certification. This seems a strange omission. In this paper, it is demonstrated that for assets some form of absolute optimality can be defined. This asset optimality can be expanded to express the optimality of the asset portfolio, and thus the optimality of the asset management system, though barriers exist to do so, like subjective value judgments, uncertainties in the assumptions and complexity of the portfolio. Neither of these barriers however seems fatal to the applicability of the concept on asset management systems. Suggestions for further research include a more precise specification of optimality and research with regard to the applicability on diverse types of assets. This could be beneficial in the debate on the value of asset management.

1 Introduction

Asset management as a separate field of interest is relatively new, given that in 2010 it was still regarded as emerging (Amadi-Echendu et al. 2010). Asset management started as terotechnology in the 1960s, with the first reference to physical

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asset management only made in the 1970s (White 1975). Terotechnology has a strong focus on increasing industrial profitability (Thackara 1975), building on disciplines as Reliability and Maintainability and the field of Maintenance Management. This focus was furthered in developments in the North Sea oil industry in the 1980s, which resulted in ageing assets being kept in operation and thus reducing capital requirement (Tombs and Whyte 1998). Furthermore, a new approach with regard to safety by means of a mandatory safety case (IAM 2002), introduced risk thinking into asset management (Woodhouse 2014). More or less in parallel the concept of asset management was picked up in Australia/New Zealand in the 1980s and extended to cover infrastructures assets as well (Burns 2010). This resulted in several efforts to standardize asset management, like the International Infrastructure Management Manual (NAMS 2000). A similar development occurred in the UK in the 1990s. To facilitate sharing of knowledge across sectors, the Institute of Asset Management (IAM) developed in collaboration with the British Standards Institution (BSI) a formal specification of the requirements for asset management (BSI 2004). After an update (BSI 2008), the specification was furthered into an international standard in 2014, the ISO55000 series (ISO 2014). Asset management thus developed from a set of tools and concepts to improve profitability into a more holistic and integral management system concerning the whole organisation.

At the heart of asset management is systematically working towards the optimal mix of costs, risk and performance. Optimization in this context is relative improvement and generally not the best against some absolute number. Figure 1 gives two extremes that are often used to indicate the range of options the asset manager has. In asset management decisions, cost risk and performance are generally quantified or even fully monetized (Wijnia et al. 2006). This allows measures to be judged on value for money and thus optimization of the portfolio of measures within constraints (Wijnia and Warners 2006). Without quantification the impressive results of asset management in the past years are hardly imaginable (Woodhouse 2014). Yet, in thinking about asset management as a whole (the asset management

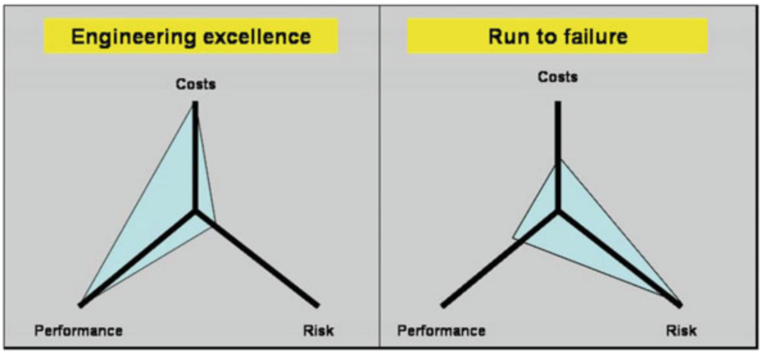

Fig. 1 Extremes in the cost/risk/performance balance, adapted from Yorkshire electricity (Wijnia and Huisma 2007)

system and the asset portfolio) any quantification is rare. There is no quantified rationale for any of the requirements in the standards. Putting it more extreme, it is not even known for certain that certified organisations (against any management system standard) outperform the uncertified organisations (Hodkiewicz 2015). Given that the whole of asset management is in its core highly quantitative, this seems a very strange omission. But the lack of a definition of asset optimality itself is an omission as well. In this paper, we develop a concept for absolute quantification of the optimality of individual assets. This will be followed by a review of the potential barriers for the application to of this concept for a whole system. The paper ends with recommendations for research to further these initial thoughts.

2 Quantifying Asset Optimality

Optimality, as a theoretical concept, is very straightforward. It is the best that is possible. Depending on the direction of the value, optimal is synonym with either maximal or minimal. Optimal costs are minimal costs, optimal profit is maximal profit. An optimal asset has no need for maintenance, is 100 % reliable, has no losses, does not pose any risks and has infinite life. The cost of the asset then only is the opportunity cost of the capital employed on the asset, whereas the benefit is the production of the asset running at maximum capacity 24/7. In reality, no such asset exist.[1] There will always be some additional costs, failure probability, limited life, losses and so on. Yet, the theoretical concept of an optimal asset provides a good benchmark for assessing the optimality of an actual asset. Consider for example an asset that is in full operation to produce some good or service. This may be a pump in a continuously operated plant, or a transformer in a power grid. The asset is critical to the production process, in the sense that if it fails the process will halt. The availability of the asset is binary, it works or it does not. Failures result in direct production losses and damages, but may also cause losses elsewhere in the production chain or impact safety, the environment or other values (external effects). The condition of the asset deteriorates over time, which increases the failure rate. Planned stops for maintenance are cheaper and shorter than unplanned stops for repairing failures and do not cause external effects. It is assumed both maintenance and repairs reset the condition of the asset to its original value, i.e. the strategy does not impact asset life.

Several maintenance strategies can be identified for this asset. The base strategy to be considered is run to failure, one of the extremes of Fig. 1. This strategy has costs because of the needed repairs, production losses because of (unplanned) downtime and external effects because of the failures. The time between failures

[1]Even though some assets may come very close. Think about cables in an electricity distribution system: no maintenance, very low failure probability, very low losses, very little safety risk, very long life.

depends on the asset condition and the occurrence of random factors and has some variation. If a little bit of preventive maintenance would be applied, some of the faults would be prevented. Because planned actions are cheaper and take less time than unplanned actions, costs go down and availability and thus production goes up. Furthermore, the external effects would decrease. The improvement with regard to costs continues until the reduction of the failure costs precisely offsets the increase of preventive costs. This is the lowest achievable cost for the considered form of maintenance. But this is not necessarily the best achievable performance. If the ratio of unplanned to planned performance loss (i.e. value of unplanned downtime plus external effects versus value of planned downtime) is larger than that of unplanned versus planned costs, increasing the amount of maintenance still would improve performance. The improvement of performance continues until the reduction of unplanned performance loss precisely equals the increase in planned performance loss. This is the best achievable performance, in other words engineering excellence. If the maintenance effort would be increased even further, the total performance would decrease again. In the extreme case, there would not be any unplanned performance loss, because the asset would be permanently offline for maintenance. In general, maintaining beyond engineering excellence would be considered over maintaining, though it depends on the value that is attached to uncertainty. The trajectory from *run-to-failure* to *over-maintaining* is shown in Fig. 2.

The cost axis comprises all direct costs for the asset, like capital, maintenance, repairs and running costs. The benefits axis comprises the economic value of the production, minus damages and losses elsewhere in the production chain (financial risk) and the equivalent value of other effects like safety incidents (non-financial risk). The dashed lines around the trajectory indicate the uncertainty of the trajectory. The more attention is given, the less the uncertainty is in cost and benefit. In

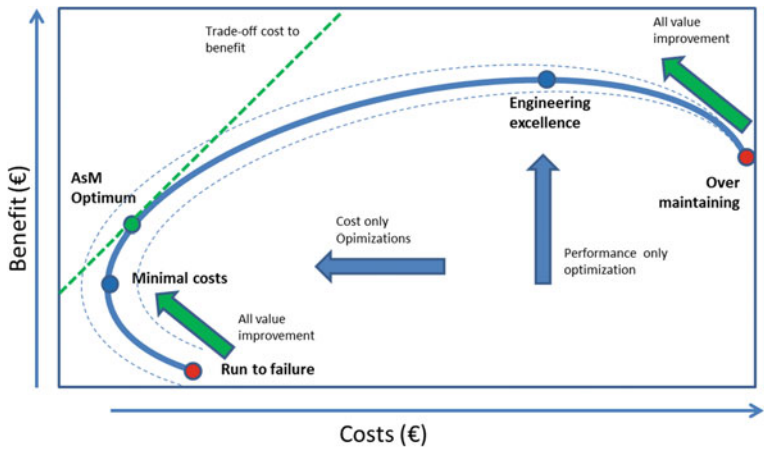

Fig. 2 The cost benefit diagram for maintenance strategies

the diagram, options for optimization are also indicated. Cost only optimizations would move the strategy towards the minimal costs extreme, and performance only optimizations towards the engineering excellence extreme. If any of these optimizations would be started from either *run-to-failure* or *over-maintaining*, the first part would be an all value improvement, indicated by the green arrows. But neither of the optimizations would stop at the true optimum of this trajectory. That would be the point where the increase of benefits would be equal to the increase of costs, in other words the point where the trajectory runs in parallel with the trade-off line between costs and benefits. This is indicated by the dashed green line in the diagram. The green point is the asset management optimum, though it has to be recognized that given uncertainties in failure consequences and their probability it is more a range of good maintenance intervals than a single best one.

When instead of the production value the value of the lost production (production at 100 % availability minus actual production) is considered, the diagram can be plotted a total cost of ownership (TCO) optimization. This is demonstrated in Fig. 3. The trajectory now is represented by the x-axis, with *over-maintaining* at the origin and *run-to-failure* at the right hand side. The optimum is where the total costs are minimal, again reached when the increase of planned costs is equal to the decrease in risk. For optimal assets (100 % availability, infinite life, no maintenance cost and no risk), the opportunity cost of the employed capital (interest * investment) is the lowest possible TCO. This means that it is possible to define optimality in an absolute sense: the opportunity cost divided by the total costs of ownership

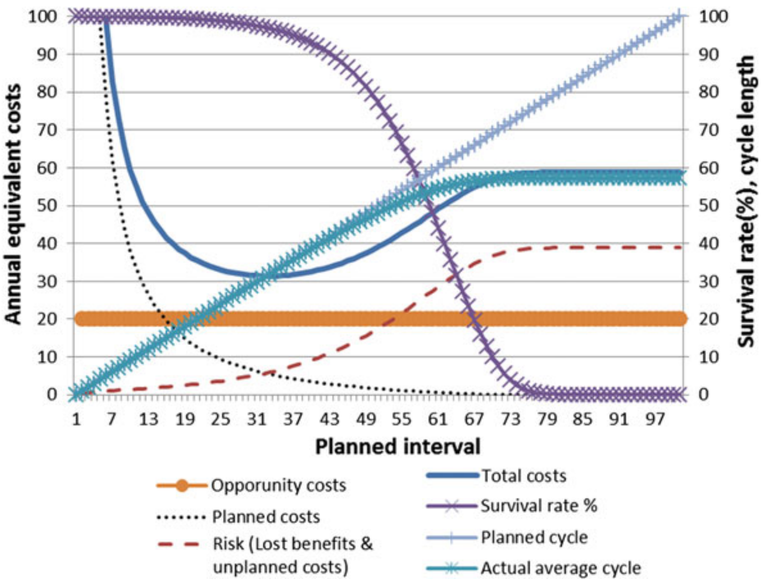

Fig. 3 Total cost of ownership for various maintenance intervals

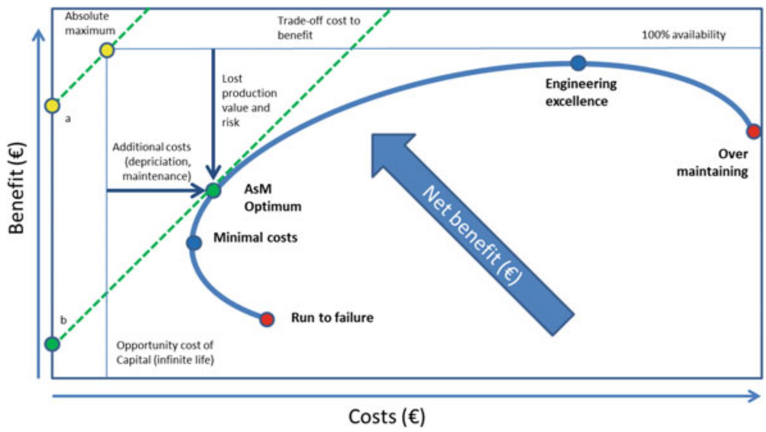

Fig. 4 Constructing the absolute optimality. Points *a* and *b* indicate the net benefit

(both to be expressed in annual equivalent terms). In the example above this would mean an opportunity cost of 20 divided by a TCO of 30, resulting in 66 % optimality.

This absolute optimality can also be constructed in the cost benefit diagram, as shown in Fig. 4. By following the trade-off line through the absolute maximum, the intersection with the y-axis gives the theoretical net benefit, *point a* (value of full production minus the opportunity costs). For any point in the diagram (i.e. combination of costs and benefits), the intersection of trade-off line through that point and the y-axis gives the realized net benefit. This is the optimal net benefit minus production losses and risk, and minus additional costs like depreciation and maintenance. The absolute optimality is the ratio between the realized net benefit and the theoretical net benefit. In the diagram the line through the AsM optimum is drawn, to construct the realized net benefit of the optimal maintenance interval, *point b*. The maximal net benefit is equivalent to minimal TCO, though the ratio between minimal and actual costs in general is not the same as the ratio between the net benefits.

3 Barriers to Quantifying System Optimality and Their Relevance

It has to be recognized that being able to quantify optimality of an asset does not immediately mean the system optimality can be quantified the same way. Two main barriers exist to do so. First of all, it requires a consistent monetization scheme for risk, otherwise the value of two risks is not necessary equal to the sum of their individual values. In many individual cases (so called normal risks, judged on their expected value) acceptable monetization factors can be found, even though aspects like safety, the environment and reputation are notoriously hard to monetize. But for some assets, like nuclear power plants, these cannot be applied, as the risks for those assets often are judged on potential effect (e.g. number of fatalities) without considering probability. This results in a variable value per expected unit of misery. If a portfolio considers such non-normal assets, system optimality cannot be determined. However, even in mixed portfolio's the optimality of the normal part may be of interest. This therefore is not a fatal problem for determining system optimality.

The second problem can be found in system complexity. If several assets are interlinked, it may be very difficult to capture all consequences of failing assets. This is especially true in redundant systems, where normally any asset may fail without consequences, but catastrophes may occur if several assets fail at the same time. Whether this is a problem depends on the difficulties in predicting the behaviour of the system as a whole from the behaviour of the elements of the system and their interactions, assuming these are understood reasonably well. Outcomes of the (often large and complex) optimization model then are very difficult (if possible at all) to validate (Morgan and Henrion 1992) and the acceptance of the optimum then depends more on the "belief" that the model is right than on factual evidence. But for systems consisting of relatively independent assets this is not relevant and system optimality can be a useful concept.

4 Concluding Remarks

Optimizations of assets are highly quantitative, weighing costs against performance and risk. Yet, for asset management systems optimization is highly qualitative. One of the problems behind this is that asset optimality is not yet expressed as an absolute number, which would be needed to "add" the optimality of several assets. In this paper it was demonstrated that such an absolute quantification is possible. Several barriers exist for translating asset optimality into system optimality, but the first impression is that the barriers are not fatal for the concept, even though system optimality will not have meaning for all systems. Further research first of all will have to identify the conditions under which optimality can be determined for individual assets. Our guess is that it should be possible for assets with only normal associated risks, but other limitations may apply. Secondly, the conditions and limitations for adding asset optimality into system optimality need to be established. Consistency of valuation and independence of assets are at least relevant. In parallel, research is needed on the precise formulation of optimality and the rules for adding asset optimality into system optimality. If such a concept of system optimality including the rules for its employment could be developed it would be very beneficial in discussing the value of asset management.

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Mapping Time-Variant Modelling of Tool Wears and Cutting Parameters on Difficult-to-Machine Materials

Peipei Zhang and Yan Guo

Abstract The cutting parameters of CNC (Computer Numerical Control) machining are spindle speed, feed rate, depth of cut and width of cut. The selection of cutting parameters for difficult-to-machine materials is very important to improve machining efficiency and ensure machining quality. The tool wears is one of the most important representation for machining efficiency and machining quality. Therefore, the purpose of this paper is to develop the mapping time-variant model between tool wear and cutting parameters on difficult-to-machine materials. The time as a factor is added to design of experiment for the first time in order to considering time-variant. The experiment is been done on the machining centre with eight fixed set of cutting parameters which is arranged by the orthogonal design. The number of measurement of tool wears is 10 during the tool life cycle. The experiments data show well the processing the tool wear. Tool wear is approximated linear with time for a fixed cutting condition. Depth of cut is most significant factor to tool wear (life). Based on these collected data, the mapping time-variant model is developed using least square method. The proposed time-variant model will be used for the prediction of the dynamic tool life and reliability-based optimization of cutting parameters.

1 Introduction

The selection of cutting parameters for difficult-to-machine materials is very important to ensure machining quality and improve machining efficiency. The traditional approach for selecting machining parameters is based on accumulated

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machining experience, which is either mastered by machinists or recorded in the form of machining handbooks. The machining parameters determined by experiential knowledge are usually safe to use, but conservative. To fully utilize the machine power and achieve maximum productivity without violating the machining constraints, optimization method with models on objectives (cutting time, quality, material removal rate, etc.) has been getting many attentions. However, accuracy of selection of cutting parameters depends on the exact of developed models. For tool wears (tool life) as one of the most important representation for machining efficiency and machining quality, the model on objective tool wear is developed by identifying constants of empirical models by regression, just different materials, and different tools. For example, Karandikar et al. (2014a, b) use classical Taylor's formula to predict the tool life and consider the uncertainty in the empirical model with Bayesian updating. Tsai et al. (2005) used training database to predict the tool life. However he hasn't use empirical models. Ojha and Dixit (2005) compared the neural networks and multiple regressions for prediction of tool life. He provided a linear model of flank wear. However, he hasn't link flank wear and empirical model. Natarajan et al. (2007) used artificial neural network (ANN) particle swarm optimization to reduce the computational time for prediction tool life. Yang et al. (2013) used finite element (FE) to analysis wear rate. Benkedijouh (2015) used support vector regressions and two nonlinear feature reduction techniques to predict remaining useful life. Khamel et al. (2012) used quadratic model of the response function to represent tool life. Mahyar et al. (2011) used artificial neural networks (ANN) and Taguchi design of experiments to do the tool life prediction. Kadirgama et al. (2008) and Lajis et al. (2008) used the response surface method (RSM) to do prediction of tool life.

Tool wear is a stochastic process. Different set of cutting parameters leads to different tool wear (tool life). In these works, the method to prediction tool life in published papers is to identify constants of empirical models by regression, just different materials, and different tools. Developing empirical model of tool life with cutting parameter doesn't consider the time factor. Few works have focused on the time-variant modelling of tool wear and cutting parameters. Therefore, this paper aims to search the relationship between tool life and time for one set of cutting parameters and different sets of cutting parameters.

In this paper, Sect. 2 introduces the experiment for collecting data of tool wear. Section 3 analyses these data and provide the processing of developing time-variant modelling of tool wear and cutting parameters. Section 4 gives a conclusion of this paper.

2 Experiments

2.1 *Work-Piece Materials*

Titanium alloy is an attractive material due to their unique high strength, which is classified as difficult-to-machine materials. The main problems in machining titanium alloy are the high cutting temperatures and the rapid tools wear. The major application of titanium alloy is to the aerospace industry. The tested material was an alpha-beta titanium alloy Ti-6AI-4V (TC4). The chemical composition of the titanium alloys (in wt%) and the mechanical properties of tested material are given in Table 1. The work piece used in the experiment was a block with the size 200 × 200 × 80 (mm).

2.2 *Cutting Tool Materials*

The inserts used for the machining experiments were cemented carbide CG10 SEKT1204AFFN-HL. The shape of the insert are square with four angles 45° cut (Fig. 1a). Five inserts were fixed in the tool handle at the same time (Fig. 1b). That means five measured values of tool wear can be obtained at the same time. The mean value will be used in following analysis.

Table 1 Chemical composition of the titanium alloys (in wt%) and mechanical properties of test materials

Element	**Ti**	**AL**	**V**	**Fe**	**C**	**N**	**H**	**O**	**Other**
Proportion	remainder	6.4	3.7	0.24	0.085	0.023	0.011	0.17	<0.10
Material	**Tensile strength σb (MPa)**		**Yield strength 0.2 % σ0.2 (MPa)**			**Elongation (%)**		**Hardness HRC**	
TC4	912		839			10		About 27	

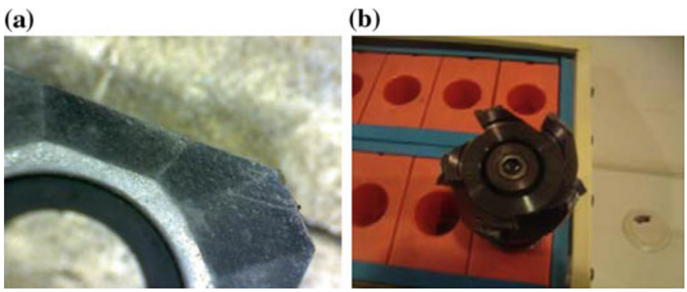

Fig. 1 Tool handle with five inserts

Fig. 2 Worktable

Table 2 Design of experiments

	Spindle speed n (rpm)	Feed rate v (mm/min)	Depth of cut dp (mm)
1	700	80	0.1
2	700	100	0.3
3	700	120	0.5
4	1000	80	0.3
5	1000	100	0.5
6	1000	120	0.1
7	1300	80	0.5
8	1300	100	0.1
9	1300	120	0.3

2.3 Machining Tests

All the machining experiments were carried out on a vertical CNC milling machine XH714 (Fig. 2), which was controlled by FANUC controller. The CNC milling has a continuously variable spindle speed. Throughout the whole experiments, the width of cut was kept constant at 40 mm. and the spindle speeds were set at 700, 1000, 1300 rpm. The feed rates were set at 80, 100 and 120 mm/min. the depths of cut were set at 0.1, 0.3, 0.5 mm. The machining experiments were carried out with cutting fluid. The cutting conditions used are design by orthogonal array. The cutting conditions used are shown in Table 2.

2.4 Wear Measurement

The insert wear were examined after a surface is milled (Twice straight cutter path; Width of cut is 40 mm; Width of the block is 80 mm). The number of measure of tool wears is 10. The time of each processing depended on the feed rate.

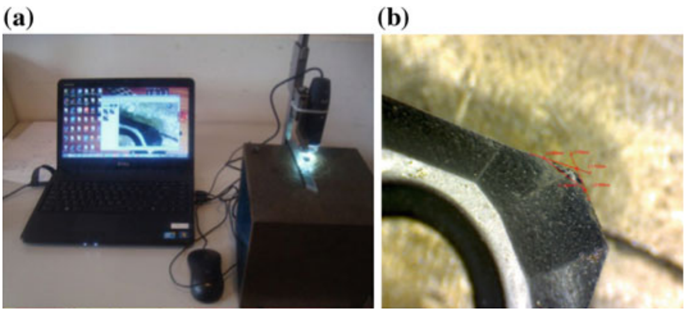

Fig. 3 Equipment and measurement. **a** Digital microscope. **b** Measurement of tool wear region

The maximum wear lands were measured in the longest and the widest by the toolbox of software in microscope (Fig. 3). Cutting was stopped after 10 processing was finished no matter the inserts was failed or not. Otherwise, cutting was stopped when catastrophic fracture of the edge was observed (appeared a lots of sparks).

3 Time-Variant Modelling

3.1 Relationship Between Time and Tool Wear

Based on the measured data that is not shown in this paper because of its big size; Fig. 4 give the trend of tool wear to times for eight cutting conditions. In this figure, we can find that tool wear increases linearly while times increase. The fastest growing is last set parameters (n = 1300 rpm, v = 120 mm/min, dp = 0.3 mm). This means spindle speed and feed rate are significant factors for tool wear. For sixth set parameters (n = 1300 rpm, v = 80 mm/min, dp = 0.5 mm), trail is halted at seventh time due to too severe tool wear and appeared lots of sparks.

3.2 Developing Variant Modelling

Based on the figure and data in Sect. 3.1, we find that tool wear is approximated linear with cutting process. The gradients (α) of approximated linear increase while cutting parameters increasing (Fig. 4). We can see that it is possible to calculate tool wear (W) if the gradient of cutting condition and time are given, see the formula (1).

$$\mathrm{W} = at + b \quad (1)$$

Now, it is necessary to determine the relationship between the cutting parameters (spindle speed n, feed rate v, depth of cut dp) and the gradient (a) and constant b.

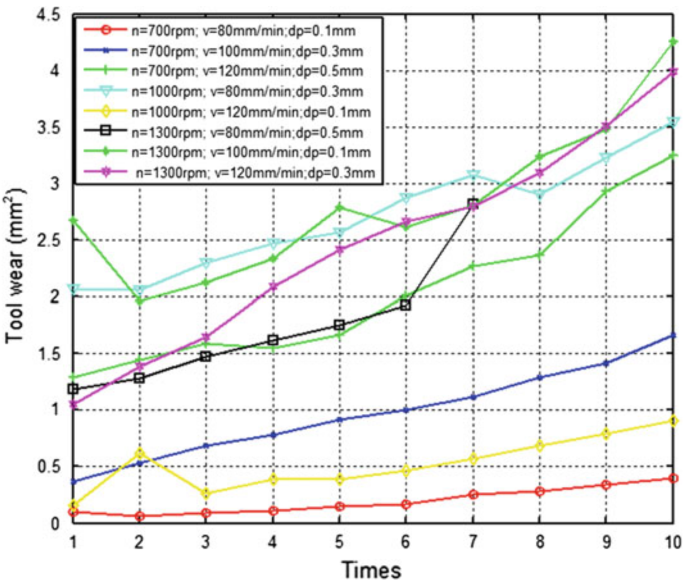

Fig. 4 Times to tool wear

Table 3 Cutting parameters and tool wear

n (rpm)	*v* (mm/min)	*dp* (mm)	T (s)	W (mm^2)	Times	Linear
700	80	0.1	447	0.3987	10	0.036x − 0.0047
700	100	0.3	357	1.6633	10	0.13x + 0.25
700	120	0.5	302	3.2452	10	0.21x + 0.89
1000	80	0.3	445	3.5497	10	0.16x + 1.8
1000	120	0.1	303	0.9058	10	0.065x + 0.17
1300	80	0.5	444	2.8191	7	0.23x + 0.8
1300	100	0.1	360	4.2565	10	0.19x + 1.8
1300	120	0.3	302	3.9886	10	0.31x + 0.77

The cutting parameters, times of cutting (T), tool wear (W), linear functions are shown in Table 3. For sixth set parameters, lots of sparks are appeared and cutting was forced to stop after seventh measurements. In other words, time-variant modelling is to develop the relationship between cutting parameters (*n, v*, *dp*) and time with tool wear (W), see the formula (2).

$$\mathbf{W} = \mathrm{F}(n, v, dp, t) \tag{2}$$

After getting the data of cutting parameters, time and response tool wear, least square method is adopted to develop the variant model for different parameters. Based on the empirical model, there are four unknowns (x_1, x_2, x_3, x_4). That means it needs four sets experiments data. Therefore, nine sets experiments (Table 3) are enough to develop this model. The empirical model is

$$\mathbf{W} = \mathbf{A} n^{x_1} v^{x_2} dp^{x_3} t^{x_4} \tag{3}$$

$$\ln(\mathbf{W}) = \ln(\mathbf{A}) + \mathrm{x}_1 n + \mathrm{x}_2 v + \mathrm{x}_3 dp + \mathrm{x}_4 t. \tag{4}$$

Based on the data in Table 3, the coefficients are calculated by least square method; See the formula (5).

$$\mathrm{W} = 2.6719 \times 10^5 n^{0.0034} v^{-0.0829} dp^{5.6623} t^{-0.0217} \tag{5}$$

4 Conclusion

The research explored the development of mapping time-variant model between tool wear (tool life) and cutting parameters in CNC milling difficult-to-machine materials (TC4). From the study, specific conclusions from the study are as follows: Tool wear is approximated linear with time for a fixed cutting condition. Depth of cut is most significant factor to tool wear (life) for difficult-to-machine materials. This is different with comment materials like aluminum alloy. Spindle speed is most significant factor to tool wear.

The model developed in this paper can be used to predict the dynamic tool life and in reliability-based optimization of cutting parameters of difficult-to-machine materials for other researchers and companies. The following work will focus on analysis demonstrate the efficacy and accuracy of the proposed time-variant model on prediction of the dynamic tool life and reliability-based optimization of cutting parameters.

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Managing Strategic Risks in the Electricity and Gas Distribution Sector—A Conceptual Model and Its Examples

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Abstract Most existing asset management models and standards recommend quantifying risks before handling them. In such a regime, the awareness of long-term stakeholder-oriented risks which are difficult to be quantified tends to be insufficient. In this paper, we will firstly identify six categories of such risks, called "strategic risks", for asset management. Then, we model several real examples of "strategic risks" in the utility sector with our conceptual model, so that the necessity to deal with these "strategic risks" will be illustrated.

1 Introduction

Managing risks associated with assets is an essential part of asset management (AM). Today's standards for asset management, such as (ISO 2015), emphasize that the risks should be optimally managed. It means that all risks should be quantified before being managed. Specifically, the Dutch electricity and gas sector uses a risk matrix defined in a national standard (NEN 2009) to quantify the potential benefits of investments. The matrix assumes that the probability of a risk is predictable, while convert six aspects of risk consequences into financial losses. For our company, the six aspects are service quality, safety, finance, compliance, public image and sustainability.

As the asset owner and manager of an electricity and gas distribution network, we are currently using the risk matrix to model all risks, with technical or non-technical stimuli in medium and long term. However, we have encountered serious challenge to identify strategic risks with the risk matrix. Typically, these risks are either triggered in ways which are missing from the structured database for risk register, or taking decades to generate the harmful effects included in the risk

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matrix. In these situations, the awareness to these risks is insufficient in our company. Consequently, these risks are seldom considered in decision making processes, so that few actions have been taken to tackle these risks.

This paper will describe our effort to solve the above difficulty. In Sect. 2, we will firstly argue that: the risk matrix is suitable at the tactical level of asset management, but not at the strategic level, since it cannot tackle the risk of three characteristics: uncertainty, complexity and ambiguity. Our modelling and examples will show that, the "strategic risks" will appear in six different types, while each type represents a combination of these characteristics. After the categorizing strategic risks in Sect. 2, Sect. 3 will concentrate on identify and controlling "complex" risks. The complexity of a risk is reflected in the topology of its causal chain. Therefore, we will introduce one of the noteworthy topological patterns of causalities, namely the feedback loop, in Sect. 3. In order to illustrate each pattern, an example from our sector will be given and our experiences on controlling this example/risk will be described.

2 Risks from the Strategic Perspective

2.1 Characteristics of Normal Risks

Before formally defining strategic risks, it is worthwhile to study the characteristics of "normal risks", i.e. those are currently studied quantitatively at the tactical level of AM. A typical example of such risks is an aging mechanism in an asset population. Figure 1 shows the causal chain of this example.

The bottom row of Fig. 1 shows what physically happened in operation on a specific asset. The initial stimulus is the (physical or chemical) stress which initiate the aging of this asset. The direct stimulus is a certain mode of failure on a specific subcomponent of the asset. The intermediate consequence is the failure (loss of functionality) of the asset and corresponding asset system. The final consequence is the loss of performance of the asset portfolio, such as SAIFI (system average

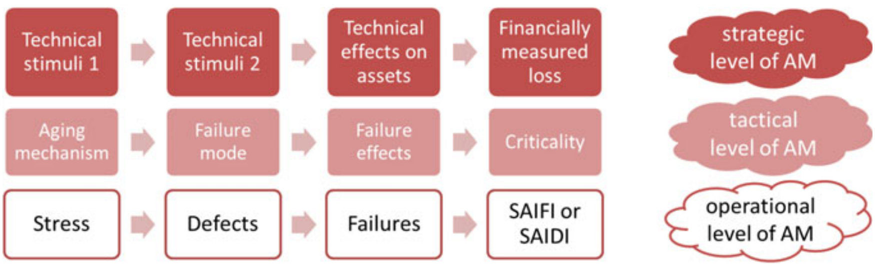

Fig. 1 An aging mechanism in an asset population is a typical "normal risk" which is suitable to be analysed at the tactical level of asset management

interruption frequency index) or SAIDI (system average interruption duration index), which should be reported to the asset owner and regulator.

At the tactical level, the initial stimulus, direct stimulus, intermediate consequence and final consequences stated above are respectively modelled for an asset population as “aging mechanisms”, “failure modes”, “failure effects”, and “criticality (of failure modes)”. They are studied in a straightforward causal chain as the middle row in Fig. 1 shows.

From the perspective of the strategic level, such a straightforward causal chain is suitable to be analyzed with the risk matrix at the tactical level, because it satisfies three conditions below.

- Firstly, it is stimulated technically, so that the knowledge of asset workers is sufficient to identify and measure the stimuli.
- Secondly, it results in technical effects on assets, which can be observed in operation, controlled with technical O&M activities and predicted according to experience.
- Thirdly, it leads ultimately to the consequences which can be financially measured, i.e. the loss can be measured with units (e.g. customer minute in SAIDI) which can be further converted to currency as, e.g. regulatory penalty.

In our opinion, a risk should not be studied at the tactical level of AM, if its causal chain does not satisfy the above three conditions. Meanwhile, to be relevant to asset manager, a risk should at least contain some of the technical elements from Fig. 1 in its causal chain. Based on these two reasoning, we will identify in the next section six categories of “strategic risks”, i.e. the risks which should be studied at the strategic level of AM.

2.2 *Six Types of Strategic Risks*

The primary goal of the strategic level of AM is to find out a feasible roadmap which satisfies all stakeholders and provides a stable business environment for the optimizations at the tactical level. In other words, the business factors threatening this primary goal will initiate the “strategic risks”.

A risk becomes strategic, when its characteristics prevent analysts from quantifying it. In risk management in general, (Klinke and Renn 2002) have identified these characteristics as uncertainty, complexity and ambiguity. We adapt their meanings to our field of AM as below.

- **Uncertainty**: the (un)availability of knowledge for the asset manager to identify, measure and quantify the elements in the causal chain of the studied risk. In AM, high uncertainty is frequently caused by missing (the knowledge from) the experts from a certain area. Such area can vary from technology, economics, to social science.

- **Complexity**: the degree to which multiple causal chains are interdependent. The straightforward causal chains analysed at the tactical level are based on a number of conditions on, for example, the load profiles on assets, the supply chain, the regulatory rules, etc. Once any of these conditions are broken, a strategic risk of high complexity is likely to be formed.
- **Ambiguity**: the variety of the interpretation of the same facts, as well as the consequent normative conflicts between different stakeholders. In AM, even when a technical stimulus is known to all internal and external parties, they can still disagree on the countermeasures, due to different personal experience or understanding on the consequences.

Different combinations of the above three characteristics can merged into the six situations, named with the Greek half gods by (Klinke and Renn 2002). These six types of (strategic) risks will be adapted to the triple level AM model, as Table 1 summarizes and we will further explain in details in this Section.

The risks of type "Pythia" and "Pandora" are featured with their high uncertainty. In AM practice, the most observable and available knowledge is about the losses or changes of the functionality of assets. From the strategic perspective, such losses or changes are the "technical effects on assets" in the causal chain (e.g. as shown in Fig. 1). With these types, the "technical stimuli" is likely to be unclear to risk analysts; the prediction of "financially measured loss" is not feasible.

The main difference between "Pythia" and "Pandora" is their final consequences. Pythia is the oracle of Delphi whose prophecies should be further interpreted in order to be linked with the real world. A strategic risk of "Pythia" in AM describes the situation when (technical) knowledge is insufficient to understand the (technical) effects on assets, either regarding its causes or its impact on asset systems.

Example Risks of type "Pythia" typically appear when the assets are not familiar to the sector. For utility companies, the wide application of information and communication technology (ICT) in the transition to "smart grid" is such an example.

Table 1 Characteristics and examples of six types of strategic risks

Type	Uncertainty	Complexity	Ambiguity	Example in AM
Pythia	High	Low	Unknown	Reliability of ICT and cyber security
Pandora	High	Medium to high	Unknown	Quality of GIS data for the network
Cyclops	Medium	High	Low to medium	New load profiles from energy transition affect existing assets
Damocles	Low	High	Low	Black start of a smart grid (e.g. after a natural disaster)
Cassandra	Low	Low	High	Hindrance of infrastructural assets in the public area
Medusa	Medium	Medium to high	High	Fear of EM field from the electricity grid

We have not yet experienced an outage caused purely by ICT failures. Without such reference information, the risk of ICT failures on power and gas delivery cannot be quantified.

In contrast, a strategic risk of type "Pandora" in AM tends to have consequences on some scarce resources provided by certain stakeholders, rather than some resources purchasable on the market. The wide range of stakeholders brings complexity to risks of type "Pandora". As its name "Pandora's box" suggests, loss of such scarce resources will disturb or even interrupt essential operation activities, and therefore threaten continuity of the business. For our sector, such resources include public support for network reinforcements, confidence of personnel on safe working environment, suppliers of critical assets, etc.

Example The technical stimulus of "Pandora" is often widely used or consumed in the normal O&M. The geographical information system (GIS) is a typical example for infrastructures which integrate tightly with the community. Low data quality of GIS will lead to low efficiency of field maintenance, which further disturbs the community. Section 3 will discuss this example.

The risks of type "Cyclops" and "Damocles" can frequently be found in the risk register, since they do not have high uncertainty. Some scenarios of their causalities have been noticed by the risk analysts. However, their high complexity prevents risk analysts from evaluating all scenarios. In the risks of type "Cyclops", the high complexity leads to a certain degree of uncertainty. In other words, when the risks have many possible causes, it is likely that some of them are missing for expert knowledge. Therefore it is named with Cyclops, the Greek giants who only have one eye, with which only a single side of the facts can be revealed.

Example Our sector is investigating intensively on one risk of "Cyclops": the new load profiles caused by energy transition can affect the reliability and remaining lives of existing assets. The aging of many assets, such as cables or switchgears, can be accelerated by these load profiles in a high rate which forces our asset owner to replace in large scale.

The uncertainty of "Cyclops" is mainly in its technical stimuli, while the uncertainty of "Damocles" is mainly in its technical effects. The sword of Damocles is a scenario of risk which has catastrophic effects, but such a scenario can be missing from risk register since its probability is extremely small.

Example In practice, the probability of a catastrophic incident (e.g. a death in failure) is frequently calculated from multiplying the probabilities of several triggering conditions (e.g. the frequency of explosion of an instrument transformer and the percentage of duration in which personnel is working near an instrument transformer). However, if the triggering conditions are not mutually independent, but both result from a certain event (e.g. an on-site diagnostic test on an instrument transformer), the calculated probability of death will be incorrect.

The risks of type "Cassandra" have a high ambiguity internally due to the "delay effect". As occurred the fall of Troy, the decision makers refuse to react to a precisely predicted risk, because the hazards take many years to appear.

Organizationally, the decision maker will no longer be accountable for the hazards. Scientifically, decision making methods such as net present value tend to downgrade the long-term effects with the discount rate.

Example The long lives of infrastructure assets make "Cassandra" quite common in the beginnings of their life cycles. Positioning new substation improperly in the public space, for example, will lead to higher expenditures of regular maintenance and future expansions. However, asset manager will neglect this problem if he only considers the cost of the present project without taking into account future costs to avoid hindrance.

In the risks of type "Medusa", asset managers are facing ambiguity from external, non-professional parties. The spread of psychological effects, such as horror like its name suggests, is the main effect of such risks. Purely technical measures decided at the tactical level of AM are normally inefficient or even powerless.

Example The negative public images on the electricity network are widely supported in today's media. In personal experiences of inhabitants, such image can result from noise or visual impact. But when the opposition against infrastructures is explicitly expressed by the community, reference is made to terrifying messages on e.g. electromagnetic fields.

3 Managing Complex Causalities of Strategic Risks

Last section have introduced the six types of strategic risks, especially regarding their characteristics, i.e. how they can lead to difficulties of quantitative risk assessment at the tactical level of AM. In this section, we will concentrate on how to identify and tackle one characteristic of the strategic risks: the complexity. As mentioned in Sect. 2.1, the complexity appears as the interdependency between causal chains. Therefore, an explicit way to identify complexity in practice is to search for certain topological patterns of causal chains. For simplicity, we will introduce one pattern of complexity, namely the feedback loop, and illustrate it with an example from the electricity distribution sector.

Feedback has been extensively discussed in cybernetics and many other disciplines which apply it. It is well-known that a positive feedback loop will lead to system instability, which should be avoided when the system is reflecting our business. Unfortunately, such causal loops cannot be easily discovered in practice of AM, especially when the causalities come from both technical side and external stakeholders.

Figure 2 illustrates one of our main strategic risks: the public resistance. The loop is composed of five links.

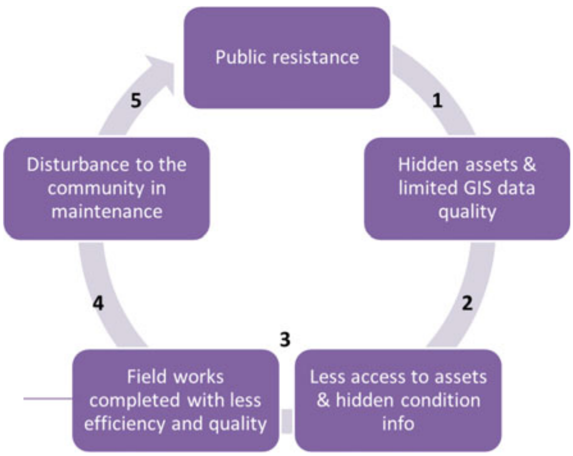

Fig. 2 The causal chain of risks in underground infrastructure assets form a positive feedback loop, which implies that these risks should be studied as a system

1. To avoid public resistance, many of our assets use compact designs, while GIS data are insufficient to reflect their location adequately.
2. The compact design of assets adds to the difficulty of personnel to assess their condition regularly, which makes condition information less available.
3. Less condition information and poor GIS data make that the field work, especially in the open public areas, is performed with less efficiency and quality.
4. Field work of poor quality and efficiency disturbs the community for a longer period with more hindrance and a higher probability to damage properties of inhabitants next to the activities.
5. As a result of the disturbances and damages, the community gives less support to new infrastructure (both above and underground).

In the past, when facing public resistance, asset owners tend to investigate Link 5 separately without recognizing Link 2–4. Meanwhile, the knowledge of acquiring condition information from underground assets is accumulated separately by technical specialists for other purposes such as reliability centred maintenance. However, the feedback loop suggests that the two sides can work together in solving three problems:

- The Pandora's Box of arbitrarily investing in compact assets. In Link 1, hiding assets is not an absolute solution of public resistance. But acquiring knowledge about the long-term impacts of underground assets, as well as improving the quality of GIS data, are necessary countermeasures.
- The Cassandra's Prophecy on hidden asset condition information. In Link 2 and 3, condition information will not show its value until assets are aged after many decades. However, the easiness to acquire the information is largely determined by the exact asset location, that is determined and known at the beginning of the life cycle. The decision making panel should include not only the system designers, but also the component specialists. Specifically, the possibility to diagnose assets should be considered in the original spatial design.

- The Medusa of maintenance activities. The opinion of community to field work in the public space, Link 4 and 5, depends heavily on the culture how to perform and other human factors. To understand the feedback from the community, non-technical information should be widely collected, not only from client service, but also from field work or even from internet platforms.

In summary, at the strategic level, risk analysts should firstly have a general picture of the causalities. Then, when a part of the mesh of causalities can be described in one of the six types of strategic risks, a local solution to each strategic risk can be found out.

4 Conclusions

The strategic level of asset management should not rely on the risk matrix to identify risks, because strategic risks are difficult to be quantified. This paper has developed a conceptual method which uses the characteristics and patterns of causalities to identify strategic risks. The method is currently being applied to manage the public resistance to our infrastructural assets, as the case study has shown.

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