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J. Paulo Davim *Editor*

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Preface

Industrial engineering is the branch of engineering that is concerned with "increasing productivity through the management of people, methods of business organization and technology" or in other words, "industrial engineering is human effort engineering and system efficiency engineering". Depending on the subspecialties involved, industrial engineering include operations management, management science, systems engineering, manufacturing engineering, ergonomics or human factors engineering, safety engineering, etc.

The purpose of this book is to present a collection of examples illustrating research advances in industrial engineering. Chapter 1 of the book provides lean manufacturing (recent trends, research and development and education perspectives). Chapter 2 is dedicated to a case study on lean product and process development. Chapter 3 contains information on lean product development enablers for product development process improvement. Chapter 4 is dedicated to discussing and evaluating the green environmental performance of manufacturers. Chapter 5 contains information on simulation study. Chapters 6 and 7 are dedicated to mathematical modelling with an application to nuclear power plant reliability analysis and gas turbine assimilation under copula-coverage approaches, respectively.

The current book can be used as a research book for the final undergraduate engineering course or as a topic on industrial engineering at the postgraduate level. Also, this book can serve as a useful reference for academics, engineers, managers, researchers, and professionals in industrial engineering and related subjects. The scientific interest in this book is evident for many important centers of research, universities as well as industry. Therefore, it is hoped this book will inspire and enthuse others to undertake research in industrial engineering.

The Editor acknowledges Springer for this opportunity and for their enthusiastic and professional support. Finally, I would like to thank all the chapter authors for their availability for this work.

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J. Paulo Davim

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Chapter 1
Lean Manufacturing: Recent Trends, Research & Development and Education Perspectives

S. Vinodh and R. Ben Ruben

Abstract Lean Manufacturing concepts are being adopted by modern manufacturing organizations to achieve competitive advantage. Lean manufacturing ensures waste elimination, streamlined processes and value addition. Applying lean concepts removes all non value added activities and focus only on enhancing customer value. Lean helps in minimizing or removing the activities that does not provide customer value. It also helps in achieving cost reduction as the non value added activities are removed. Modern manufacturing engineers are required to understand the importance of lean manufacturing. In this context, this chapter presents the core lean concepts/principles, lean tools/techniques and application domain of lean manufacturing. Recent trends and development in lean manufacturing field are also being presented. The importance of lean concepts in modern manufacturing curriculum as well the curriculum contents are also being highlighted.

1.1 Introduction

The modern manufacturing systems have been exhibiting a shift from mass production to lean manufacturing due to increasing demands of customers and product complexities (Abdulmalek and Rajagopal 2007). Lean manufacturing concepts has its origin in Toyota Production System, Japan by Taiichi Ohno and Shigeo Shingo at Toyota. The term lean manufacturing has come into existence after the release of book titled "The machine that changed the world" by James Womack in 1990. The term "Lean" was coined in the 1980s by researcher John Krafcik, as he and others at MIT were discovering that Japanese techniques of automobile production were

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providing companies like Toyota a significant advantage in the marketplace. Lean production is "lean" because it uses less of everything when compared with mass production. Lean manufacturing enables the elimination of wastes. Wastes include seven categories namely overproduction, overprocessing, waiting, motion, transportation, defects and inventory (Hines and Rich 1997). Recently, underutilization of workforce creativity and environmental waste are included as eighth and ninth waste (Vinodh and Chintha 2009). The ultimate focus of lean manufacturing is to minimize and eliminate wastes. This should enable streamlining of processes and improving the flow of process by minimizing fluctuation in value stream. Lean system aims to improve value addition by means of removal of non-value added activities, making the value stream smooth, and converting push production to pull production and perfection by continuous improvement. A lean system understands about customer's value and focuses to improve it consistently. A clear understanding and selection of appropriate lean tools/techniques is essential to achieve improvements. Lean manufacturing improvements include waste reduction, value improvement, inventory reduction, cost reduction, improved quality yield and productivity. Lean manufacturing has diversified applications in several industrial sectors such as automotive, aerospace, electronics, service industries etc. The ultimate goal of lean manufacturing is to provide perfect value to the customer through a perfect value creation process that has zero waste.

This chapter focuses on highlighting core concepts, tools/techniques and application domains of lean manufacturing. Various new trends and research & development issues in the context of lean manufacturing are presented. Also, the importance of lean manufacturing in modern manufacturing curriculum and curriculum contents are being included.

1.2 Concepts/Principles of Lean Manufacturing

Lean manufacturing is generally defined as the process of consistent elimination of wastes. The goal is to provide the customer with a defect free product or service when it is needed at the right quantity. Lean can also be defined as an activity which focuses on reducing wastes and maximizes the activities that add value from customer's perspective. It is a customer-centric methodology used to continuously improve any process through the consistent elimination of waste. Lean concepts are based on the ideas of continuous improvement and respect for people. Value is equivalent to anything that the customer is willing to pay. Value is to be defined by the customer and it is the key in transforming a product or service. Waste must be consistently eliminated from the system. Waste comes in three main forms namely Muda, Mura an Muri. Muda refers to the seven forms of lean wastes namely overproduction, overprocessing, waiting, motion, transportation, defects and inventory. Mura is the waste due to variation or unevenness and Muri refers to waste due to overburdening or stressing. So, elimination of waste is the basic principle of lean manufacturing (Shingo 1998). For achieving this, a set of principles need to be followed. On reviewing the literature, five key lean principles of lean manufacturing as discussed by Womack and Jones include:

1. Specify value from view point of customer.
2. Identify all steps involved in manufacturing the product and map value stream to eliminate the non-value added activities.
3. Create a smooth flow of the product towards customer's reach.
4. Make customers to pull value from the next upstream activity.
5. Begin the process again and continue it until a state of perfection is reached to create perfect value with no waste.

Based on the above five key principles as shown in Fig. 1.1, Womack (1990) highlighted the principles as Value, Value Stream, Flow, Pull and Perfection. It is important to understand what the customer needs and expects from the product or service. It is this value that determines how much money that the customer is willing to pay for product and services. So, it is important to identify the value from customer's viewpoint. After identifying the value, value stream for the entire product is being mapped to identify the wastes involved. Performing the value stream, makes the firm to understand about the value added and non-value added activities. Later the non-value added activities and wastes are being eliminated to create a flow without any stops in the production process. A properly designed flow across the entire value chain will tend to minimize waste and increase value to the customer. A pull approach means, it is not required to make anything until the customer places order. To achieve this, the system must be flexible with very short cycle times of design, production, and delivery of products and services must be required. The production type must be a pull driven approach rather than a push approach for effective utilization of resources to avoid uncertainty due to demand. Finally, after creating flow and achieving pull, more layers of wastes become visible and the process continues towards theoretical end point of perfection. This point of perfection is the key attitude for an organization to be lean.

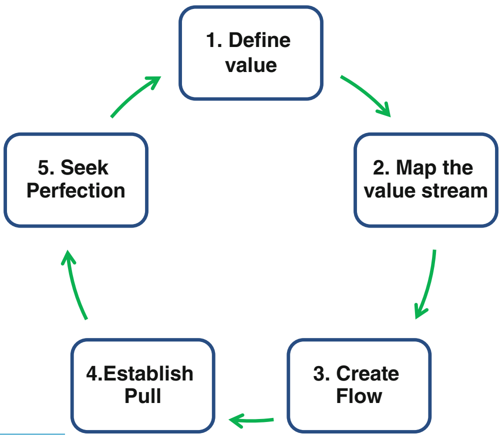

Fig. 1.1 Five key principles of lean manufacturing

Apart from five key principles, researchers have also mentioned several other concepts and principles for understanding and implementing lean manufacturing. Though five key principles of lean manufacturing are considered as guiding principles, further other lean principles that are useful in implementing the practices are Continuous Improvement, Respect for humanity, Leveled production, Just in time production, Built-in quality, etc. (Hino 2006). The 14 principles of Toyota which drive the techniques and tools of Toyota Production System and management of Toyota Corporation in general are classified into four categories namely Long term philosophy, Right process, People and partners and Problem solving (Liker 2005) which helps in achieving waste reduction. Few other principles of lean manufacturing include focusing on effectively delivering value to customers, respecting and engaging the people, improving the value stream by eliminating all types of wastes, maintaining flow, pull though the system, and striving for perfection (Sayer and Williams 2012).

The five principles of lean framed by Womack and Jones (1990) help the firms to perform consistently and ensures that value is delivered to the customer consistently and maintains a high level of service.

1.3 Tools/Techniques of Lean Manufacturing

The process of waste elimination is achieved through the application of lean tools and techniques. Lean manufacturing tools are employed to eliminate the wastes that prevail in the workplace. There are several lean manufacturing tools which provide better outcomes when applied properly. Most of these tools concentrate on only a single aspect of lean production. The biggest challenge lies in selecting the appropriate tool for eliminating wastes, as each tool has its own uniqueness. After identifying the source of waste, suitable lean tool is chosen to reduce or eliminate them and to make the system waste free. Figure 1.2 shows some of the basic lean manufacturing tools used in the waste elimination process. This section discusses about some of the basic lean tools and techniques widely used for reducing and eliminating wastes. The basic tools and techniques of lean manufacturing are discussed in the following sections.

1.3.1 5S

5S is a workplace organization technique developed in Japan. 5S stands for Japanese words seiri (tidiness), seiton (orderliness), seiso (cleanliness), seiketsu (standardization), and shitsuke (discipline). The main scope of 5S is to eliminate wastes that results from a poorly organized workplace. The translated meaning for the Japanese terms includes:

1. Sort—eliminate that which is not needed
2. Set In Order—organize remaining items

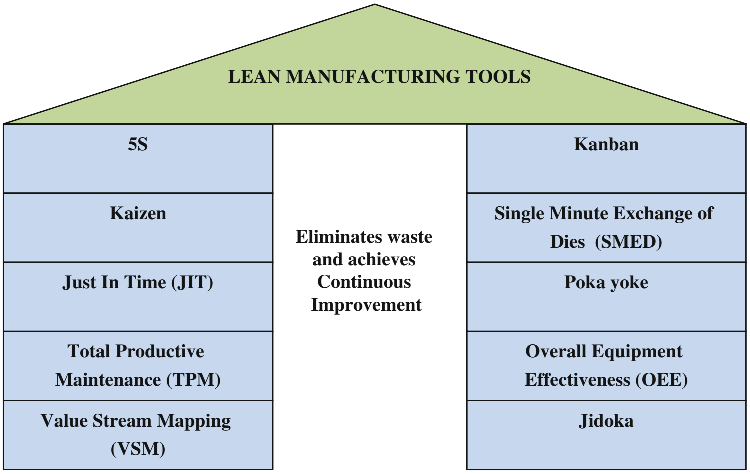

Fig. 1.2 Basic lean manufacturing tools

3. Shine—clean and inspect work area
4. Standardize—develop standards for above
5. Sustain—regularly apply the standards

5S produces a workplace that is clean, uncluttered, safe and organized. It is a culture that should be followed in the workplace.

1.3.2 Kaizen (Continuous Improvement)

Kaizen is a Japanese term which means 'change for better'. It is a strategy where employees work together proactively to achieve regular, incremental improvements in the manufacturing process. Kaizen usually delivers small improvements; the culture of continual aligned small improvements and standardization yields large results in terms of overall improvement in productivity. It involves setting standards and then continually improving those standards.

1.3.3 Just in Time (JIT) Concepts

JIT is a production strategy where parts are pulled through production based on customer demand instead of pushing parts through production based on projected demand. Just in time is a type of operations management approach which originated in Japan in early 1950s. It was adopted by Toyota and other Japanese manufacturing firms. It is highly effective in reducing inventory levels and improves cash flow. The main focus of JIT technique is having "the right material, at right time, at right place, and in exact quantity".

1.3.4 Total Productive Maintenance (TPM)

TPM is a technique which aims at maintaining and improving production and quality systems through proactive and preventative maintenance to maximize the operational time of equipment. It creates a shared responsibility for equipment that encourages greater involvement of shop floor workers. It is an effective tool to improve productivity by reducing cycle time and eliminating defects. It places a strong emphasis on operators to maintain their equipment, thus creating a state of ownership. The main objective of TPM is, it engages all functions and levels of an organization to maximize overall effectiveness of the production equipment.

1.3.5 Value Stream Mapping (VSM)

VSM is an effective tool to identify the non-value added activities associated with manufacturing process. It helps in analyzing the current state and designing the future state for a series of activities that are involved during manufacture of the product. It uses a standard set of symbols to depict and improve the flow of information and inventory. It visually maps the flow of the production process and also highlights improvement opportunities. The wastes are being identified in the current processes and a roadmap for improvement through the future state is provided. This tool can be applied to all types of organizations, including process and service industries.

1.3.6 Kanban

The term Kanban literally means a signboard in Japanese term. It is a systematic method of regulating the flow of goods both within the factory and with outside suppliers and customers. It is based on the principle of automatic replenishment through signal cards that indicate when more goods are needed. Kanban maintain inventory levels by generating a signal to produce and deliver a new shipment as material is consumed. These signals are tracked by the replenishment cycle and bring visibility to suppliers and buyers. It is a useful tool which helps in achieving JIT by reducing inventory levels.

1.3.7 Single Minute Exchange of Dies (SMED)

SMED is a setup time reduction technique where the setup/changeover is made in less than 10 min. It is one of the key lean techniques to reduce waste in the manufacturing process. For implementing SMED, a sequence of steps that must be followed includes:

- Converting setup steps into external task, i.e. performing the setup while the process is running
- Simplify internal setup by replacing bolts with levers and knobs
- Eliminate non-essential operations
- Create standardized work instructions

It enables manufacturing in small lots, reduces inventory, improves customer responsiveness and thereby improves the flow.

1.3.8 Poka-Yoke (Error Proofing)

It is a documented procedure for manufacturing that captures the best possible procedure for performing a job. It is one of the most powerful lean tools as it creates a new standard for manufacturing and forms a baseline for future improvements. It consists of realigning and orienting three lean elements namely takt time, work sequence and standard inventory for capturing and documenting the best manufacturing practices.

1.3.9 Overall Equipment Effectiveness (OEE)

It is a framework for measuring productivity loss for a manufacturing process. It provides measures to track progress in eliminating waste from manufacturing processes. OEE splits the performance of a manufacturing unit into three measurable components namely Availability, Performance, and Quality. Each component indicates an aspect of the process that can be aimed for improvement. Mathematically OEE is calculated as the product of availability, performance and quality. OEE measurement is also commonly used as a Key Performance Indicator (KPI) in conjunction with lean manufacturing efforts to provide an indicator of success. It also quantifies how well a manufacturing firm performs relative to its designed capacity, during the periods when it is scheduled to run.

1.3.10 Jidoka

It is one of the two pillars of Toyota Production System. It is a technique to partially automate the manufacturing process and to automatically stop when defects are detected. It is also described as automation with a human touch. This technique applies four principles namely:

1. Detect abnormality
2. Stop the process
3. Fix or correct immediate condition
4. Investigate the root cause and install a counter measure

Implementing Jidoka techniques help the operators to frequently monitor multiple stations and to detect quality issues.

Though there are several tools and techniques available for implementing lean manufacturing, this chapter discusses only the important tools and techniques that play a crucial role in eliminating waste and are considered as startup tools in implementing lean practices. Each tool has its own way of eliminating waste and supports the lean transformation process in order to remove waste, variability and overburden and to deliver improvements.

1.4 Applications of Lean Manufacturing

The benefits and process improvements of lean manufacturing principles can be experienced only on its successful implementation. The principles, tools and techniques of lean are applied across various industrial sectors for waste elimination and achieving operational excellence. Initially lean manufacturing principles were applied only on manufacturing sectors, as it was developed by an automotive manufacturing firm (Toyota Production System) as the need for consistent elimination of wastes were more in the case of manufacturing industries. Later, the application of lean manufacturing principles was extended to other sectors like service, processing, etc., as there exists a scope for process improvement. Conceptually, these applications follow similar routes to those in manufacturing settings. The approach and methodology used for application may differ depending upon the sector where the concepts are to be applied.

Further, various research and investigations are being carried out on extending the application of lean principles to various sectors. The applications of lean manufacturing principles in different sectors are discussed in the following sections.

1.4.1 Lean Applications in Manufacturing Sector

Lean manufacturing principles are widely applied in manufacturing sectors as the role played by man, machine and materials are crucial towards the manufacture of the product. Applying lean principles in a manufacturing firm makes the firm to improve its productivity and to achieve operational excellence. Three contextual factors namely plant size, plant age and structure of the organization are the key facets of lean production systems (Shah and Ward 2007). Most of the manufacturing firms adopt Value Stream Mapping as the main tool to identify the opportunities for various lean techniques, as it helps in identifying the Value Added (VA) and Non Value Added (NVA) costs. The potential benefits of application of lean principles in manufacturing lie in reducing production lead-time and work-in-process inventory (Abdulmalek and Rajagopal 2007). Though the strategy used and methodology followed for applying lean in small and large firms may vary, the benefits obtained after successful implementation remains the same. On analyzing the literature, several case studies are available on application of lean manufacturing principles in manufacturing sectors. The types of industries include component manufacturing, assembly lines, automotive industries, machine shops, etc. After successful application of lean concepts, the improvements can be measured in terms of process ratio and productivity.

1.4.2 Lean Applications in Process Industries

Lean principles can be applied in both continuous manufacturing environment and discrete system. Process manufacturing firms are different from discrete manufacturing environment with respect to material flows (King 2009). Material flows in a continuous stream in a process manufacturing environment. The framework and methodology adopted for applying lean concepts in process industries must focus more on identifying the root causes/bottlenecks, and must provide improvement plans to systemically eliminate them. Some of the process industries where lean concepts are applied include metal processing, chemical and pharmaceutical, painting, fiber, synthetics etc.

1.4.3 Lean Applications in Banks and Financial Sectors

Lean manufacturing principles can be applied to banking and financial sector to improve the business opportunities in terms of customer satisfaction, decrease transaction costs and to increase the processing pace (Wang and Chen 2010). Successful application of lean principles, improve revenue growth as the speed and quality of service gets improved. Lean can contribute significantly to maintain proper cost-efficiency ratios and improves information flow.

1.4.4 Lean Applications in Public Sectors

Lean principles are being adopted by government to deliver better health care, education, transportation etc. It is possible to improve the service of public sectors

Table 1.1 Application domains of lean manufacturing concepts in different sectors

Functional domain	Benefits	Application area
Manufacturing sectors	Increases productivity by reducing the cycle time and increasing the customer value	Component manufacturing, assembly lines, automotive industries, machine shops, etc.
Process industries	Increases efficiency of the process by effective utilization of resources	Metal processing, chemical, textile, etc.
Financial sectors	Improves transaction process by minimizing the processing time and maximizing customer satisfaction	Banks, insurance firms, stock exchanges, etc.
Health care	Helps in reducing medical errors and improves the quality of treatment provided	Hospitals, clinics, diagnostic centers, etc.
Software development	Makes software development process flexible and helps in prompt delivery of software to the clients	Software development firms, IT enabled services, call centers, software testing units, etc.
Food and beverage	Achieves effective handling and usage of inventories and reduces waste through improved food handling methods	Restaurant chains, food packing industries, bottling centers, etc.
Construction	Helps in pursuing perfection in construction projects by effective usage of materials and labor	Construction firms, design centers, construction warehouses etc.
Education	Provides improved learning processes and guides in effective utilization of funds	Universities, schools, educational institutes etc.

by providing a proper optimization of costs, quality, and customer service frequently. Lean approach helps in achieving this by engaging and equipping employees to focus on creating and delivering value (Bhatia and Drew 2006). A proper lean method must be designed considering the needs of customers (public) and organization's (government) goals to improve efficiency and quality aspects. Applications of lean principles in public sectors include urban planning, city development, road laying, hospitals, income tax department, military department, air force etc.

Lean thinking is not only applicable to manufacturing, but also enables to improve any kind of organization's service. Table 1.1 shows the application domains of lean manufacturing concepts in different sectors. Based on the above discussions, it is evident that the application of lean manufacturing principles is not only limited to manufacturing firms, but also be applied to all sectors based on their needs and business requirements. Some of the other sectors where lean can be applied include construction projects, software development, hospital emergency departments, Information Technology sectors, hotels etc. Since lean focuses on waste elimination, its concepts can be applied in different sectors and consistent improvements can be observed.

1.5 Research & Development (R&D) Issues of Lean Manufacturing

Various Research and Development (R&D) activities are being carried out in lean manufacturing to develop problem solving culture and to extend its concepts towards wider perspectives. The main scope of conducting R&D activities is to find and remove the barriers that obstruct the process of lean implementation and to find appropriate models and methodologies in implementing the theoretical aspects of lean manufacturing. As a result of the ongoing R&D activities, various new lean tools and techniques has been developed and validated. R&D activities are carried out by both industries and research based organizations. The activities conducted include both theory building and implementation models. The research design methods include single case study, multiple case study, panel study, focus study and surveys (Vamsi Krishna Jasti and Kodali 2014). But the most widely used approach for research in lean manufacturing is the survey based research method. Most of the research studies are carried out with high precision, accuracy but the chances of error could not be ruled out. The studies must be performed with bigger sample size to strengthen the inferences of study, and reduce the unanticipated error associated with the respective sample size. Various R&D studies are being carried out to apply lean manufacturing principles to various sectors to expand its scope.

A proper lean strategy must be chosen considering the driving elements like type of industry, size, and products manufactured etc. for maximizing process improvements without any obstacles. In recent times, there exists a need for manufacturers to produce goods/services as per the willingness of the customer as mass customization plays a key role. Due to the prevailing uncertainty in the demand, the firm must come up with advanced planning and manufacturing strategies to cope up demand reducing the non-value adding activities and costs involved. For achieving this, lean manufacturing is a useful tool which helps in reducing these activities and costs. To meet the lean needs of the volatile industries, academicians, researchers and practitioners have come up with various lean models and methodologies to meet their present needs. R&D activities and recent trends of lean manufacturing pertaining to different elements are discussed in the following sections.

1.5.1 Performance Evaluation of Lean Systems

The performance of a lean manufacturing system must be measured to track the improvements after implementing lean concepts (Behrouzi and Wong 2011). Recently, various performance measurement and assessment models are being developed for identifying the improvement opportunities. Some of the recently developed performance evaluation models include lean assessment models based on fuzzy logic, dynamic approach of performance evaluation, evaluation using multi-dimensional approach, multi criteria decision making, Interpretive Structural Modeling (ISM) etc. The performance measurement and assessment models help in evaluating the lean system and also helps in improving the lean performance of the organization.

1.5.2 Development of Decision Making Models

Decision making models and frameworks are used for selecting the best possible techniques, tools and implementation models relevant to particular applications and business environment (Anand and Kodali 2008). Most of the available lean decision making models and framework are used as assessment models and decision support systems for improvement of business performance of manufacturing firms. The developed decision making models are based on a particular technique or algorithm which supports in decision making. Some of the recent techniques that are used for designing decision making models include simulation applications, fuzzy logic, Analytical Hierarchy Process (AHP), Preemptive Goal Programming (PGP), Collaborative Lean approach, Structured Equation Modeling etc. Various decision making models using newer technologies are being developed to eliminate complexity and vagueness that exist in the current models to maximize operational performance.

1.5.3 Development of Framework for Lean Implementation

An implementation framework of lean manufacturing supports waste elimination process and provides a step by step procedure in investigating lean implementation initiatives. The existing frameworks for lean implementation are being categorized as implementation frameworks, Conceptual frameworks, Descriptive frameworks and Road maps (Mostafa et al. 2013). The recently developed frameworks not only supports lean implementation process, but also helps in finding out barriers that slows down implementation process. These frameworks are being developed based upon the lean initiatives and structure of the organization (Anand and Kodali 2009). In recent times, frameworks are being developed considering the factors of expert team building, situational analysis, communication models, gap and Strength Weakness Opportunities Threats (SWOT) analysis, cause and effect diagram etc. which makes the framework as an iterative process to validate and standardize the implementation results.

1.5.4 Integration of Lean Concepts with Other Strategies

Recently, Lean manufacturing is integrated with different methodologies like six-sigma (Arnheiter and Maleyeff 2005), supply chain management (Naylor et al. 1999), sustainable manufacturing (Mason-Jones et al. 2000), agile manufacturing (Jorgensen et al. 2007), etc. to form a collaborative approach which helps in achieving add-on benefits concurrently with lean benefits. Lean when integrated with different methodologies provides high flexibility and enhances the organization's ability to rapidly drive towards continuous improvement. Moreover, it facilitates the innovation dimension and helps in arriving at high moral improvements. Various studies have been conducted by the researchers on integrating lean with other methodologies and are being validated appropriately.

1.5.5 Lean Product Development

Lean product development adopts lean philosophy and principles during the stages of product development thus eliminating unnecessary wastes that exists in each stage of product development. It helps in reducing cycle time and product development costs and meets customer's needs in terms of quality and innovation (Mynott 2000). Lean product development adopts techniques like reusable knowledge, set based concurrent engineering and visual management during different stages of product development. Adopting Lean product development methodology eliminates wastes during different stages of product development and increases product value.

A few research studies have also been conducted to find the congruence between dimensions of national culture and lean manufacturing practices. The results showed that that lean manufacturing practices are more effective in countries that value high uncertainty avoidance, low assertiveness, low future orientation, and low performance orientation. It also showed that lean manufacturing effectiveness is sensitive to national cultural dimensions, and helps production managers to adopt lean manufacturing practices worldwide.

There are also few research centers exclusively available for lean manufacturing research. This center develops, test and validate experimental hypotheses and provides new methods for organizational transformation. They also often conduct conferences and summits through a strong community and supports in travelling through the lean path. Some of the research centers for lean manufacturing include Lean Enterprise Institute (LEI) USA, International Lean Enterprise Research Center (LERC), Cardiff university UK.

1.6 Lean Manufacturing: Education and Curriculum

Lean thinking is not only applicable to manufacturing, but also enable to improve any kind of organization's service. Since the application of lean principles has been extended to various sectors and domains, efforts were taken by academicians and researchers to apply lean principles to education system. Lean is a dynamic and authentic continuous improvement process that reduces associated non value added activities of the system. Education system when viewed as an organization has its own kind of wastes. Here, value can be defined as the knowledge that students acquire after successful completion of course. The knowledge transfer which happens between faculty and student may be termed as value added activity. Assignments, tests and grade points are the performance measures, whereas student is the ultimate customer. The activities pertaining to the seven deadly wastes of lean manufacturing can also be mapped in the education system. After identifying the non-value added activities, proper improvement actions must be planned. A lean transformed university provides improvement opportunity and helps in redesigning the current education system. It also helps the teachers in monitoring students and generates response to the actions quickly (Alp 2001). The lean culture in education promotes a positive can-do attitude and greater involvement in improving processes that support student learning and also provides an effective way for educational institutes to develop and deliver world-class education with currently available funding (Ziskovsky and Ziskovsky 2007). Lean thinking is a viable process improvement approach and helps to fix the problems that arise in educational institutes including inadequate funding, ineffective remediation, and lack of developmental learning opportunities for students (Flumerfelt 2008). The application of certain lean manufacturing tools and their application in educational system is shown in Table 1.2. On successfully applying lean in education, the following benefits can be attained:

- It is possible to achieve pull, as the student chooses his/her courses
- Better understanding between faculty and student
- Easy access to programs, courses and curriculum
- Efficient use of funding
- Improved learning opportunities
- Eliminates multi-layer approvals
- Better utilization of resources

A very few research insights are available on application of lean manufacturing principles in education system. Due to the applications of lean manufacturing principles in a varied stream and its adaptability and reach, many educational institutes and universities around the world have included lean manufacturing as a course in their curriculum. Studying the course on lean manufacturing makes the students to understand about Value Added and Non Value Added activities and improves their knowledge on eliminating the wastes. A sample lean manufacturing curriculum include: Principles and implications of lean manufacturing, value

Table 1.2 Application of lean tools in educational system

Lean tool	Application in educational system
5S	Creating an organized classroom, organized office room, scheduling of time tables, administrative tasks etc.
Kanban	Helps in purchasing, supplying and maintaining the stocks, registers and stationery items
Total productive maintenance (TPM)	Helps in maintaining laboratory equipments, power equipments and facilities used for transportation
Value stream mapping (VSM)	Helps in creating a flow for entire organization consisting of individual processes in student registration, supply and book ordering, delivery of the teaching material, meetings, planning, scheduling and transportation etc.
Kaizen	Creates continuous improvement opportunities for effective knowledge transfer
Visual management	Allows the management, teachers and staff to visually observe their measures and standards and to control their own areas
Standardized work	Helps in creating a standardized system and processes to deliver quality education

creation, waste elimination, primary and secondary lean tools/techniques, team establishment, transformation process, project management, lean implementation, and reconciling lean with other systems. It also teaches them the measures on improving the operational performance of enterprise. The course on lean manufacturing is designed in such a way that it helps both engineers and managers to efficiently handle problem solving situations and arrive at strategic decisions.

1.7 Conclusions

Lean manufacturing concepts are essential for modern manufacturing industries to achieve competitiveness and sustain in the dynamic markets. In order to enable this task, modern manufacturing professionals must possess a clear understanding of core principles, selection and usage of appropriate tools of lean manufacturing. Some of the benefits experienced after successful implementation of lean principles include improved productivity, reduced waste, improved stock turns and improved customer service. Despite the benefits of lean, there are some challenges along the implementation process. Depending on the planning and effort put into implementation, these challenges could be easily overcome. Lean manufacturing has varied applications in industrial sectors. Recent trends and research development issues of lean manufacturing are being highlighted. In order to prepare engineers to understand and effectively implement lean concepts, the inclusions of lean manufacturing in modern manufacturing curriculum as well as curriculum contents are also being highlighted. This chapter provides insights on the challenges for modern manufacturing engineers and usage of lean tools for effecting improvements.

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Chapter 2
A Case Study on Lean Product and Process Development

S. Vinodh and A.G. Chethan Kumar

Abstract Current products in the market are customer oriented. Customers demand for low priced products in minimum possible time of production. To achieve competitiveness and to stay ahead in the business, manufacturers adopt lean manufacturing strategies. Lean principles are focused on elimination of wastes, streamlining the processes there by reducing cost and product delivery time. Lean concepts are widely used in process perspective; there exists scope for applying lean principles for product development. Product development involves various stages associated from collection of customer requirement till the realization of products. In this context, this chapter presents a framework for Lean Product Development using a primary lean tool Value Stream Mapping. The chapter is exemplified with a case study conducted in an Indian automobile component manufacturing organization. The approach starts with the preparation of current state map indicating the details associated with each and every stage of Value Stream Map (VSM). This is followed by detailed analysis of VSM, followed by the identification of areas where improvements can be brought about. Then Quality Function Deployment (QFD) is integrated into VSM to facilitate design improvements and to achieve customer oriented products; also, elimination and integration of certain processes in process map is done to achieve stream lined process. Finally, Future state Product Development map is developed indicating the improvement proposals and possible time reduction as a result of modifications in the design process. This methodology would facilitate a framework for product development process with the incorporation of lean methodologies.

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2.1 Introduction

Lean Principles are focused on identification of wastes associated in manufacturing process and classifying them into specific categories and also eliminating these wastes by application of necessary or possible changes and thereby ensuring streamlined processes. Lean principles are widely applied in process perspective but the application of same in product design and development perspective is less. Hence, there exists vital scope to apply lean principles in the context of product development. Product development involves two major Wastes in design refer to recycling design and their testing, elimination of Non Value Added (NVA) activities that typically extend the lead time of product to market and minimal production cost and quality related issues. Lean Product Development (LPD) follows the same analogy as process based creation of value stream, determining the flow and pull and elimination of wastes. Few researchers have contributed studies in the context of Lean Product Development.

The research objective addressed in the present study is to develop a framework for Lean Product Development (LPD) coupled with Value Steam Mapping (VSM) to achieve more detailed and customer oriented products with minimum wastes.

2.2 Literature Review

The literature has been reviewed from the perspectives of lean product development and application of VSM and QFD for lean product development.

2.2.1 Review on Lean Product Development

Khan et al. (2013) explained the need for application of lean principles in product and process development. A questionnaire was developed and interviews were conducted to identify the enablers influencing product development. Walton (Walton 1999) conducted a study on LPD to spread the awareness of the same in industry. Certain tools such as Set Based Concurrent Engineering (SBCE) and metrics in Product Development are defined. Lindlöf et al. (2012) suggested the need for data exchange or knowledge transfer in LPD. They emphasized on the need for scheduled meetings at regular intervals to achieve knowledge transfer throughout the entire organization. Oppenheim (2004) explained the need for 'system engineering' for product development to achieve product quality. Cost reduction is considered as the basic need which could be achieved by reduction or elimination of wastes. The term Lean Product Development Flow (LPDF) was explained in this chapter. Pullan et al. (2013) suggested the importance of concurrent engineering in the context of product development. They also integrated product process platform for ease of information flow, a Knowledge based decision support system was prepared using Oracle 9i.

2.2.2 Review on QFD Applications for Lean Product Development

Liu (2009) conducted a study on Product Development. For ease of Product Design, they utilized Fuzzy QFD. The prototypes are generated by the incorporation of engineering characteristics obtained from fuzzy QFD. Sakao (2007) explained the need for environmentally conscious products. The author utilized tools such as Life Cycle Assessment (LCA), Theory of Inventive Problem Solving (TRIZ). QFD is renamed as Quality Function Deployment for Environment (QFDE), with the addition of environmental aspects into the earlier one. Zhai et al. (2008) proposed a rough set theory and its use along with QFD. This Rough set QFD was used in product design to transfer customer needs to design characteristics and it was done on the case product with more imprecise and indefinite input values. Smith (2012) explained the need for development of custom products in industry. This was further elaborated by the use of lean techniques. VSM and kaizens were used to improvise the process. Chen and Chang (2009) explained the need for QFD in product development. Since this development process possessed vagueness, fuzzy logic was used to reduce it. Further, Failure Mode and Effect Analysis (FMEA) was used to identify the defect location for new product development. Kreng and Lee (2004) explained the modular product design which includes physical and functional features of a product. QFD was deployed to enhance modular product design and hence to achieve enhanced product characteristics.

2.2.3 Review on VSM Applications for Lean Product Development

Fritzell (2012) presented a case study utilizing concept maps and Design Structure Matrix (DSM) for better understanding of process. A VSM was developed as per the literature and certain modifications were incorporated to enhance product development process. Kumar et al. (2009) developed Advanced Dual Stage Performance (ADSP), which included both current state as well as future state. This VSM was developed for new product development and feedback loops were utilized to check the product. The best article was selected among various available articles and it was done using ADSP. Smith (2012) identified product development activities and classified them based on associated similarities. These activities extended the study to high-volume low-mix product development process. The entire product development process was mapped using VSM, Bill of Materials (BoM), Check sheets, kaizen bursts were used to enhance process understanding. Haque and James-Moore (2004) classified product development into concept generation, detailed design and customer delivery. More focus was directed towards new product introduction with the utilization of techniques such as Concurrent Engineering and SBCE. Finally a VSM was developed incorporating details such as key characteristics, detailed characteristics and enabling tool. McIvor (2001) explained the need for cost reduction associated with product development process. A supply chain network was developed with addition of both customer and supplier into product development process; this facilitated the development of lean supply model. This organized supply chain would result in satisfaction among suppliers and customers as well as proper information flow amongst them. Schulze et al. (2013) incorporated a lean tool VSM to facilitate NPD process and also explained knowledge transfer in product development using 4Is (Intuiting, Interpreting, Integrating, and Institutionalizing) in the organization. These 4Is include the classification of product development processes and this classification would enable Organization Learning (OL) and help in managerial decision making.

2.2.4 Research Gap

There exists a need for designing Lean Product Development (LPD) framework. In this context, wastes in the context of Product Development needs to be emphasized and also improvement locations are to be identified. Improvements which could reduce or eliminate wastes associated with product development process needs to be proposed. Finally, future state is to be mapped with the incorporation of proposals and necessary improvements.

2.3 Methodology

The methodology is presented in the following section. This section also includes details related to various tools and techniques used in this chapter.

The detailed steps followed in this chapter are shown in Fig. 2.1.

The steps include the collection of details from industry relating to the case product, followed by categorization of development process into different categories. These categories can further be divided into two groups which include the design process and manufacturing process followed by the identification of improvement locations for application of lean improvements. Finally both product design and process development process are integrated into single map, with inclusion of improvements.

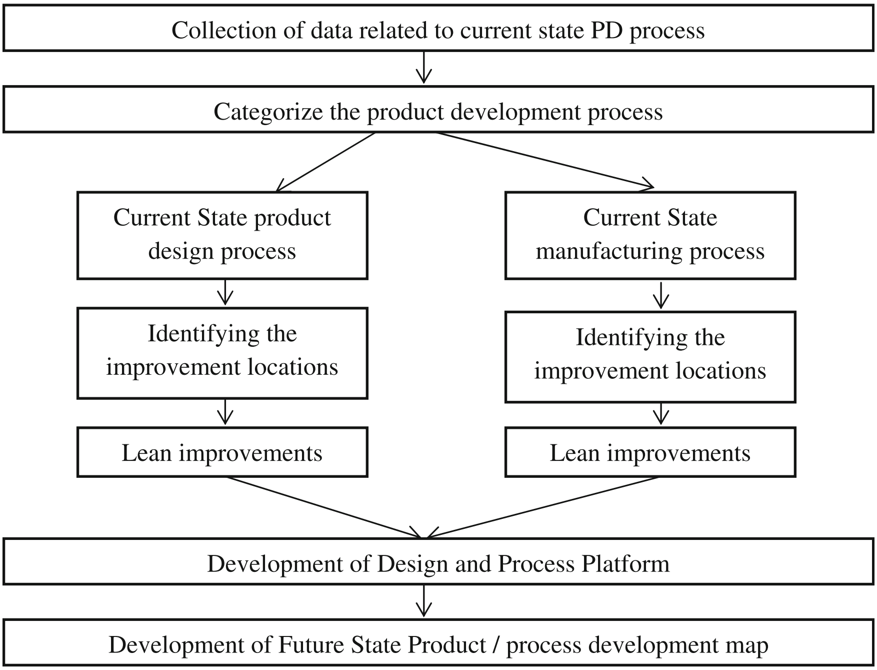

Fig. 2.1 Detailed scheme of the chapter

2.3.1 Tools and Techniques

The tools and techniques used in this chapter are discussed in this section.

2.3.1.1 Value Stream Mapping

Value Stream Mapping (VSM) is a method used by industry to take a product or service from its start till it reaches the customer. VSM is one of the lean manufacturing methodology indicating all value adding and non-value adding activities associated with entire manufacturing process. It also indicates inventory associated with process.

$$\text{Uptime} = (\text{Net Available Time} - \text{Cycle Time})/\text{Net Available Time}$$

$$\text{Takt time} = \text{Net Available Time}/\text{Demand per day}$$

In this study, VSM is modified for Product Development application called PDVSM. The entire product development process is mapped using VSM. The current Product Development process for the industry indicates the time associated such as Total time (TT) Change Over time (C/O) and is mapped using Current state PDVSM. This product development process can be categorized into design and production stages.

2.4 Case Study

The case study is conducted in an automotive component manufacturing organization situated in Tamil Nadu state of India. The implementation of lean principles in product development process was necessary. In this context, a critical product in the automotive system was considered for mapping the development process. Also there exist a need for modification of design process and reduction of time associated with product development process.

2.4.1 Current State Design VSM

Current state design VSM is mapping of the entire product design process of the case component. It involves grouping the stages associated with design process and collection of cycle time, changeover time associated with the each process. Also, it involves data indicating available time and uptime. Finally, the total cycle time associated with the development process is found to be 29.4 h. The current state design VSM involves four stages which include collection of customer voice, generation of three dimensional sketch, detailed drawing and finite element analysis (Fig. 2.2).

After the detailed analysis of Current state design VSM, it was found that there were certain locations where improvements can be initiated.

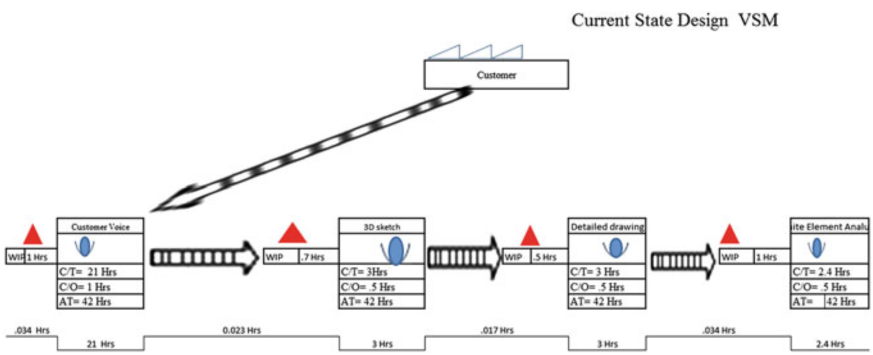

Fig. 2.2 Current state design VSM for case component

2.4.2 *Current State Process VSM*

Current state process VSM involves mapping entire product manufacturing process of the case product. It involves various stages such as drilling and milling, drilling and reaming, broaching (Seration), drifting, phase I milling and phase II milling. A daily demand of 45 products is to be produced, while time associated with each process is indicated below each process. Also the current state process map involves other two rows indicating available time and uptime. The work in process (WIP) inventory is indicated intermediate to each process.

With the detailed analysis of process VSM, certain regions are identified where excess time is consumed and regions which could be integrated or run simultaneously to reduce total manufacturing time. In this perspective, the following changes were suggested for implementation. Categorization of processes which are done by drilling machine could be done in a single stretch, which would in turn reduce the time associated for change over as set ups. Similar grouping can be done for milling process; this would consume little extra time for setup, but could reduce change over and total time associated with the process. Further, lean improvements such as 5S could be implemented to reduce work in process by properly organizing the entire process and allocating the time accordingly.

2.4.3 *Future State Design VSM*

The future state map involves the following stages.

2.4.3.1 Customer Voice

Customer voice is collected using both quantitative and qualitative terms. The quantitative values for the case product could be organized in the form of a questionnaire. The questionnaire which used is shown in Fig. 2.3. Generally for design of case component, dimension values are prefixed. But in order to accommodate the changes of design of automotive component, the following values are varied accordingly with the need of particular model. In this case, the earlier basic

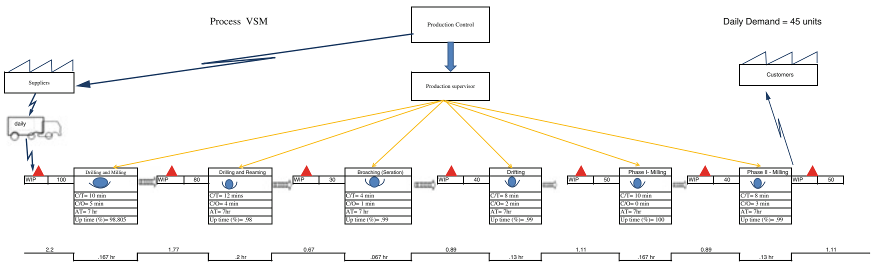

Fig. 2.3 Current state case component manufacturing process VSM

Questionnaire

General requirements

1. Case component center distance	……………..
2. Offset distance positive	……………..

Taper requirements

3. Major/ Minor diameter	……………..
4. Taper designation	……………..
5. Taper length	……………..

Fig. 2.4 Detailed questionnaire used to collect customer voice customer voice

designs are retained whereas new variants are added to component. In the case of case component, the center distance and offset length are varied. The details related to quantitative terms are logically taken from customer (Fig. 2.4).

Questionaire

The time associated with collection of these requirements would vary as per the response from the customer whereas the time consumed to prepare questionnaire and analyze the same could be noted. In the case of automotive component, the time consumed was around two days considering the discussions amongst workers and also considering approvals from superiors.

2.4.3.2 QFD for Case Component

In order to generate customer oriented products, the data obtained as customer voice is to be transferred into part characteristics. To achieve this, Quality Function Deployment (QFD) can be utilized. Here in QFD, the rows are taken as customer requirements, which are further categorized into primary and secondary requirements. The primary requirements include: safety, reliability, durability, performance and service of case component and associated secondary requirements include: no breakage, high speed sensitivity, flexible steering, works in all operating conditions, usage, steering rotation, output torque, serviceability, easy to lift/compact, fitment. These horizontal requirements are to be transferred as part characteristics; hence part characteristics are considered along vertical column which are as follows: Case product material, diameter at both ends, Offset length, Distance between two centers, Thickness of flange, Bend radius of flange.

The following are the scale associated with QFD:

The relationship between customer requirements and design characteristics are depicted using symbols: Strong (S), Medium (M) and Weak (W) with ratings 1, 3 and 9 respectively. The importance to customer is rated using 1–10 scale (1—least important and 10—most important). The target value is required to decide whether the product remains unchanged, improve the product, or make the product better than competitor and is rated using a scale of 1–5 (5 to keep product unchanged and 1 to discard the product). Scale up value indicates the ratio between target value and product rating. Sales point indicated how well the customer requirement will sell and value is assigned between 1 and 2. Degree of technical difficulty indicates the difficulty associated with the implementation of certain quality related improvements using 1–10 scale (1—least difficult and 10—highly difficult).

The equations used for computing absolute weight and relative weight in prioritizing product characteristics are presented as follows (Besterfield et al. 2003)

$$\text{Absolute weight, } (a_{ij}) = \sum_{i=1}^{n} Rij * Ci \tag{2.1}$$

where, a_j is row vector denoting absolute weights corresponding to case component part characteristics (j = 1…m), *Rij* is a square matrix where weights are assigned to relate product characteristics and customer requirements (i = 1…n, j = 1…m); C_i is a column vector of importance to customer (i = 1…n).

The relative weight of jth product characteristic is determined by replacing the importance to customer in the previous stage with absolute weight for prioritizing the part characteristics.

$$\text{Relative weight} (b_{ij}) = \sum_{i=1}^{n} Rij * Di \tag{2.2}$$

where b_j, row vector of relative weights for part characteristic (j = 1…m); Di column vector of absolute weights for part characteristics (i = 1…n).

From the obtained values, it has been found that offset length and distance between centers of case product are inferred to possess highest relative and absolute weights; hence these are to be given highest priority while designing products. The time associated with the collection of these data and calculation is around 3 h where as to develop a HOQ it may take around 2 h while the time taken for modification, verification and approval which would take around 1 h are also being considered.

2.4.3.3 Conceptual Design and Detailed Design of Case Product

The conceptual model is generated using CAD tool. This would facilitate easy understanding of conceptual design. Conceptual design is generated as per the specifications provided by the customer while the rest of the dimensions are selected accordingly. The time consumed for each step is noted during the generation of conceptual model in the CAD software. While the detailed design shows the material used as well as heat treatment process used for production. The detailed drawing is generated using the same steps followed as in the conceptual model. The material is selected as per standards based on load capacity requirement. Whereas material to be quenched also would consume certain amount of time which is considered with earlier detailed design generation.

2.4.3.4 Load Calculation and Engineering Analysis

Following are load calculations done for the case product. The case component specifications are as follows: Material used—Mg cu alloy, Density $\rho = 7900\ \text{kg/m}^3$, Poisson's ratio $\gamma = 0.28$, Young's modulus $E = 210 \times 10^3$ Mpa.

The load acting on the case product is obtained from the customer which is further categorized into horizontal and vertical component as: Case Product force = 1377.8 kg, Horizontal force at smaller dia $F_H = 1.205 \times 10^3$ kgf, Vertical force at smaller dia $F_v = -668$ kgf.

The resultant force obtained at the smaller end of the case product is found to be: Resultant force $F_{resultant}$ is given by Eq. (2.3)

$$\mathrm{F_{resultant}}^2 = Fh^2 + Fb^2 \tag{2.3}$$

$$\mathrm{F_{resultant}}^2 = 1452025 + 446224$$
$$\mathrm{F_{resultant}} = 1377.77\,\mathrm{N}$$

This is the total load which can be applied on the case product the smaller end. With the availability of the following inputs, Finite Element analysis is done to check the deformation associated with the product. While the analysis of case product is done using Abaqus software. The inputs involve the model sketch which was developed in earlier stage followed by inputs such as material properties, displacement characteristics, applied constraints, mesh size and load applied the component in specific direction. Further these inputs are saved and executed to achieve necessary displacement associated with part and also indicate critical locations with maximum stress.

With the available data, the entire design stage is mapped using VSM as shown in Fig. 2.5. The future state map involves the following stages: collection of customer voice, transfer of customer voice into product characteristics, development of conceptual design, and development of detailed design followed by load calculation and finally engineering analysis. Future state map is more elaborate and detailed with the addition of stages such as inclusion of QFD and load calculation before engineering analysis. Future state map also indicates the cycle time and change over time associated with each stage. The improvements are indicated using kaizen bursts: generation of customer oriented products using QFD which would translate customer voice into part characteristics. The use of 5S would facilitate the process to be more ordered and hence can be recorded and same can be reused for future purpose. The use of Failure Mode and Effect Analysis (FMEA) facilitated the identification of failure location regions. Finally, the use of Poka Yoke also called

			Case Part characteristics								
	Level 1	Level 2	Material	Diameter at both ends	Offset length	Distance between the two centers	Thickness of the flange	Bend radius of the flange			
Customer Requirements	Safe	No breakage	S	M	S	S	S	S	9	1.9	17.1
		High speed sensitivity	S	W	S	S			8	1.5	12
		Flexibility		M	S	S			7	1.8	12.6
	Reliable	Works in all operating conditions	S					M	5	1.8	9
	Durable	Usage	S	M	S	S	S		5	1.7	8.5
	Performance	Rotation		S	M	S			6	1.6	9.6
		Output torque	M		S	S	S		6	1.3	7.8
	Service	Serviceability	M					M	3	1.5	4.5
		Easy to lift / compact	M		S			M	5	1.5	7.5
		Fitment	S		M	M	M		6	1	6
	Degree of technical difficulty								Importance to customer	Sales point	Absolute weight
	Absolute weight		352	150	404	400	232	158			
	Relative weight		555	247.8	649.8	647.4	373.8	273.4			

Fig. 2.5 QFD for case component

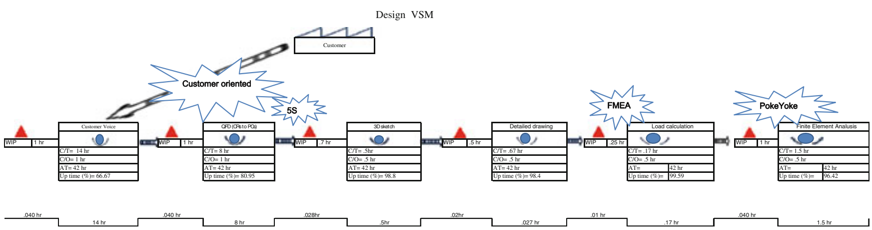

Fig. 2.6 Future state design VSM

failure proofing would help in reduction of mistakes which are bound to happen in future. After all these necessary additions, the design process is made more streamlined by reduction of time at necessary locations. The total cycle time after all improvements is found to be 24.5 h which was found to be reasonably lesser than the current state. Also, the future state is more descriptive and elaborate (Fig. 2.6).

2.4.4 Future State Process VSM

The use of Single Minute Exchange Dies (SMED) would reduce setup time while Kaizen is used to facilitate minor improvements in the process. The use of work cell is to group similar processes such as grouping of drilling related processes and milling related processes. The entire production process is to be standardized and documented for future use (Fig. 2.7).

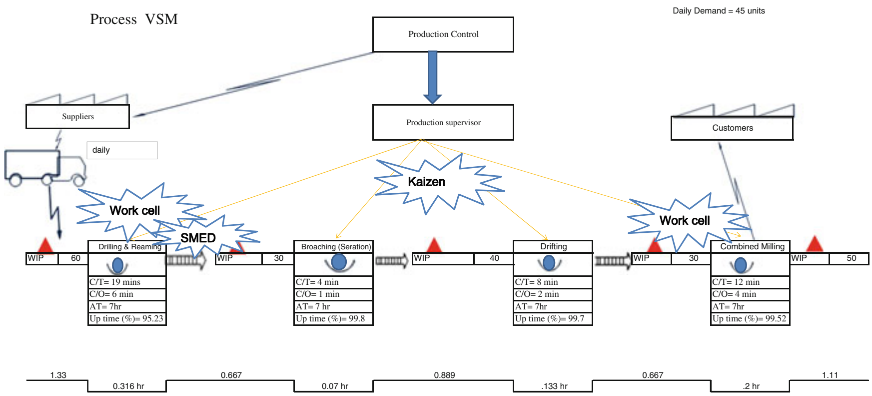

Fig. 2.7 Future state manufacturing process VSM

2.5 Results and Discussions

After detailed analysis of current study, certain suggestions were derived and the resulting improvements are listed in Table 2.1.

Detailed questionnaire in future state map facilitates the collection of both quantitative and qualitative values from the customer, compared to earlier stage where only few dimensions were collected. Also the use of QFD enhance product development process by producing more customer oriented products, since the customer voice is directly transferred into part characteristics (Fig. 2.8).

The cycle time for current state is found to be 29.8 h while after modifications in future state the cycle time is reduced to 24.5 h. A reduction of **17.75 %** is achieved despite having a descriptive and more elaborate future state (Fig. 2.9).

Table 2.1 Suggestions and future state improvements

Suggestions	Improvements
Product design related	
• Need for a detailed questionnaire	Necessitates collecting all quantitative and qualitative needs of customer
• Use of QFD in product development	Helps in conversion of customer needs into part characteristics, hence results in production of more customer specific products
Manufacturing process related	
• Combination of identical processes	Process which could be done using the same machine by varying certain changes in setup would reduce change over time
• Reduction of WIP	By properly organizing process steps, in process WIP could be reduced

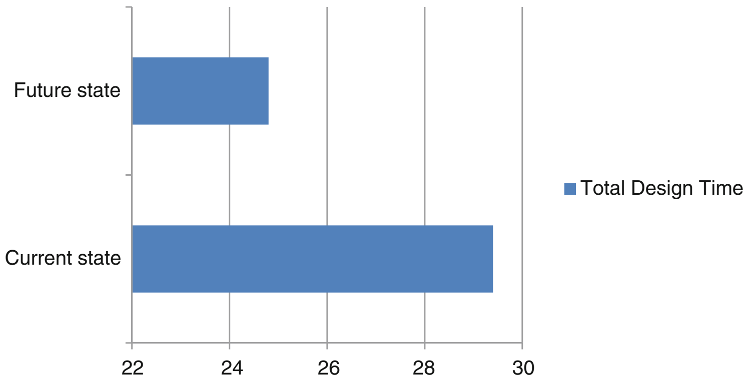

Fig. 2.8 Comparison of total design time for product design process

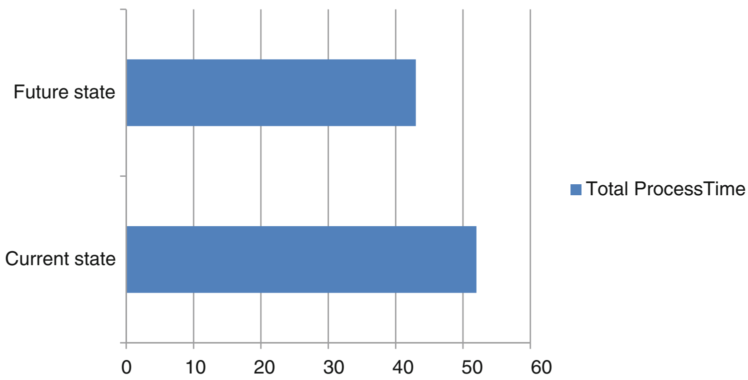

Fig. 2.9 Comparison of total process time

Based on the comparison of current state and future state, the following improvements were identified: current state process time was found to be 52 h; while in the future state, the time was around 43 h. A reduction of 9 h is achieved by making certain necessary modifications.

2.6 Conclusions

The potential of applying lean principles in the context of Product Development is explored. The case study was carried out in an automotive component organization where the scope of lean product design and development was identified. Entire product development process was mapped and wastes associated with product development process were identified. With the identified gaps, the necessary improvement proposals were suggested. Finally, a Future state Product Development VSM was developed with the identification of necessary modifications.

The improvements achieved through this study include:

- A time reduction of **17.75 %** is achieved despite having a descriptive and more elaborate future state product design.
- A time reduction of **17.30 %** is achieved despite having a descriptive and more elaborate process design.

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Chapter 3
Lean Product Development (LPD) Enablers for Product Development Process Improvement

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Abstract The enablers are recommended to improve the performance of Lean New Product Development (NPD) processes. This chapter presents an alternative to select enablers for improving the implementation of Lean NPD according to the difficulties of the company's NPD process. Based on this literature review, a questionnaire was developed to identify the level of implementation for the Lean NPD enablers and the frequency of occurrence of each problem in the portfolio of NPD projects. The likelihood of the implementation of the Lean NPD enabler to decrease the frequency of NPD problems is represented by the correlation level between Lean NPD enablers and problems. The comprehension around this subject allows project managers to drive the NPD process improvement to lean culture, saving resources and maximizing the benefits of this effort.

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3.1 Introduction

Lean product development (LPD) is the application of lean thinking, originally conceived for manufacturing processes, in New Product Development (NPD) processes. LPD departs from the customer's perception of value to create new and profitable values streams within the organization, exploring synergies between processes, people, tools, and technology (Kennedy 2003; Slack 1999). Browning and Worth (2000) emphasize that the concept of LPD goes beyond the goal of waste elimination: it aims at maximizing the value added to customer, shareholders, employees, society, and suppliers. The concept of LPD has been given increasing practical significance by companies that have succeeded in improving their manufacturing processes, and find that product design is the new operations bottleneck (Reinertsen 2009). Besides the widely known lean principles, this implementation comprises the application of numerous interrelated enablers, such as the existence of chief engineer, employee empowerment, customer focus, early problem solving, minimal constraint and value stream mapping.

There are several ways to identify these enablers for NPD in the literature, such as practices (Khan et al. 2013), principles (Cooper and Edgett 2008) and critical success factors (Nepal et al. 2011). These enablers are recommended to improve the performance of Lean NPD processes. It might be complex for a practitioner to define a comprehensive approach to improve the NPD process for a specific organization. Moreover, the companies still have limited resources for implementing several Lean NPD enablers simultaneously in their NPD process. Therefore, this paper presents an alternative to select enablers for improving the implementation of Lean NPD according to the difficulties of the company's NPD process.

This paper investigates which LPD enablers impact or influence the improvement of usual problems in companies' NPD process. Based on the comprehension of such influence, it is possible to identify and select a set of LPD enablers that will allow the mitigation of NPD problems occurrence. The aforementioned association was determined and validated through a survey carried out with 64 Brazilian companies. First, we assessed the frequency of occurrence of product development problems in our sample of companies using an adapted version of the questionnaire proposed by Paula et al. (2012). Next, we assessed the implementation level of LPD enablers most frequent cited in literature. Correlations between LPD enablers and NPD problems from the two questionnaires were calculated and analyzed.

3.2 LPD Enablers

Several methods have been proposed to improve the traditional product development process (Clark and Wheelwright 2010; Eppinger 2002). Such methods, although providing some benefits to companies, do not seem sufficient to achieve the breakthrough improvements that characterize LPD (Letens et al. 2011; Liker and Morgan 2011; Morgan and Liker 2008). Khan (2012) states that research is still required in order to distinguish between the most critical enablers and those which can be substituted with other equivalents. Field research may also be required to determine whether or not these enablers have presence in industry.

Ballé and Ballé (2005) comment that any of the enablers, worthwhile as they may be, taken out of the system will not yield significant efficiency gains in the development process. Moreover, no integrated framework of the identified LPD enablers has been put forward in the surveyed literature, nor has a methodological guide been formulated to support the application of lean thinking on an engineering project (Dekkers et al. 2013; Reis et al. 2013; León and Farris 2011; Jayanth et al. 2010). Table 3.1 consolidates the frequency of appearance of LPD enablers in literature.

3.3 NPD Problems

The problems addressed by NPD literature form two groups. The first of these are concerned with development process effectiveness; the subsequent market success of the newly developed product (Hines et al. 2006). Specific problems within this group include lack of alignment of the product development strategy with the wider business strategic plan, unnecessary development activity, lack of understanding of customer requirements, and ultimately high new products failure rates (Graebsch 2005; Haque and Moore 2004; Bauch 2004).

The second group of problems is concerned with the efficiency of the development process itself. These include the lack of a formal or standardized process, ineffective control of high volume development environments, poor internal communications and lack of common focus (Reinertsen 2009; Oppenheim 2004). They also include an inability to improve or learn from mistakes, and ultimately poor project deadline achievement and fiscal control. As a consequence of this problem-solution focus, the LPD literature adopts as its major theme of study the identification of the best practices associated with alleviating these problems (Hoppmann et al. 2011; Kato 2005). Table 3.2 shows the appearance frequency of the main problems cited in NPD literature.

3.4 Method

The research method was divided into two stages: (i) questionnaire development and data collection; and (ii) correlating LPD enablers and NPD problems. All analyses were performed using SPSS® v.18 software.

Some criteria were used to select the companies and the respondents. First, the studied companies needed to be undergoing a lean implementation at both the shop

Table 3.1 LPD enablers and references

LPD Enablers	Ward et al. (1995)	Sobek et al. (1998)	Sobek et al. (1999)	Kennedy (2003)	Oliver et al. (2004)	Kato (2005)	Hines et al. (2006)	Ward (2007)	Matsui et al. (2007)	Morgan and Liker (2008)
Chief Engineer (technical leadership)	*	*	*	*	*			*	*	*
Integrating/target events	*		*	*	*		*	*	*	*
Set-based concurrent engineering	*		*	*	*			*	*	*
Employee empowerment/ individual responsibility		*		*			*	*	*	*
Checklists	*	*	*	*				*	*	*
Standardization (skills, process, design)		*		*	*			*	*	*
Product development value focus				*			*	*	*	*
Technical design standard/ rules			*	*			*		*	*
Knowledge focus				*	*			*	*	
Multi project management (portfolio)		*					*	*	*	*
Extensive prototyping	*	*	*	*				*		*
Learning cycles			*	*	*			*	*	*
Expert workforce development		*		*			*	*	*	*
Customer focus							*	*	*	*
Vision shared company (honshin management)				*		*	*	*	*	*

(continued)

Table 3.1 (continued)

LPD Enablers	Ward et al. (1995)	Sobek et al. (1998)	Sobek et al. (1999)	Kennedy (2003)	Oliver et al. (2004)	Kato (2005)	Hines et al. (2006)	Ward (2007)	Matsui et al. (2007)	Morgan and Liker (2008)
Knowledge databases (searchable know-how database)				*		*	*			*
Knowledge/information pull (right place at right time)				*				*	*	*
Supplier concurrent engineering	*					*		*	*	*
Trade off curves	*	*					*			*
Knowledge flow/cadence				*				*	*	*
Design structure functional plan	*		*			*	*			*
Obeya (collaboration) team room				*				*	*	*
Value Stream Mapping (VSM)								*	*	*
Keiretsu (interlocking suppliers)	*			*		*			*	*
Systems thinking						*		*	*	*
Visual management/control				*					*	*
Knowledge reuse				*				*	*	*
A3/problem and action report		*						*		*
Design concept matrix			*				*		*	*

(continued)

Table 3.1 (continued)

LPD Enablers	Ward et al. (1995)	Sobek et al. (1998)	Sobek et al. (1999)	Kennedy (2003)	Oliver et al. (2004)	Kato (2005)	Hines et al. (2006)	Ward (2007)	Matsui et al. (2007)	Morgan and Liker (2008)
Cross functional teams	*						*		*	*
Quality function deployment (QFD)	*	*					*			*
Digital engineering (simulation and analysis tools)	*									*
Levelled workload							*			*
Standard architectures/ common parts		*			*					*
Nemawashi (consensus decision making)			*						*	*
Kaizen (continuous improvement)				*			*		*	*
Hansei (lesson learned/ reflection)									*	*
Product lifecycle plan (strategy)		*					*			
Process sheets (manufacturing process per part)										*
Concept Paper/blueprint	*	*					*			*
Root cause analysis									*	*
Competitor benchmark Report										*
Design automation (*Jidoka*)										*

(continued)

Table 3.1 (continued)

LPD Enablers	Kennedy et al. (2008)	Cooper and Edgett (2008)	Gautam and Singh (2008)	Oehmen and Rebentich (2010)	Oppenheim (2011)	Letens et al. (2011)	David and Goransson (2012)	Khan (2012)	Wang et al. (2012)	Dal Forno et al. (2013)
Chief Engineer (technical leadership)	*	*	*	*	*	*	*	*	*	*
Integrating/target events	*	*	*	*	*	*	*	*		*
Set-based concurrent engineering	*	*	*	*	*	*	*	*		*
Employee empowerment/ individual responsibility	*	*	*	*	*			*	*	*
Checklists	*	*			*		*	*	*	
Standardization (skills, process, design)			*	*	*		*	*	*	*
Product development value focus	*		*	*	*	*		*	*	*
Technical design standard/ rules	*		*	*	*		*	*	*	*
Knowledge focus	*		*	*	*		*	*	*	*
Multi project management (portfolio)		*	*		*	*	*	*		*
Extensive prototyping		*	*		*		*	*	*	
Learning cycles	*				*	*		*	*	*
Expert workforce development	*		*	*	*			*		*

(continued)

Table 3.1 (continued)

LPD Enablers	Kennedy et al. (2008)	Cooper and Edgett (2008)	Gautam and Singh (2008)	Oehmen and Rebentich (2010)	Oppenheim (2011)	Letens et al. (2011)	David and Goransson (2012)	Khan (2012)	Wang et al. (2012)	Dal Forno et al. (2013)
Customer focus	*		*	*	*		*	*		*
Vision shared company (honshin management)		*			*			*	*	*
Knowledge databases (searchable know-how database)		*	*		*	*		*	*	*
Knowledge/information pull (right place at right time)	*		*	*	*		*	*		*
Supplier concurrent engineering				*	*	*		*	*	*
Trade off curves			*	*	*		*	*		*
Knowledge flow/cadence	*	*			*		*	*		*
Design structure functional plan				*	*		*	*		*
Obeya (collaboration) team room	*		*	*				*	*	*
Value Stream Mapping (VSM)	*			*	*		*	*	*	*
Keiretsu (interlocking suppliers)				*			*	*		*

(continued)

Table 3.1 (continued)

LPD Enablers	Kennedy et al. (2008)	Cooper and Edgett (2008)	Gautam and Singh (2008)	Oehmen and Rebentich (2010)	Oppenheim (2011)	Letens et al. (2011)	David and Goransson (2012)	Khan (2012)	Wang et al. (2012)	Dal Forno et al. (2013)
Systems thinking				*	*	*		*		*
Visual management/ control				*	*	*		*	*	*
Knowledge reuse		*			*	*		*		*
A3/problem and action report	*	*	*		*		*	*		
Design concept matrix			*	*	*			*		
Cross functional teams			*	*			*	*		
Quality function deployment (QFD)		*	*		*			*		
Digital engineering (simulation and analysis tools)	*	*	*		*			*		
Levelled workload				*	*			*	*	*
Standard architectures/ common parts			*	*		*		*		
Nemawashi (consensus decision making)		*	*		*			*		
Kaizen (continuous improvement)					*			*	*	
Hansei (lesson learned/ reflection)	*			*	*			*	*	

(continued)

Table 3.1 (continued)

LPD Enablers	Kennedy et al. (2008)	Cooper and Edgett (2008)	Gautam and Singh (2008)	Oehmen and Rebentich (2010)	Oppenheim (2011)	Letens et al. (2011)	David and Goransson (2012)	Khan (2012)	Wang et al. (2012)	Dal Forno et al. (2013)
Product lifecycle plan (strategy)					*	*	*	*		
Process sheets (manufacturing process per part)		*			*			*	*	*
Concept Paper/blueprint		*						*		
Root cause analysis	*							*		
Competitor benchmark Report		*						*		
Design automation (*Jidoka*)								*		

Table 3.2 NPD problems and references

NPD Problems	Dal Forno et al. (2013)	Meybodi (2013)	Reis et al. (2013)	Wang et al. (2012)	León and Farris (2011)	Letens et al. (2011)	Liker and Morgan (2011)	Oppenheim (2011)	Oehmen and Rebentich (2010)	Reinertsen (2009)	Cooper and Edgett (2008)	Pessoa (2008)
Project leader without formal authority				*	*		*	*	*	*		
Achieve true cross-functional integration		*		*		*	*		*	*	*	
Lack of feedback		*		*	*	*		*	*	*	*	
No partnership with suppliers		*	*	*	*		*	*			*	*
Lack of product portfolio strategy					*		*		*		*	*
LPD measurement system					*				*		*	
No IT integration	*	*	*				*	*	*			
Poor operational decision making process					*	*			*	*		*
Lack of discipline	*		*		*		*					
Lack of knowledge reutilization	*		*		*	*						
No simultaneous engineering		*	*		*	*						

(continued)

Table 3.2 (continued)

NPD Problems	Dal Forno et al. (2013)	Meybodi (2013)	Reis et al. (2013)	Wang et al. (2012)	León and Farris (2011)	Letens et al. (2011)	Liker and Morgan (2011)	Oppenheim (2011)	Oehmen and Rebentich (2010)	Reinertsen (2009)	Cooper and Edgett (2008)	Pessoa (2008)
Coordination and time-consuming activities						*		*	*	*		*
Lack of project vision sharing						*		*				*
Inexistence of leveled workload		*					*	*	*			

NPD Problems	Schuh et al. (2008)	Ward (2007)	Baines et al. (2006)	Hines et al. (2006)	Bauch (2004)	Haque and Moore (2004)	Oliver et al. (2004)	Tsinopoulos and McCarthy (2002)	MIT (2001)	Browning and Worth (2000)	Cusumano and Nobeoka (1998)	Karlsson and Ahlstrom (1996)	Womack et al. (1991)
Project leader without formal authority	*		*				*	*	*	*	*	*	
Achieve true cross-functional integration			*		*		*		*	*	*	*	
Lack of feedback	*	*		*			*				*		
No partnership with suppliers							*					*	
Lack of product portfolio strategy	*			*		*			*		*		

(continued)

Table 3.2 (continued)

NPD Problems	Schuh et al. (2008)	Ward (2007)	Baines et al. (2006)	Hines et al. (2006)	Bauch (2004)	Haque and Moore (2004)	Oliver et al. (2004)	Tsinopoulos and McCarthy (2002)	MIT (2001)	Browning and Worth (2000)	Cusumano and Nobeoka (1998)	Karlsson and Ahlstrom (1996)	Womack et al. (1991)
LPD measurement system	*					*	*		*	*	*		*
No IT integration		*	*		*			*					
Poor operational decision making process	*			*				*		*			*
Lack of discipline		*			*			*	*	*			*
Lack of knowledge reutilization		*	*						*		*		*
No simultaneous engineering			*				*				*	*	
Coordination and time-consuming activities					*					*		*	
Lack of project vision sharing				*	*							*	
Inexistence of leveled workload				*		*							

floor and administrative areas. Second, the geographic location was restricted for companies placed in the South of Brazil, in order to reduce any effect of external environment (e.g. availability of skilled labor). The non-random selection of companies for surveys is a common approach in other studies (e.g. Saurin et al. 2010; Boyle et al. 2011).

Furthermore, a minimum 5-year experience in lean implementation and product or process development was required for all survey respondents. Such sample characteristics were similar to previous studies about lean, namely: (i) to limit the sample to a specific geographical location (Sanchez et al. 2011; Bhasin 2012) and; (ii) to emphasize experienced companies in lean implementation (Shah and Ward 2007). The questionnaires were sent and received by email during the first quarter of 2014.

Table 3.1 was used to develop questionnaire about LPD enablers. Enablers that appeared to be overlapping were merged, while others that combined multiple practices were divided (Table 3.3). A scale from 0 to 9 was used to assess the intensity of the adoption of the LPD enablers, in which 9 denotes full adoption and 0 the lack of adoption of each enabler.

A list of frequent product development problems proposed by Paula et al. (2012) was used to develop the questions about the NPD problems. The initial 52 typical product development problems were classified into categories of NPD problems that appeared in the NPD literature (Table 3.2). Six of those problems were merged with others as they overlap similar meanings. Table 3.4 presents the 44 NPD problems and 13 categories. The questionnaire asked the frequency at which each problem occurred at the company using a 6-point scale, from 1 (very rare) to 6 (very frequent). The procedure used to validate the questionnaire was the Cronbach's alpha. Cronbach alpha was assessed to assure the internal consistency of the questionnaire. Values above 0.7 were considered enough to validate questionnaire's internal consistency (Hair et al. 2006). The following step was to investigate the relationship between the LPD enablers and NPD problems. A Pearson's correlation analysis was used, as it measures the relationship between two quantitative variables (Rencher 2002).

3.5 Results

The internal consistency of the entire group of variables was very high, with a Cronbach's alpha of 0.977 and 0.968, for the LPD enablers and problems, respectively. The correlation analysis between the 30 LPD enablers and the 44 NPD problems resulted in a matrix with i-enablers (i = 1, …, 30) and j-problems (j = 1, …, 44). Table 3.5 shows all correlations that are significant at 0.05 and 0.01 levels. From the 1320 possible correlations, 694 were considered significant and presented a negative correlation. The fact that there were no significant positive correlations is logical, as LPD enablers are expected to reduce the presence of problems. However, a few problems presented significant correlation with more

Table 3.3 LPD enablers

Enablers
LE-1-Multiple alternatives (designed)
LE-2-Delaying specification
LE-3-Minimal constraint
LE-4-Extensive simulation/prototyping (possibly including full-scale models)
LE-5-Early problem solving
LE-6-Test-then-design
LE-7-Convergence on optimum solution
LE-8-Supplier strategy (supplier types and interlocking)
LE-9-Supplier set-based concurrent engineering
LE-10-Mistake proofing
LE-11-Design in quality
LE-12-Robust design methods
LE-13-Integration/target events
LE-14-Value stream mapping
LE-15-Customer-focus (customer needs/wants)
LE-16-Multi-project plan and strategy
LE-17-Cross-functional module development teams and manufacturing involvement
LE-18-Knowledge/information flow/cadence/pull (in right place at right time)
LE-19-Knowledge reuse
LE-20-Expert workforce development
LE-21-Mentoring by senior employees
LE-22-Test-to-failure
LE-23-Rapid learning/comprehension
LE-24-A3 group problem solving
LE-25-Learning cycles (Plan-Do-Check-Act)
LE-26-Root-cause analysis and 5 whys
LE-27-Employee empowerment/individual responsibility
LE-28-Lessons learnt reflection process
LE-29-Standardization of processes, skills and design methods
LE-30-Separating research from development

than one enabler, which indicates that the problem occurrence would be significantly reduced if simultaneously applied such enablers. This finding provides companies an orientation with regards to the application of a proper set of enablers in order to mitigate NPD problem's frequency. Moreover, the strongest correlations are also highlighted in Table 3.5.

Out of the thirty studied LPD enablers, two of them did not present a significant correlation with any of the listed NPD problems: LPD enablers 1 (Multiple alternatives) and 4 (Extensive simulation/prototyping). Although the literature suggests

Table 3.4 LPD problems and categories

Problems		Categories
P1	Lack of teams management	Project leader without formal authority
P2	Project coordinator not prepared to perform expected duties	
P3	Lack of team empowerment	
P4	Many hierarchical levels which delay functional teams integration	Achieve true cross-functional integration
P5	Not effective cross-functional teams	
P6	Teamwork not stimulated	
P7	Low improvement ideas generation	Lack of feedback
P8	Communication and information sharing among areas is not organized and systematic	
P9	There is no clear guidelines or priorities definition	
P10	The project is incompatible with the production capacity	No simultaneous engineering and partnership with suppliers
P11	No systematic approach for interacting with customers/suppliers	
P12	Inexistence of a problem solving evaluation process for product development	
P13	Product development process does not start from the proper sector	
P14	No strategic definition at the beginning of product development	Lack of product portfolio strategy
P15	No business focus	
P16	Lack of market orientation (no trends identification)	
P17	Inexistence of product strategic planning	
P18	Lack of a systematic product performance evaluation through metrics	LPD performance measurement system
P19	Project exclusively controlled based on timeline	
P20	Lack of performance analysis regarding milestones and final results achievement	
P21	No systematic follow up for product development process performance	
P22	Insufficient search for information	No IT integration
P23	Delays or improper information flow during projects development	
P24	No information system integration	
P25	Low utilization of product development supporting tools	
P26	Without a consistent decision making process which delaying projects	Poor operational decision making process
P27	No involvement and commitment from senior management resulting in delays on decision making	
P28	No scope change management that assess the impact of decisions	

(continued)

Table 3.4 (continued)

Problems		Categories
P29	Lack of rigour in the pursuit of failures root-causes	Lack of discipline
P30	Low compliance to activities' deadlines	
P31	Lack of a responsibility definition for involved individuals	
P32	No formal knowledge control and management among projects	Lack of knowledge reutilization
P33	Lack of a systematic knowledge storage along product development	
P34	Process highly dependent on individual capacity and knowledge	
P35	Lack of knowledge regarding product development supporting tools	
P36	Loss of time due to lack of synchronization in workflow	Coordination and time-consuming activities
P37	Capital approval process is not performed in time	
P38	No formal methodology for product development	
P39	Product development teams do not know company's strategic vision	Lack of project vision sharing
P40	Lack of perception that the product development is a business process	
P41	Lack of products information sharing among company's employees	
P42	Lack of proper equipment	Inexistence of levelled workload
P43	There is excessive centralization of development work in a sector or area	
P44	No activity definition and detailement	

that the enabler "Multiple alternatives" is an important enabler in the LPD implementation, results show that it does not present a significant correlation with most cited NPD problems. Many authors from LPD literature (David and Goransson 2012; Khan 2012) proposed a strong relationship between NPD problems and the process of set-based concurrent engineering, which, among its main enablers, include the practice of exploring multiple alternatives. However, Kato (2005) and Gautam and Singh (2008) argue that stressing a wide variety of alternatives in a NPD process may lead to dubious consequences; i.e., if, on the one hand the discussion of multiple alternatives can bring innovative solutions, on the other, it may result in loss of focus on the customer and what he perceives as value. Thus, based on this study sample, this enabler is not significantly influential for problems frequency reduction.

Table 3.5 Correlation between LPD enablers and NPD problems

LPD enabler	NPD problems								
	Project leader without formal authority			Achieve true cross-functional integration			Lack of communication and feedback		
	P1	P2	P3	P4	P5	P6	P7	P8	P9
1									
2									
3									
4									
5	−0.354*				−0.446**				
6									
7		−0.309*			−0.418**				
8		−0.379*			−0.342*	−0.315*			
9	−0.311*	−0.398**			−0.367*	−0.368*		−0.322*	−0.435**
10	**−0.490****	−0.363*	−0.337*		**−0.456****	**−0.495****			−0.338*
11	**−0.469****	**−0.585****			−0.374*	−0.314*			
12	**−0.503****	**−0.540****	−0.324*		**−0.539****	−0.414**			−0.369*
13	−0.434**	**−0.559****	−0.328*		**−0.532****	−0.366*			−0.364*
14	−0.408**	**−0.457****			**−0.455****	−0.309*	−0.354*		
15	−0.393**	**−0.453****	−0.332*		−0.359*				
16		**−0.521****			−0.316*			−0.428**	
17	**−0.503****	**−0.650****			**−0.570****	**−0.485****		−0.372*	−0.372*
18	**−0.565****	**−0.617****	−0.335*	−0.340*	**−0.519****	−0.430**	−0.383*	−0.326*	**−0.496****
19	**−0.520****	**−0.588****			**−0.458****	−0.357*	−0.346*		
20	−0.448**	**−0.466****			−0.436**	−0.368*			−0.366*
21	−0.343*	−0.380*			−0.440**	−0.321*			−0.319*
22	−0.431**	**−0.490****			−0.437**				−0.375*
23	**−0.526****	**−0.573****		−0.326*	**−0.527****	**−0.457****	−0.412**		**−0.545****
24	−0.391**	**−0.536****			−0.433**	−0.319*		−0.335*	−0.344*
25	−0.332*	**−0.501****			**−0.465****	−0.329*		−0.331*	
26		**−0.495****			−0.344*				
27	−0.405**	**−0.558****			**−0.566****	−0.436**	−0.335*	−0.320*	
28	**−0.518****	**−0.559****	−0.300*		**−0.583****	−0.402**	−0.317*	−0.330*	−0.489**
29	**−0.484****	**−0.533****			**−0.571****	−0.392**		−0.394**	−0.330*
30	**−0.494****	**−0.569****			**−0.578****	**−0.522****	**−0.501****	−0.375*	**−0.451****

(continued)

Table 3.5 (continued)

LPD enabler	NPD problems											
	No simultaneous engineering and partnership with suppliers				Lack of product portfolio strategy				LPD performance measurement system			
	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21
1												
2												
3										−0.358*		
4												
5	−0.331*		−0.536**		−0.351*		−0.296*	−0.392**	−0.369*	−0.367*	−0.438**	−0.381**
6			−0.307*							−0.332*	−0.363*	
7			−0.341*						−0.307*	−0.349*		−0.329*
8			−0.399**									−0.418**
9			−0.392*					−0.352*			−0.312*	−0.450**
10	−0.331*		−0.532**		−0.452**		−0.484**	−0.567**	−0.364*		−0.623**	−0.533**
11			−0.603**					−0.278*	−0.375*	−0.342*	−0.625**	−0.515**
12			−0.595**				−0.377*	−0.419**	−0.400**		−0.551**	−0.571**
13			−0.478**				−0.326*	−0.362*	−0.403**		−0.512**	−0.577**
14			−0.551**			−0.292*	−0.333*		−0.443**	−0.371*	−0.451**	−0.457**
15			−0.328*								−0.279	−0.318*
16			−0.311*								−0.330*	−0.380*
17			−0.612**			−0.327*	−0.389**		−0.379*	−0.302*	−0.481**	−0.595**
18	−0.397**	−0.349*	−0.716**			−0.395**	−0.442**	−0.409**	−0.413**	−0.308*	−0.510**	−0.611**
19			−0.543**				−0.328*	−0.327*	−0.379*		−0.498**	−0.555**
20	−0.368*		−0.637**				−0.392*	−0.450**	−0.413**		−0.509**	−0.551**
21	−0.316*		−0.463**								−0.354*	−0.494**
22			−0.606**					−0.351*	−0.349*		−0.508**	−0.464**
23	−0.371*		−0.702**				−0.464**	−0.405**	−0.443**	−0.321*	−0.556**	−0.623**
24			−0.590**			−0.316*	−0.300*	−0.321*	−0.415**		−0.510**	−0.488**
25			−0.567**				−0.363*			−0.314*	−0.449**	−0.481**
26	−0.324*		−0.528**							−0.329*	−0.399**	−0.404**
27	−0.399**		−0.634**	−0.337*		−0.433**	−0.505**	−0.413**	−0.450**	−0.357*	−0.460**	−0.522**
28	−0.348*		−0.703**			−0.330*	−0.453**	−0.392**	−0.407**	−0.324*	−0.539**	−0.613**
29	−0.339*		−0.612**			−0.317*	−0.412**	−0.314*		−0.343*	−0.471**	−0.504**
30			−0.691**			−0.381*	−0.562**	−0.391*	−0.461**	−0.381*	−0.520**	−0.629**

(continued)

Table 3.5 (continued)

LPD enabler	NPD problems									
	No IT integration				Poor operational decision making process			Lack of discipline		
	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31
1										
2										
3										
4										
5	−0.366*	−0.424**	−0.316*	−0.393**	−0.350*			−0.419**	−0.343*	−0.388*
6										
7	−0.319*			−0.389*				−0.396*		−0.339*
8				−0.392*				−0.321*		−0.407**
9				−0.443**				−0.308*		**−0.456****
10	−0.424**	−0.341*	−0.434**	−0.389*		**−0.468****		−0.435**	**−0.517****	**−0.511****
11	−0.420**			−0.382*		−0.430**		**−0.458****	−0.334*	−0.415**
12	**−0.458****	−0.435**	−0.424**	**−0.584****		−0.397**		**−0.560****	**−0.507****	**−0.594****
13	−0.446**	−0.313*	−0.337*	**−0.563****		−0.374*		**−0.581****	−0.332*	**−0.474****
14	−0.313*	−0.375*		−0.335*	−0.315*	−0.361*		**−0.547****	−0.313*	−0.407**
15				−0.378*				−0.415**		−0.409**
16	−0.401**			−0.341*				−0.373*		−0.360*
17	**−0.499****	−0.347*	−0.437**	**−0.542****		−0.444**		**−0.603****	**−0.455****	**−0.623****
18	**−0.529****	**−0.540****	**−0.493****	**−0.676****	−0.311*	−0.441**		**−0.649****	**−0.578****	**−0.631****
19	−0.362*	−0.382*		**−0.500****		−0.432**		**−0.588****	**−0.486****	**−0.513****
20	−0.424**	−0.389*		**−0.554****		−0.353*		**−0.512****	**−0.469****	**−0.566****
21				**−0.541****				**−0.511****		−0.376*
22	**−0.456****	−0.347*	−0.359*	**−0.550****		−0.359*		**−0.542****	−0.396*	**−0.462****
23	−0.446**	−0.443**	−0.444**	**−0.691****		−0.408**		**−0.708****	**−0.512****	**−0.571****
24	**−0.519****	−0.392**	**−0.452****	−0.449**	−0.316*	−0.322*		**−0.546****	−0.419**	**−0.529****
25	−0.391**		−0.338*	**−0.451****				**−0.497****	−0.361*	**−0.486****
26	−0.384**			−0.428**	−0.303*	−0.309*		**−0.463****	−0.339*	−0.404**
27	−0.420**	**−0.507****	**−0.477****	**−0.500****	−0.329*	−0.408**		**−0.582****	**−0.620****	**−0.696****
28	**−0.478****	**−0.487****	−0.452**	**−0.650****		**−0.455****		**−0.701****	**−0.563****	**−0.626****
29	−0.420**	−0.372*	−0.439**	**−0.468****	−0.333*	**−0.464****		**−0.611****	**−0.598****	**−0.598****
30	−0.447**	**−0.516****	**−0.512****	**−0.605****		−0.405**		**−0.681****	**−0.549****	**−0.651****

(continued)

Table 3.5 (continued)

LPD enabler	NPD problems												
	Lack of knowledge reutilization				Coordination and time-consuming activities			Lack of project vision sharing			Inexistence of levelled workload		
	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44
1													
2											0.334*		
3													
4													
5	−0.389**	−0.360*		−0.380*			−0.408**	−0.432**	**−0.495****	−0.324*	−0.339*	**−0.457****	
6													
7	−0.367*		−0.321*	−0.377*			−0.404**	−0.400**	−0.438**				
8	−0.356*		−0.356*				**−0.478****	−0.396*	−0.389*			−0.349*	
9	−0.347*		−0.402**	−0.335*			**−0.470****	−0.443**	**−0.482****			−0.446**	
10	**−0.491****	−0.358*	−0.434**	−0.389*	−0.313*		−0.342*	−0.408**	**−0.491****			−0.439**	
11	−0.426**	−0.315*	−0.396**	−0.265			−0.379*	−0.406**	−0.349*	−0.412**		−0.343*	
12	**−0.467****	**−0.476****	**−0.546****	**−0.534****	−0.416**		**−0.543****	**−0.527****	**−0.568****	−0.405**	−0.323*	**−0.474****	
13	−0.426**	−0.406**	**−0.460****	−0.411**	−0.334*		**−0.549****	−0.413**	**−0.506****	−0.435**	−0.372*	**−0.450****	
14	−0.340*	−0.393**	−0.357*	−0.413**			**−0.503****	**−0.546****	**−0.541****	−0.350*		**−0.463****	
15	−0.382*		−0.401**				−0.388*						
16	−0.323*				−0.365*		**−0.461****	−0.380*				−0.355*	−0.324*
17	**−0.494****	−0.429**	**−0.482****	**−0.488****	**−0.456****		**−0.568****	**−0.531****	**−0.522****	−0.350*	−0.363*	**−0.480****	
18	**−0.505****	**−0.486****	**−0.513****	**−0.615****	**−0.510****		**−0.618****	**−0.551****	**−0.578****	−0.406**	−0.396*	**−0.530****	−0.358*
19	−0.378*	−0.403**	**−0.508****	**−0.453****	−0.422**	−0.336*	**−0.558****	−0.412**	**−0.457****	−0.375*	−0.323*	−0.392*	−0.314*
20	**−0.493****	−0.377*	**−0.475****	**−0.515****	−0.327*		**−0.610****	−0.476**	**−0.571****	**−0.496****	−0.328*	−0.388*	−0.330*
21	−0.330*	−0.297	−0.381*	−0.351*	−0.286	−0.332*	**−0.480****		−0.349*			−0.434**	
22	−0.375*	−0.390*	−0.395*	**−0.489****	−0.364*		−0.409**	−0.359*	**−0.461****	**−0.507****		**−0.466****	
23	**−0.510****	−0.407*	**−0.508****	**−0.625****	−0.402*	−0.322*	**−0.540****	**−0.480****	**−0.566****	−0.437**	−0.356*	**−0.519****	
24	−0.420**	**−0.507****	−0.398**	**−0.500****	**−0.458****		**−0.558****	**−0.514****	**−0.531****	−0.375*	−0.357*	**−0.520****	−0.357*
25	−0.360*	−0.331*		−0.441**	−0.355*		**−0.617****	−0.447**	**−0.525****			**−0.599****	−0.371*

(continued)

Table 3.5 (continued)

LPD enabler	NPD problems												
	Lack of knowledge reutilization				Coordination and time-consuming activities			Lack of project vision sharing			Inexistence of levelled workload		
	P32	P33	P34	P35	P36	P37	P38	P39	P40	P41	P42	P43	P44
26				−0.394**	**−0.472****		**−0.569****	−0.399**	−0.437**	−0.387*		**−0.613****	−0.438**
27	**−0.556****	**−0.513****	**−0.504****	**−0.591****	**−0.493****		**−0.633****	**−0.661****	**−0.682****		−0.446**	−0.439**	−0.316*
28	**−0.577****	**−0.524****	**−0.539****	**−0.582****	**−0.458****		**−0.605****	**−0.565****	**−0.612****	−0.422**	−0.369*	**−0.528****	−0.362*
29	**−0.565****	**−0.509****	**−0.530****	**−0.501****	**−0.501****		**−0.495****	**−0.527****	**−0.491****			**−0.512****	−0.342*
30	**−0.583****	**−0.461****	**−0.503****	**−0.659****	**−0.450****		**−0.608****	**−0.540****	**−0.650****	−0.403*	−0.367*	**−0.555****	

* Correlation is significant at 0.05 level
** Correlation is significant at 0.01 level

Contrary to popular belief, the results show that enabler 4 "Extensive simulation/prototyping" does not have a significant impact on any of the NPD problems. This result is somewhat surprising in light of conventional wisdom about the difficulty of developing any new product without a minimum level of simulation or prototyping within the organization. However, this result is consistent with the findings of Oliver et al. (2004) and Matsui et al. (2007), who infer that the manufacture and testing of prototypes along a product development is extremely expensive and difficult. Moreover, few companies have an exclusive area for prototyping, which makes its manufacture occur in current production lines, affecting the productive capacity and even the condition of their machinery. Moreover, since one of the main objectives of LPD implementation is NPD lead time reduction, Schuh et al. (2008) and Oliver et al. (2004) state that, especially in technology business, longer times for simulation and prototyping may cause loss in the product time to market, which impacts its innovative aspect for consumers.

Overall, the sum of correlations for each LPD enabler and all NPD problems indicate that enablers 18 (Knowledge/information flow/cadence/pull), 28 (Lessons learnt reflection process), 30 (Separating research from development), 27 (Employee empowerment/individual responsibility) and 23 (Rapid learning/comprehension) are the ones that present the strongest impact for mitigating NPD problems and, therefore, the most indicated for companies that are struggling with their NPD processes. These results are aligned with the findings of Dal Forno et al. (2013) and Oppenheim (2011), who emphasize the importance of employee involvement practices and the process of reflection and learning from past activities. However, such result neglects the company's context, whose maturity level for NPD process must be taken into account. Further, the occurrence of NPD problems must be properly considered, since they are the main input for decision on LPD enablers adoption.

3.6 Conclusion

This chapter showed an alternative to select enablers for improving the implementation of LPD according to the most cited NPD problems in literature. Among the 30 LPD enablers and the 44 NPD problems it was identified 694 significant negative correlations at 0.05 and 0.01 level. This finding provides the companies an orientation with regards to the application of the proper enablers in order to mitigate NPD problems' frequency. The correlations indicated that some LPD enablers are associated to the frequency of many NPD problems. Therefore, the comprehension around this subject allows project managers to drive the NPD process improvement to lean culture, saving resources and maximizing the benefits of this effort.

Furthermore, the results of this study are intended to complement the usual recommendation and categorization of LPD enablers based on benchmarking of previous researches. Our findings indicate that the implementation of LPD enablers matters with regards to occurrence frequency of LDP problems, although not all enablers matter to same extent. Moreover, some results demonstrate that, although literature indicates a certain level of impact, the correlation between enablers and problems may present different impacts than the expected ones.

Each of the LPD enablers under study is associated with a significant lore about their impact on the occurrence frequency of LPD problems of companies undergoing a lean implementation. Overall, the evidence presented here suggests that the studied LPD enablers, presented in the literature as fundamental for a lean implementation, significantly affect the likelihood of LPD problems occurrence. In particular, the impact of four out of five enablers' constructs appears to be the most substantial across the frequency of occurrence of LPD problems. The influence of the enabler construct "Set-based concurrent engineering for concept generation", however, does not appear to be as significant for mitigating LPD problems occurrence as expected.

The results also indicate that there is not a fixed recipe for success since every organization starts with a different set of problems and constraints, which is supported by the findings of Singh et al. (2010) and Bhasin (2012). In general, the success of implementation of any particular management practice depends upon organizational characteristics, and not all organizations can or should implement the same set of enablers. The understanding of the company's current context, specifically its NPD problems occurrence frequency, is fundamental for the appropriate adoption of LPD enablers. According to contingency arguments, organizations should use LPD enablers that are effective to their NPD problems. Therefore, the contingency approach assumes that it is the company's context that, in the long run, determine the organizational responses in the lean implementation, whether it is on the shop floor or NPD process.

There are some limitations due to the nature of the sample used in the survey that must be highlighted. First, the respondents were mostly from companies located in the South of Brazil, their answers might be linked to regional issues, where the spread of lean may have come under local influences. Thus, as this limitation restricts the results to this geographic condition it also increases the certainty that the results apply to those companies. It is worth noting that companies of other countries may experience the same contextual conditions. Second, the sample size effectively confirmed only some relationships between the LPD enablers and NPD problems and it was not possible to reject all null hypotheses proposed. Those hypotheses that were not rejected may exist in a lower level. If that is the case, larger sample sizes can highlight those effects. Nevertheless, the exploratory nature of this research provided important evidences for developing more structured models that should be empirically tested.

Due to poor evidence in literature about the likelihood of any interdependent influence, further investigation would add more data and help to establish a holistic perspective about the problem and identify interactions among the LPD enablers and their influence over NPD problems. Such research opportunity would raise a more extensive and coherent analysis in order to really comprehend and specify the contexts in which problems are expected to occur.

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Chapter 4
Discussing and Evaluating the Green Environmental Performance of Manufacturers

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Abstract The primary objective of green production (GP) and green supply chains (GSCs) is to enhance corporate green environmental performance (GEP). Therefore, implementing GP and GSCs strategies is essential to measuring corporate GEP accurately. Enterprises typically incorporate GP and GSC matters into their management systems and relevant environmental requirements and approaches into their green performance management systems to comply with GEP regulations stipulated by the government, resolve challenges and bottlenecks faced when manufacturing green products, and elevate green industrial competitiveness. This study adopted the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to evaluate the environmental performance of manufacturing enterprises. By using a DEMATEL model, this study accurately determined the influence strengths and causal relationships among various GEP measurement criteria.

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4.1 Green Environment of Manufacturing Enterprises

In recent years, the prevalence of globalization, international environmental awareness, and green consumption concepts have elevated people's awareness toward the environmental performance and social responsibilities of enterprises. In this regard, manufacturing enterprises are challenged with improving production performance and concerns related to green (clean) production (GP) and green supply chains (GSCs) to enhance their overall green competitiveness. Enterprises are required to improve both productivity and environmental management to enhance their green competitiveness and reinforce their overall environmental performance (Chiang et al. 2011; Cheng et al. 2013).

Since the introduction of green regulations by the European Union (EU), earth protection concerns have become a considerable burden for conventional electrical and electronic industries. These regulations—which include the Waste Electrical and Electronic Equipment Directives, Restriction of Hazardous Substances, and European Ecodesign (EuP) Directives that took effect on July 1, 2006—stipulate the production of green (clean) products and regulate the protection responsibilities of enterprises toward the product environment. The EU introduced the EuP Directive in 2005, in which product manufacturers were requested to consider product life cycle and incorporate ecodesign requirements into product design and development. Furthermore, these directives primarily aim to encourage enterprises to reduce the environmental pollution, decrease energy demand, and enhance environmental protection.

4.2 Green Production, Green Supply Chains, and Green Environmental Performance

4.2.1 Green (Clean) Production

The GP of an enterprise is one of the primary indicators for its green environmental performance (GEP). According to the United Nations Environment Programme, GP is defined as "the continuous application of an integrated environmental strategy to processes, products, and services to increase efficiency and reduce risks to humans and the environment." Therefore, GP advocates pollution prevention and elucidates pollution prevention as the product and environmental responsibilities of manufacturers aiming to achieve "eco-efficiency" and "sustainable development" (Cheng et al. 2013; Tsireme et al. 2012).

The content of GP can be classified into two categories: green energy and production processes, and green products.

Green Energy and Production Processes:

1. Selecting green resources and using new, pollution-free energy and resources, such as renewable energy (e.g., solar, wind, ocean, tidal, geothermal, and biomass).
2. Using clean fossil fuel to accelerate the technical innovation of energy conservation and improve energy efficiency.
3. Using pollution-free or low-pollution techniques and equipment to conserve energy and resources, and recycling and reusing raw materials as well as utilizing scraps and waste materials to improve resource usage and reduce the consumption of the Earth's resources.
4. Strengthening the management of technologies, equipment, material transportation and storage, and production organization processes to reduce material waste and leakage.
5. Conducting comprehensive governance on the emitted pollutants.

Green Products:

1. Product materials should be nontoxic to produce decomposable, clean, and sustainable products.
2. Products should demonstrate appropriate functionality and lifespan, and should be energy, water, power, and noise efficient.
3. Product use should pose no harm to human health or the ecological environment, and products should be easily recyclable, reusable, and renewable.

GP also aims to achieve the following objectives (Cheng et al. 2013; Despeisse et al. 2012; Oliver and Abhishek 2013):

4. To eliminate or reduce the generation and emission of wastes and pollutants during the production process and rationally utilize resources, thereby promoting product production and consumption processes that are compatible with the environment, which reduces the damage posed to human health and the environment.
5. To slow resource depletion by effectively using resources, identifying alternatives to rare resources, reusing resources, and conserving energy, materials, and water.

4.2.2 Green Supply Chains

GSC management (GSCM) encompasses the entire life cycle of a product from initial design to final recovery. GSCM can be examined in several dimensions, including green design, green materials, green supplier, GP, green marketing and packaging, green transportation, and green recycling (Kumar et al. 2012; Ahi and Searcy 2013; Constantin et al. 2014).

GSCM can be defined as the process in which enterprises voluntarily incorporate green environmental concepts into supply chain management (SCM) by introducing environmental concepts into their original production management regimes, expanding these concepts into the entire SCM system, and appointing environmental staff to reinforce environmental management (Winn and Roome 1993). Therefore, procurement, transportation, and pollution and recycling management become decisive factors in the green management implemented by such enterprises.

GSC encourages suppliers to consider product and environmental management collectively. In addition, GSC integrates environmental protection into supplier management systems to incorporate environmental concepts into products and elevate the market competitiveness of enterprises.

Before pollution tax regulations, enterprises could overlook environmental concerns. However, the prevalence of green consumption, continuous revision of environmental regulations, and demands of environmental activists have increased the environmental pressure on enterprises. Lam et al. (2011) classified the GEP motivations (driving forces) of enterprises into internal and external driving forces. Internal driving forces include managers' perception of rights and responsibilities, increased product quality requirements, increased product and company image requirements, decreased cost requirements, innovation capacity, and increased employee motivation requirements; external driving forces include government promotion, market demands, social environmental requirements, competitor threat, suppliers, and trade organization pressure.

4.2.3 Green Environmental Performance

Enterprises typically incorporate GP and GSC concerns into their management systems and relevant environmental requirements and practices into their green performance management systems. Enterprises perform these procedures to comply with governmental GEP regulations, resolve challenges and bottlenecks faced when manufacturing green products, and elevate green industrial competitiveness.

The environmental performance evaluation (EPE) assesses the environmental performance of enterprises based on the goals of environmental protection, allocation of enterprise resources, and management and control of environmental factors. The systematic procedures for measuring and evaluating environmental performance involve continually collecting and evaluating past, present, and future information to review the management system, operating system, and the immediate environment of an enterprise (Lam et al. 2011; Lin and Yu 2004). Based on a "What gets measured, gets managed" principle, the EPE measures verifiable environmental performance by establishing relevant performance criteria, continually collecting objective and reliable data, and evaluating environmental matters and stakeholders' opinions.

Conrad and Morrison (1989) argued that under the restrictions of environmental regulations, enterprises may invest their limited funding in unproductive pollution control equipment, rather than productive equipment. This reduces the productivity of an enterprise and eventually causes decreased environmental performance. However, Carter et al. (2009) conducted an empirical study and asserted that abiding to environmental regulations stimulates enterprises to achieve effective production and improve environmental performance. Tseng and Lin (2008) argued that in supply chains, suppliers and clients collaborate with each other to reduce the negative effect of production on the environment and maintain environmental performance. Tseng et al. (2009) emphasized that enterprises must endeavor to determine favorable suppliers and develop strategic procurement plans to elevate their environmental performance. They also conducted an empirical study, maintaining that the dimensions of green design, green material procurement, GP, green products, green transportation, green packaging, and green recycling influence GEP considerably. Zhu et al. (2011) empirically verified that improved environmental performance stimulates business performance, increasing the market share of the enterprise.

The present study divided the EPE system into the following dimensions: green development, GP, green management, and green recycling (Fig. 4.1). Detailed descriptions of each dimension are provided below.

1. **Green development**
   Green development comprises green design and green procurement. Before a product can be manufactured, planning and design processes are required to materialize the product. Green design concepts should be incorporated into product manufacturing to produce environmentally friendly products and avoid violating environmental regulations. Chu et al. (2009) reported that green design must be coordinated with green procurement when designing the life cycle of a product so that products and environmental optimization are interdependent. In the design stage, enterprises must carefully inspect all

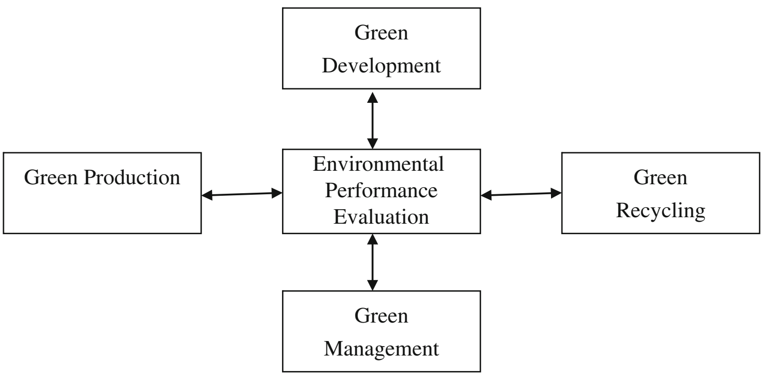

Fig. 4.1 Environmental performance evaluation system

components and suppliers to eradicate any toxic substances from the production process, thereby achieving a GP process.

Green procurement entails incorporating green concepts in selecting and purchasing green materials from suppliers during the preparation stage of product manufacturing. In GSCs, the green materials provided by suppliers can assist enterprises with improving their environmental performance (Kainuma and Tawarw 2006).

2. **Green production**

   GP facilitates reducing air and water pollution, waste generation and pollution, and energy consumption in production processes. Zhu et al. (2011) performed an empirical study, determining that implementing GP did not influence the production costs of enterprises; instead, it increased business and environmental performance.

3. **Green management**

   Green management comprises green marketing, green image, and green transportation. Green marketing emphasizes the various communication tools used in conventional marketing, such as promotional activities, appropriate advertisement, personnel sales, sales promotions, public relations, and direct marketing. These tools are then used to propagate clearly the "green" messages of a product to consumers and the community to elevate the green image of the enterprises. Tsai et al. (2013) argued that the primary objective of green marketing is to raise consumer awareness regarding the negative effects of environmental deterioration on quality of life, thereby stimulating consumers' purchase intention for green products and facilitating establishing a sound understanding of environmental performance.

   Green transportation aims to gain customer satisfaction and to achieve a centralized distribution, reduce energy consumption, and develop appropriate transportation routes. Green transportation links the green demands of manufacturers with the green materials of suppliers and effectively manages transportation-related services and activities.

4. **Green recycling**

   Green recycling comprises green packaging and green recycling. Typically, consumers dispose of products once the product is rendered unusable. If enterprises can guide consumers to reuse or recycle their products via design or package labeling, the environmental performance of the enterprise can be substantially improved. Green packaging reduces the amount of waste generated by products once they are disposed, whereas product recycling promotes the repeated use and regeneration of products, both of which reduce the environmental burden (Tsai et al. 2013).

4.3 Measuring Green Environmental Performance

4.3.1 Evaluation Dimensions and Criteria

Based on the preceding discussion on the environmental performance evaluation system, this current study established 10 criteria and divided them into four dimensions. These criteria are “green design” (a1), “green material procurement” (a2), “air and water pollution” (b1), “waste pollution” (b2), “energy consumption” (b3), “green marketing” (c1), “green transportation” (c2), “green image” (c3), “green packaging” (d1), and “product recycling” (d2), and the dimensions are “green development,” “GP,” “green management,” and “green recycling,” (Table 4.1).

This study adopted the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to evaluate the environmental performance of manufacturing enterprises. By using the DEMATEL model, this study accurately determined the influence strengths and causal relationships among various GEP measurement criteria.

4.3.2 Decision-Making Trial and Evaluation Laboratory

DEMATEL originated from Natural Sciences and Humanities Research Plan conducted by the Battelle Institute in 1971. During the initial stages of development, DEMATEL primarily focused on complex global problems, such as race, hunger, environmental protection, and energy shortage. Therefore, DEMATEL was primarily employed in three major research fields, which are (1) researching global problem structures; (2) analyzing and developing appropriate methods in response to complex global problems; and (3) reviewing studies, models, and data related to global problems (Gabus and Fontela 1973; Fontela and Gabus 1976).

Table 4.1 GEP evaluation dimensions and criteria

Dimensions	Criteria
(a) Green development	(a1) Green design
	(a2) Green material procurement
(b) Green production	(b1) Air and water pollution
	(b2) Waste pollution
	(b3) Energy consumption
(c) Green management	(c1) Green marketing
	(c2) Green transportation
	(c3) Green image
(d) Green recycling	(d1) Green packaging
	(d2) Green recycling

The DEMATEL involves using matrices to calculate the degree of influence and causal relationships among factors and creating a direct relation diagram to explain the degree of influences between factors within systems. In addition, causal diagrams can be developed to structure complex problems, where all criteria are grouped into either a cause group or an effect group to clarify the nature of problems, determine core problems, and establish solutions (Fontela and Gabus 1976; Lee et al. 2010; Tsai and Xue 2013).

Lee et al. (2010) reported that the DEMATEL method is characterized by its ability to calculate the degree of influence and causal relationships among factors by using matrices, and structure complex problems by using causal diagrams to clarify the nature of problems, thereby determining core problems and establishing improvement methods.

The analysis elements within a DEMATEL model must satisfy the following assumptions:

1. The nature of the problems must be explicit: The nature of the problems must be clear during the problem formation and planning to establish accurately a resolution direction for the problems.
2. The level of association among problems must be explicit: The relationships between each factor and other factors must be clearly presented using a numerical values of 0–4 to express the level of association.
3. The essential characteristics of each problem element must be known: A supplementary explanation, including agreements and disagreements, for each problem element must be provided based on relevant problems.

In recent years, DEMATEL has been widely employed in different fields to resolve various problems. Tzeng et al. (2007) used DEMATEL to evaluate the performance of e-learning. Lee et al. (2010) used the DEMATEL to verify the benefits of applying the DEMATEL to the technology acceptance model. Wu et al. (2010) evaluate performance criteria of employment service outreach program personnel. Lee and Hsieh (2011) analyzed causal relationships among service attributes in the telecommunication industry by using DEMATEL to adjust the importance of various service attributes and resolve competitiveness problems. Tsai and Xue (2013) employed DEMATEL to investigate job acquisition in the manufacturing industry and proposed an efficient competitiveness improvement strategy.

The structure and calculation steps of DEMATEL are presented as follows.

Step 1: Establish a measurement scale and determine the causal relationships among factors

Methods such as literature review, brainstorming, or expert opinions are used to develop a list of factors that influence complex systems and define each of the factors. Next, measurement scale is designed to express the influence degrees of the factors, which are then subjected to pairwise comparison to determine the causal relationships among the factors. According to a table listing the semantic values and operational semantics definition by Lee et al. (2010) the degrees of influence of the factors are represented using numbers 0 (*no influence*), 1 (*low influence*), 2 (*high influence*), and 3 (*extremely high influence*). Previously, Kim (2006), Tsai and Xue (2013) have proposed a 6-level scale and an 11-level scale, respectively. No specific restrictions or regulations currently apply to scale design.

Step 2: Establish a direct relation matrix

After the measurement scale is defined, a questionnaire survey is conducted, inviting experts to perform a pairwise comparison on the various factors based on their influential relationship and degree of influence. Subsequently, a direct relation matrix is developed, in which each value within the matrix represents the degree of influence among the various factors. Finally, the diagonal values of the matrix are set to 0.

$$X = \begin{bmatrix} 0 & x_{12} & \cdots & x_{1n} \\ x_{21} & 0 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & 0 \end{bmatrix} \tag{4.1}$$

Step 3: Normalize the direct relation matrix

The normalization method proposed by Tsai et al. (2013) is used to normalize the direct relation matrix, using the row vector and maximum as the normalization benchmarks.

$$\lambda = \frac{1}{\underset{1 \le i \le n}{\mathrm{Max}} \left(\sum_{j=1}^{n} x_{ij} \right)} \tag{4.2}$$

$$N = \lambda X \tag{4.3}$$

Step 4: Calculate the direct/indirect relation matrix (T), referred to as the total-relation matrix

$$T = \lim_{k \to \infty} \left(N + N^2 + \cdots + N^k \right) = N(I - N)^{-1} \tag{4.4}$$

Step 5: Calculate the sum of the values in individual rows and columns

The values in individual rows and columns within the total-relation matrix (T) are summed, using D_i to represent the sum of the *i*th column and R_j to denote the sum of the *j*th row. Next, D_i and R_j values can be obtained, including both the indirect and direct influences.

$$D_i = \sum_{j=1}^{n} t_{ij} \quad (i = 1, 2, \ldots, n) \tag{4.5}$$

$$R_j = \sum_{i=1}^{n} t_{ij} \quad (j = 1, 2, \ldots, n) \tag{4.6}$$

Step 6: Illustrate the DEMATEL causal diagram

$(D + R)$ is defined as the prominence value, where $k = i = j = 1, 2, \ldots, n$. This value represents the total relation of the service attribute (k), which can be examined to determine the core level of k in all problems. $(D - R)$ is defined as the relation value. This value represents the total differences in the service attribute, which can be examined to determine the causal relationships of k in all problems. A positive (negative) value indicates that the service attribute belongs to the cause (effect) group. The causal diagram depicts $(D + R)$ on a horizontal axis and $(D - R)$ on a vertical axis, simplifying complex causal relationships into an easy-to-understand visual structure. Decision-makers can then determine the classification of each factor based on the position of the factor on the diagram and formulate appropriate solutions to problems according to the degree of influence of these factors.

If $(D_k - R_k)$ is a positive value, Indicator k is classified into the cause group, whereas k is classified into the effect group when $(D_k - R_k)$ is a negative value. An increased $(D_k - R_k)$ value suggests an increased influence of k on other indicators and an increased influence of other indicators on k. Based on the coordinates of $(D_k + R_k)$ and $(D_k - R_k)$, attribute zones can be characterized into the follow four types:

1. Positive $(D_k - R_k)$, High $(D_k + R_k)$ Values: The sum of the total influence on and the degree of being influenced by other factors is characterized as a high degree of influence. This factor is classified as a cause attribute and a driving factor for problem solutions.
2. Positive $(D_k - R_k)$, Low $(D_k + R_k)$ Values: This factor considerably influences other factors, but demonstrates a relatively low degree of total influence. Thus, it is characterized as a cause factor that exhibits a low degree of influence. It is typically independent and influences only a few other factors.
3. Negative $(D_k - R_k)$, High $(D_k + R_k)$ Values: This factor is highly influenced by other factors, but exerts a relatively low influence on other factors. The total influence is characterized as a high degree of influence. This factor is classified as an effect attribute and is a core problem that requires a solution. However, this factor cannot be directly improved because it is an effect attribute.
4. Negative $(D_k - R_k)$, Low $(D_k + R_k)$ Values: This factor is substantially influenced by other factors, but demonstrates a relatively low degree of total influence. Thus, it is characterized as an effect factor exhibiting a low degree of total influence. It is typically independent and is influenced by few other factors.

4.4 Results and Discussion

Printed circuit boards (PCBs) are produced using numerous advanced techniques, such as printing, etching, plating, and drilling. The manufacturing processes of PCBs are extremely complex and require numerous chemical agents. Therefore, such processes generate various gas, liquid, and solid waste containing diverse organic pollutants and copper, lead, and nickel waste, which are extremely strong pollutants. Therefore, such processes may cause severe environmental pollution if appropriate pollution prevention policies are not adhered to. In this context, methods for reducing environmental pollution within the entire PCB industrial chain and for improving environmental performance have become focal topics of discussion among government units and enterprises.

China is one of the global leaders in PCB manufacturing, ranking first in the world for output value and third for technical capacity, preceded only by Japan and Taiwan. PCB manufacturers in China possess technical advantages. According to statistics released by the China Printed Circuit Association, the global output value for PCBs reached US$59.79 billion in 2012. China occupied US$25.53 billion of this value, accounting for 42.7 % of global production, followed by Japan (14.4 %), and Taiwan (13.4 %).

The present study employed the DEMATEL model to examine the GEP of China's PCB industry and establish a comprehensive evaluation method.

4.4.1 Research Questionnaire

The GEP questionnaire comprised 10 evaluation criteria divided into four dimensions. These criteria are "green design" (a1), "green material procurement" (a2), "air and water pollution" (b1), "waste pollution" (b2), "energy consumption" (b3), "green marketing" (c1), "green transportation" (c2), "green image" (c3), "green packaging" (d1), and "product recycling" (d2), and the dimensions are "green development," "GP," "green management," and "green recycling."

The questionnaire was administered between September 8 and 25, 2014, to obtain the opinions of experts regarding the GEP of Chinese PCB manufacturers. A 7-point scale was used to score the questionnaire, with scores 6–0 representing *extremely high influence* and *no influence*. The questionnaire was administered to 14 experts, six of whom were general managers of PCB enterprises, four were professors, and four were government officials serving in the environmental protection units. The researchers of the current study visited each expert to deliver the questionnaire personally and explain the content. In total, 14 formal questionnaires were administered and 13 were recovered, thus resulting in a valid return rate of 93 %.

Table 4.2 DEMATEL expert opinion survey results (direct relations matrix; *X*)

X	a1	a2	b1	b2	b3	c1	c2	c3	d1	d2
a1	0	5.2	2.9	2.5	2.4	2.5	3.1	3.7	4.1	4.5
a2	2.1	0	2.6	4.1	2.2	2.6	2.8	4.5	4.4	4.1
b1	1.6	1.7	0	3.5	4.7	4.6	0.8	5.1	0.9	0.8
b2	1.6	0.8	2.7	0	2.9	4.6	0.6	5.1	1.2	0.2
b3	1.4	1.1	2.8	1	0	4.5	1.1	0.8	1.5	0.4
c1	0.2	0.3	0.4	0.3	0.4	0	1.9	3.6	0.5	0.3
c2	0.4	0.3	0.3	0.2	2.7	2.3	0	3.8	0.4	0.3
c3	0.3	0.4	0.4	0.2	0.2	3.9	1.1	0	0.3	0.4
d1	0.3	0.3	0.9	1.3	1.4	1.8	2.5	3.2	0	4.1
d2	0.2	0.5	0.9	0.5	1.8	2.1	3.3	4.1	4.5	0

4.4.2 Results

4.4.2.1 Establishing the Direct Relation Matrix

Based on the data collected from the expert questionnaires and interviews, the study employed the DEMATEL method to analyze the interrelations and degree of influence of the 10 criteria. Table 4.2 shows the DEMATEL expert opinion survey results; 100 grids are presented for the 10 criteria. After excluding the 10 diagonal grids that presented no influence, 90 grids showing degrees of mutual influence were obtained. An average score was determined for the scores provided by the 14 experts and rounded off to the first decimal place.

For example, green material procurement (a2) influences green design (a1) at a degree of 2.1, air and water pollution (b1) at a degree of 2.6, waste pollution (b2) at a degree of 4.1, energy consumption (b3) at a degree of 2.2, green marketing (c1) at a degree of 2.6, green transportation (c2) at a degree of 2.8, green reputation (c3) at a degree of 4.5, green packaging (d1) at a degree of 4.4, and product recycling (c2) at a degree of 4.1.

4.4.2.2 Normalizing the Direct Relation Matrix

To normalize the direct relation matrix, the row vector and maximum values serve as the normalization benchmarks. Equation (4.2) can be used to calculate the sum of the values in the green design (a1) row as follows: 0 + 5.2 + 2.9 + ⋯ + 3.7 + 4.1 + 4.5 = 30.9. This method can be used to derive the sum of the values in the remaining rows, and these are a2 = 29.4, b1 = 23.7, b2 = 19.7, b3 = 14.6, c1 = 7.9, c2 = 10.7, c3 = 7.2, d1 = 15.8, and d2 = 17.9. Next, the reciprocal of the maximum value among the various rows (30.9) was selected as the λ value. The direct relation

Table 4.3 Normalized direct relation matrix (*N*)

X	a1	a2	b1	b2	b3	c1	c2	c3	d1	d2
a1	0.00	0.17	0.09	0.08	0.08	0.08	0.10	0.12	0.13	0.15
a2	0.07	0.00	0.08	0.13	0.07	0.08	0.09	0.15	0.14	0.13
b1	0.05	0.06	0.00	0.11	0.15	0.15	0.03	0.17	0.03	0.03
b2	0.05	0.03	0.09	0.00	0.09	0.15	0.02	0.17	0.04	0.01
b3	0.05	0.04	0.09	0.03	0.00	0.15	0.04	0.03	0.05	0.01
c1	0.01	0.01	0.01	0.01	0.01	0.00	0.06	0.12	0.02	0.01
c2	0.01	0.01	0.01	0.01	0.09	0.07	0.00	0.12	0.01	0.01
c3	0.01	0.01	0.01	0.01	0.01	0.13	0.04	0.00	0.01	0.01
d1	0.01	0.01	0.03	0.04	0.05	0.06	0.08	0.10	0.00	0.13
d2	0.01	0.02	0.03	0.02	0.06	0.07	0.11	0.13	0.15	0.00

matrix (*X*) was multiplied by the λ value by using Eq. (4.3) to determine the normalized direct relation matrix (*N*). The influence coefficients were rounded off to the second decimal place (Table 4.3).

4.4.2.3 Calculating the Direct/Indirect Relation Matrix (T)

Equation (4.4) was used to calculate the direct/indirect relation matrix (*T*), and influence coefficients were rounded off to the second decimal place (Table 4.4).

4.4.2.4 Calculating Prominence and Relation

Equations (4.5) and (4.6) were used to calculate the *Di* values of the various columns and *Rj* values of the various rows within the matrix to determine the prominence ($D + R$) and relation ($D - R$) of the factors. For example, D_3 represents

Table 4.4 Direct/indirect relation matrix (*T*)

X	a1	a2	b1	b2	b3	c1	c2	c3	d1	d2
a1	0.05	0.21	0.17	0.16	0.19	0.26	0.21	0.33	0.23	0.23
a2	0.11	0.05	0.15	0.19	0.17	0.25	0.19	0.33	0.22	0.20
b1	0.09	0.09	0.06	0.16	0.21	0.28	0.10	0.30	0.09	0.08
b2	0.08	0.06	0.13	0.04	0.15	0.26	0.08	0.27	0.09	0.05
b3	0.07	0.06	0.12	0.07	0.05	0.22	0.09	0.13	0.09	0.05
c1	0.01	0.02	0.03	0.02	0.03	0.04	0.08	0.15	0.03	0.02
c2	0.03	0.02	0.03	0.02	0.11	0.13	0.03	0.17	0.03	0.03
c3	0.02	0.02	0.02	0.02	0.02	0.15	0.06	0.04	0.02	0.03
d1	0.03	0.03	0.06	0.07	0.09	0.14	0.13	0.19	0.05	0.16
d2	0.03	0.04	0.06	0.05	0.10	0.16	0.16	0.22	0.18	0.04

Table 4.5 Summary of DEMATEL prominence and relation

	D	*R*	*D* + *R*	*D* − *R*
a1	2.04	0.50	2.54	1.54
a2	1.86	0.62	2.48	1.25
b1	1.46	0.84	2.30	0.62
b2	1.20	0.79	1.99	0.41
b3	0.96	1.12	2.08	−0.17
c1	0.44	1.90	2.34	−1.47
c2	0.60	1.11	1.71	−0.51
c3	0.41	2.13	2.54	−1.72
d1	0.94	1.03	1.97	−0.10
d2	1.03	0.88	1.90	0.15
Ave.	1.09	1.09	2.18	0.00

the sum of the values in the row of the influential coefficients for air and water pollution (b1), where $D_3 = 0.09 + 0.09 + 0.06 + \cdots + 0.30 + 0.09 + 0.08 = 1.46$, and R_3 represents the sum of the values in the row of the influential coefficients of the air and water pollution (b1), where $R_3 = 0.17 + 0.15 + 0.69 + \cdots + 0.02 + 0.06 + 0.06 = 0.84$. Table 4.5 shows the values of *Di*, *Rj*, (*D* + *R*), and (*D* − *R*) of the remaining criteria. In addition, Fig. 4.2 illustrates a distribution diagram for the 10 criteria; in the diagram, the prominence and relation are adopted as the *x* and *y* axes, respectively.

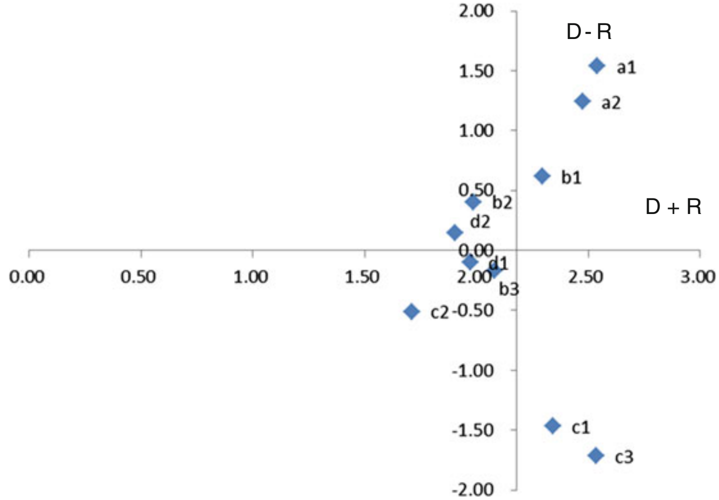

Fig. 4.2 DEMATEL distribution diagram for the 10 criteria

4.4.3 Discussion

This study classified the 10 research criteria using ($D - R$; relation) and ($D + R$; prominence). The results shown in Table 4.5 and Fig. 4.2 were evaluated and a detailed discussion involving the mutual influence and causal relationships of the 10 criteria is provided subsequently.

1. High Relation, High Prominence: The criteria in this classification include green design (a1), green material procurement (a2), and air and water pollution (b1). These criteria are attributed to the cause group. They are the core criteria influencing the other criteria, and are the driving factors for solving problems.
2. High Relation, Low Prominence: The criteria in this classification include green marketing (c1) and green image (c3). These criteria influence several of the other criteria, at a relatively low degree.
3. Low Relation, High Prominence: The criteria in this classification include waste pollution (b2) and product recycling (d2). These criteria are attributed to the effect group. They are influenced by the other factors and cannot be directly improved.
4. Low Relation, Low Prominence: The criteria in this classification include energy consumption (b3), green transportation (c2), and green packaging (d1). These criteria are influenced only slightly by other criteria, indicating that these criteria are relatively independent.

4.5 Conclusion

A considerable limitation exists in previous research conducted on GEP in that past studies have typically assumed that evaluation criteria were mutually independent, did not mutually influence each other, and did not possess causal relationships. These assumptions consequently hindered the advancement of corporate GEP evaluation.

The present study employed the DEMATEL method to evaluate the EPE of manufacturing enterprises. The DEMATEL model can accurately calculate the degree of influence and causal relationships among the GEP measurement criteria.

In this study, the results obtained by analyzing the degree of influence and causal relationship indicate that green development and GP are the key dimensions influencing the other dimensions, and are the driving factors for solving problems. Through analysis and discussion, this study concludes that the green design (a1) criterion within the green development dimension is a core criterion that can be proactively developed by enterprises into business strategies to improve their GEP. In addition, the green material procurement (a2) criterion is another aspect enterprises can emphasize. Enterprises should implement green concepts by insisting on purchasing green materials from suppliers when selecting materials for product production. Within GSCs, the green materials provided by suppliers assist manufacturers in improving their environmental performance. Manufacturers actively invest research and development as well as environmental protection funds in the air and water pollution (b1) criterion within the GP dimension to improve their GEP by reducing air and water pollution conditions.

The green design (a1), green material procurement (a2), and air and water pollution (b1) criteria are the key factors for solving problems, implying that improving these criteria also increases the performance levels of the other evaluation criteria.

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Chapter 5
A Simulation Study on Bullwhip Effect in Supply Chain Based on Theory of Constraint

Amir Hossein Azadnia, Mazaher Ghorbani and Seyed Mohammad Arabzad

Abstract TOC offers a proposal that is complementary in many aspects and very distinguishable in others about the way some key processes and elements of supply chain management (SCM) are managed, especially outbound logistics. This chapter deals with the paradigm that "TOC diminishes the forecasts in supply chain management by its buffer management strategy to handle difficulties". Developing a model and examining it with simulation is helpful to investigate and evaluate the contribution of TOC to supply chain management. To our knowledge, the proposed basic model is the first model to consider such viewpoints by TOC and opens new doors to more research on this area.

5.1 Introduction

Over the past two decades, practitioners and researchers alike have reacted to changing needs within the manufacturing industry. Increased competition in both domestic and foreign markets coupled with increasing scarcity of resources prompted us to re-examine how we manage our manufacturing processes. Over these two decades, terms such as manufacturing resource planning (MRP), just-in-time (JIT), and theory of constraints (TOC) and more recently enterprise resource

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planning (ERP), six sigma, and supply chain management (SCM) have entered our vocabulary to help us explain what is happening in our plants and how to effectively manage these new forces.

Two specific manufacturing philosophies TOC and SCM and their respective systems have received significant attention in the academic literature as well as in real industry around the world. In the last decade, the need for regional warehouses stemmed from the need to supply the market very quickly. As competition became keener, companies were plagued by the fluctuations in demand and inevitably present inventory management challenges of the right inventory in the right place at the right time. Therefore, an effective inventory replenishment method was needed in the supply chain to achieve low inventory while maintaining high customer delivery performance (Wu et al. 2012). The need motivated the researchers to integrate a philosophy of TOC proposed by Goldratt (1990) as a method to inventory control by SCM.

The theory of constraints supply chain replenishment system (TOC-SCRS) is one of the effective inventory replenishment methods utilized in the industry. The TOC-SCRS is now being implemented by a growing number of companies. The performance reported by the implemented companies includes reduction of inventory level, lead-time and transportation costs and increasing forecast accuracy and customer service levels (Hoffman and Cardarelli 2002; Watson and Polito 2003; Belvedere and Grando 2005; Tsai et al. 2008; Wu et al. 2010). The TOC-SCRS has also been considered frequently as an important research issue. Xu (2010) reviewed the applications of TOC in different business areas such as production, distribution, project management, performance measurement, and especially in SCM. Dos Santos et al. (2010) described an alternative TOC approach to SCM, which uses Vendor Managed Inventory (VMI) and Business-to-Business (B2B) to minimize the bullwhip effect and inventory levels therefore as a supply chain performance improvement. The proposed approach was illustrated by means of a real case study in a Brazilian middle size company, related to the small appliances production. Leng and Wang (2012) proposed an allocation procedure in SCM between one supplier and multiple retailers based on TOC in face of meeting peak demand in certain period for the whole supply chain. The Genetic algorithm (GA) has been selected in solving the optimal model in their work. Wu et al. (2013) proposed an evaluation and enhancement model to release the inventory shortage occurrence during the replenishment frequency conversion periods. They claimed that employing the proposed methodology will facilitate a plant to successfully implement an effective TOC-SCRS. Jiang et al. (2013) proposed a diverse replenishment frequency model for TOC–SCRS with capacity constraints so that the replenishment frequency will only moderately increase in inventory. They believed that the proposed model will enable a plant or a central warehouse to successfully implement an effective TOC–SCRS. Jiang and Wu (2013) presented a novel approach to solve the conflict problem between setup frequency and production quantity by using particle swarm optimization and genetic algorithms. An optimization approach that consists of two optimization stages was constructed to realize high production quantity and fast setup frequency for TOC-SCRS with capacity constraints.

In recent years, simulation technique has been frequently used to deal with the TOC-SCRS problem. Wu et al. (2010) developed an enhanced simulation replenishment model for TOC-SCRS under capacity constraint. They claimed that employing the proposed methodology will facilitate a plant or a central warehouse to successfully implement an effective TOC-SCRS. Kaijun and Yuxia (2010) proposed three different inventory control policies based on TOC buffer management framework. They used simulation approach to compare them with traditional adaptive (s, S, T) policy. The computational results indicated how specific problem characteristics influence the performance of whole system and demonstrate the efficiency of the proposed control policy. Tabrizi et al. (2012) considered a supply chain consisting of a manufacturer and a retailer for which both are implementing the buffer management based on the concept of TOC. They discussed how the vendor and the retailer can take advantage of demand information created by buffer management, through a process of bargaining, to coordinate their supply chain and increase their profitability. To do so, they have simulated the buffer management process and used response surface methodology (RSM) to obtain each party's profit function. Wu et al. (2013) firstly reviewed and modeled the concept and method of TOC-SCRS. A virtual supply chain case was secondly designed to show the behavior of the TOC-SCRS. A three factorial experiment, i.e., fluctuation of demand, time of replenishment and frequency of replenishment, was then presented to explore the feasibility and effectiveness of TOC-SCRS. Finally, a simulation model was designed to complete the experiment.

This paper is based on a proposed solution by TOC to bullwhip effect in supply chain. The objective of the paper is to study how the proposed ordering policy can control bullwhip effect. We identify equations according to the TOC ordering policy. Then, by increasing demand fluctuations in the supply chain, the bullwhip effect is explored and efficiency and effectiveness of such systems is evaluated. To best of our knowledge, none of the research papers deal with this problem. Also, considering demand fluctuations, a trade-off between costs related to holding inventory, which is due to the buffer management system proposed by TOC, and mitigating the bullwhip effect can be achieved. There is also a potential direction to extend this study and compare it with other ordering policies in supply chain to get better insight about the proposed TOC solution for bullwhip effect.

5.2 TOC Replenishment Policy

A supply chain is a set of nodes which consist of production plants (PP), central warehouse (CW), regional warehouses (RW) and points of sales (POS), as shown as Fig. 5.1. The chain links supplies and customers, beginning with the production of products by a supplier, and ending with the consumption of a product by the customer (Beamon 1998).

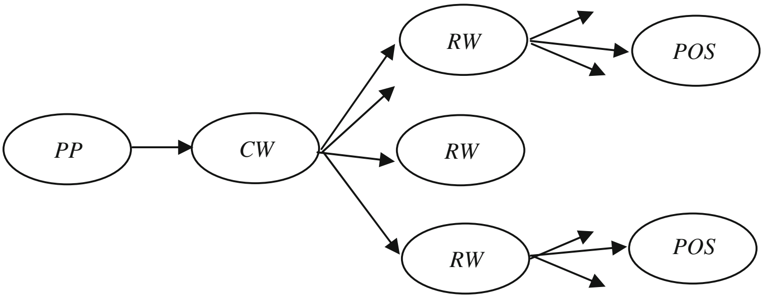

Fig. 5.1 A typical supply chain structure (Beamon 1998). *Note PP* production plant; *CW* central warehouse; *RW* regional warehouse; *POS* point of sale

An effective inventory replenishment method employed in the supply chain is one of the key factors to achieving low inventory while maintaining high customer delivery performance. An effective replenishment method should resolve the following three basic issues: (1) how often the inventory status should be determined? (2) when a replenishment order should be placed? and (3) how large the replenishment order should be? Replenishment methods proposed in the traditional inventory theory can be classified as either continuous review systems [(s, S) or (s, Q) policy] or periodic review systems [(R, S) or (R, s, S) policy] (Silver et al. 1988). However, researches report that order based on these replenishment methods swing due to downstream supply chain partners' fluctuation of demand. The swing is amplified as the order moves up to the supply chain. This phenomenon of demand amplification is named as bullwhip effect. Bullwhip effect causes excessive inventory, loss of revenue, and inaccurate production plans throughout supply chain systems (O'Donnell et al. 2006). The improvement of bullwhip effect in a supply chain is a key challenge for a manager. The TOC-SCRS is one of the solutions for the improvement of the bullwhip effect in a multi-echelon supply chain (Smith 2001; Yuan et al. 2003; Simatupang et al. 2004).

The TOC-SCRS is based on the following two strategies to decouple the bullwhip effect (or excess inventory in each node) and maintain the inventory availability to consumers (previous nodes), as shown in Fig. 5.2: (1) each node holds enough stock to cover demand during the time it takes to reliably replenish. (2) Each node orders only to replenish what was sold (Cole and Jacob 2002).

Under the TOC-SCRS mechanism, each sale point has stored the largest inventory that was occurred during the replenishment period, and the volume lies in the sales quantity between the two replenishment periods, hence we can be certain that the sale point has the lowest inventory. And under the Buffer Management mechanism, impacts caused by unexpected situations are to be determined, and request of emergency replenishment will be alerted if necessary, as a result, out of stock can be avoided.

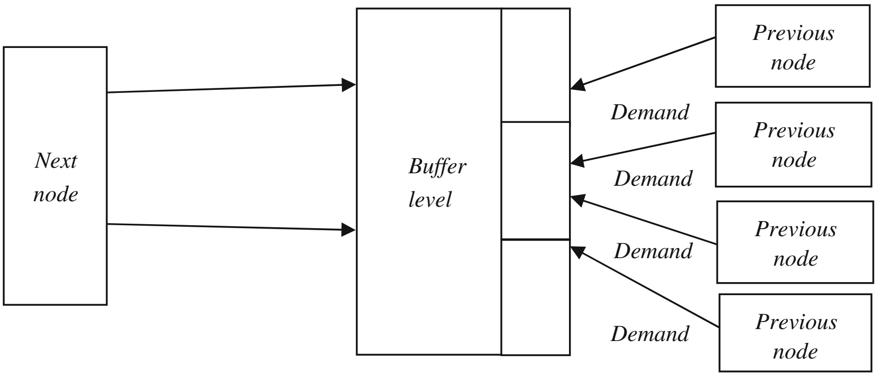

Fig. 5.2 The basic concept of TOC-SCRS (Cole and Jacob 2002)

5.3 Dynamic Buffers Management (DBM)

Thus, the supplier uses buffer management to control buffer size adjustments. Corrective action is taken to decrease or increase the buffer whenever required. Because the buffer size reflects the consumption pattern, the supplier should monitor the consumption of the buffer to determine appropriate actions (Simatupang et al. 2004). Such adjustments are made using the dynamic buffer management (DBM) technique.

According to DBM, stock buffers should be divided into three initially equal areas called green, yellow and red areas. Depending on the dynamic behavior of on-hand stock, DBM establishes some criteria to adjust the replenishment level (Simatupang et al. 2004; Umble and Umble 2002; Goldratt and Goldratt 2007). Yuan et al. (2003) offer some interesting contributions to the DBM technique. Most of the time, on-hand stock would be significantly lower than the replenishment level. At the same time, it would be expected to be above a certain level, below which it would be considered as almost losing sales. Thus, the three zones of replenishment level can be defined as follows (Goldratt and Goldratt 2007):

1. Green: where the on-hand stock is close to the theoretical maximum;
2. Yellow: the intermediate level, where the normal on-hand stock should be; and
3. Red: where there is a risk of the impossibility of delivering the entire demand.

If the on-hand stock level has penetrated the red area too deeply during a period equal to the replenishing time, the target should be increased. Conversely, if the on-hand stock level is always within the green area during a period equal to the replenishing time, the target level should be reduced. Except in special cases, such a reduction or increase should be done by subtracting or adding to the replenishment level an amount equivalent to an entire area, i.e. one-third (33 %) of the target level (Goldratt and Goldratt 2007).

According to DBM, shortages are avoided not only by adjusting buffers levels, but also by taking accelerated actions whenever an almost losing sales situation is identified. When the red level is reached, actions should be taken not to endanger product availability. The idea behind DBM can be summarized as the identification of situations where the planned protection is almost exhausted. Once such a local case is identified a warning is issued, causing high priority to be given to the problematic orders and then using the rest of the protection to remedy the disruption. Almost exhausting the protective buffer means very low on-hand stock (penetration into the red zone) to the point that it could be totally depleted before the arrival of replenishments. Once the red zone has been penetrated, the supplier should take action to speed up the replenishment until the buffer has returned to the top of the green zone (Schragenheim 2002). The justification for such hastening actions is that any increase in costs would be more than offset by the increase in throughput of the SC. The objective of DBM, however, is not to increase sales solely by reducing shortages, but also by reducing excess stock kept in the system. The throughput orientation is visible here, as well. The main effect resulting from the elimination of excess stock, from the TOC standpoint, is the increase in sales and not the welcome reduction of costs.

5.4 The Model of TOC-SCRS

In this stage, a mathematical modeling is proposed to control inventory and reduce the bullwhip effect based on the philosophy of TOC. The flow diagram of goods and information has shown as Fig. 5.3.

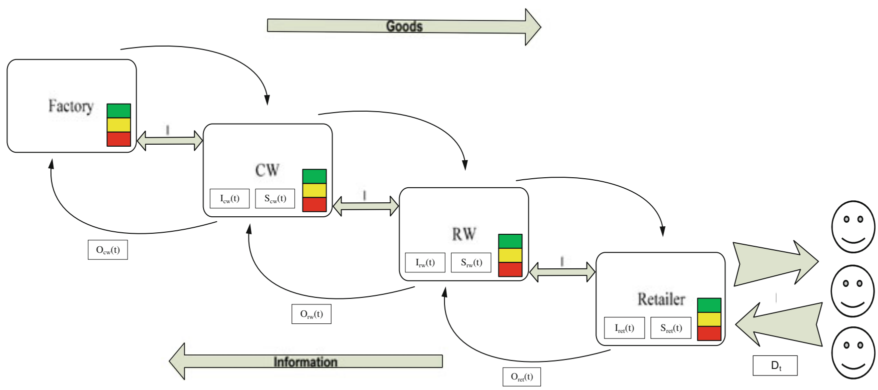

Fig. 5.3 The flow diagram of goods and information

5.4.1 Index Sets

i Index for echelons in supply chain $i \in CW, RW, Ret$
t Index for periods

5.4.2 Parameters

h_i^t Holding cost
B_i Buffer quantity
D^t Demand of final customer

5.4.3 Decision Variables

I_i^t Amount of Inventory
O_i^t Order quantity
X_i Zero-one variable

The model is presented as follows:

$$\min Z = \sum_{i,t} I_i^t h_i^t \tag{5.1}$$

$$I_{Ret}^t = I_{Ret}^{t-1} + O_{Ret}^{t-1} - D^{t-1} \tag{5.2}$$

$$I_{RW}^t = I_{RW}^{t-1} + O_{RW}^{t-1} - O_{Ret}^{t-1} \tag{5.3}$$

$$I_{CW}^t = I_{CW}^{t-1} + O_{CW}^{t-1} - O_{RW}^{t-1} \tag{5.4}$$

$$I_{Ret}^t \geq \frac{1}{3} B_{Ret} - \frac{1}{3} B_{Ret} \cdot X_{Ret} \tag{5.5}$$

$$I_{Ret}^t \leq \frac{1}{3} B_{Ret} + \frac{2}{3} B_{Ret} \cdot (1 - X_{Ret}) \tag{5.6}$$

$$O_{Ret}^t \geq \left(B_{Ret} - I_{Ret}^t\right) - B_{Ret} \cdot (1 - X_{Ret}) \tag{5.7}$$

$$I_{RW}^t \geq \frac{1}{3} B_{RW} - \frac{1}{3} B_{RW} \cdot X_{RW} \tag{5.8}$$

$$I_{RW}^{t} \leq \frac{1}{3} B_{RW} + \frac{2}{3} B_{RW} \cdot (1 - X_{RW}) \quad (5.9)$$

$$O_{RW}^{t} \geq \left(B_{RW} - I_{RW}^{t}\right) - B_{RW} \cdot (1 - X_{RW}) \quad (5.10)$$

$$I_{CW}^{t} \geq \frac{1}{3} B_{CW} - \frac{1}{3} B_{CW} \cdot X_{CW} \quad (5.11)$$

$$I_{CW}^{t} \leq \frac{1}{3} B_{CW} + \frac{2}{3} B_{CW} \cdot (1 - X_{CW}) \quad (5.12)$$

$$O_{CW}^{t} \geq \left(B_{CW} - I_{CW}^{t}\right) - B_{CW} \cdot (1 - X_{CW}) \quad (5.13)$$

The objective function (Eq. 5.1) minimizes the holding cost of the supply chain. Eqs. 5.2–5.4 are balance equations for inventory level in each echelon. Eqs. 5.5–5.13 determine that if inventory level is in the red area, according to the TOC replenishment policy, then order should release to avoid stock-out and otherwise, no order should be released.

5.5 A Numerical Example: A Simulation Study

We considered a simple example to illustrate the applicability of the proposed TOC-SCRS modeling to reduce the bullwhip effect of whole inventory in a ten-period horizon in a supply chain. Suppose a four-layer supply chain from factory to retailers in which three warehouses comprised of retailer, regional, and central are made to control the inventory (Fig. 5.3). The number of only one member for each of these layers has defined to simply illustrate the desire concept. The parameters of the example such as the determined buffer level, initial inventory, holding cost and demand has shown in the Table 5.1.

Table 5.1 The parameters

Warehouses	Buffer level	Initial inventory	Holding cost	Demand
Retailer warehouse	60	30	10	Uniform (20, 30)
Regional warehouse	150	75	10	–
Central warehouse	450	225	10	–

In order to solve the proposed TOC-SCRS modeling simulation study has done. Arena as most applicable and powerful simulation software has employed to solve the modeling with the parameters and variables in ten horizon times.

The result of solving the mathematical modeling with simulation has shown separately in Tables 5.2 and 5.3. These results are comprised of two outcomes of the orders' trend and the inventory level in time horizons. Figures 5.4 and 5.5 has also shown these trends schematically.

Table 5.2 The order's trend in time horizons

Warehouses	Time horizons									
	1	2	3	4	5	6	7	8	9	10
Retailer warehouse	28	28	21	25	22	30	29	28	27	25
Regional warehouse	0	53	0	46	0	42	0	50	0	54
Central warehouse	0	0	0	353	0	0	0	0	0	0

Table 5.3 The inventory level in time horizons

Warehouses	Time horizons									
	1	2	3	4	5	6	7	8	9	10
Retailer warehouse	30	7	36	14	39	18	39	10	35	6
Regional warehouse	75	75	22	150	104	104	62	62	12	150
Central warehouse	225	225	225	97	450	450	450	450	450	312

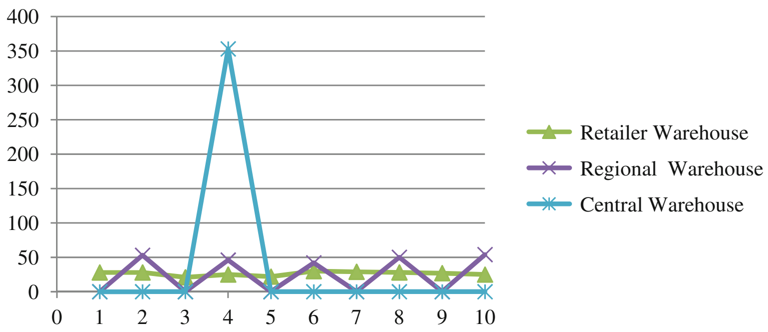

Fig. 5.4 The order's trend in time horizons

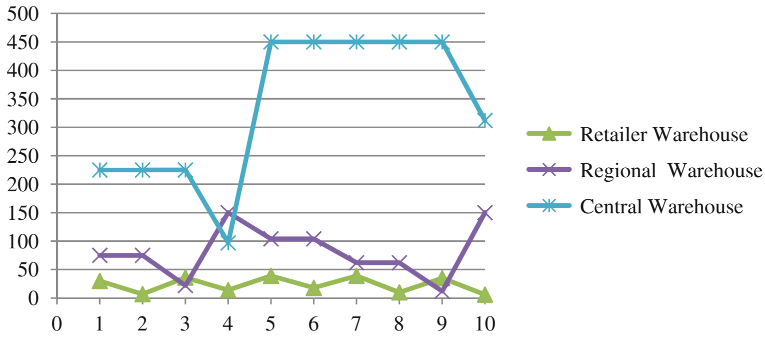

Fig. 5.5 The inventory level in time horizons

5.6 Conclusion

In this chapter, TOC-SCRS is modeled and evaluated using simulation. It is worth noting that this is the first basic model to examine the effect of TOC-SCRS on inventory level in echelons of supply chain. The basic model, considers a supply chain with a central warehouse (CW), regional warehouse (RW), retailer and customer. Dynamic buffer management proposed by TOC was evaluated via simulation and trends of orders and inventory in different periods can be examined to make management decisions in tactical and operational level. This is the beginning of the research on the TOC-SCRS. Further research can be done by considering the fluctuations of demand on inventory in different echelons of supply chain known as bullwhip effect. Simulation can help to determine the best buffer in the supply chain to reduce the costs and also satisfy demands. Another interesting topic is to evaluate the performance of this system and compare it with other management strategies in supply chain.

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Chapter 6
Mathematical Modelling with an Application to Nuclear Power Plant Reliability Analysis

Mangey Ram, Kuldeep Nagiya and Nupur Goyal

Abstract The safety performance of the nuclear power plant is the key factor in improving the nuclear energy option. Many incidents in the nuclear power plants are frequently caused by human error and equipment failure. Many of them outcome of poor managerial strategies. These types of errors could have been prevented if safety instructions had been correctly followed and supported in the maintenance system. The main aim of this chapter is to present a semi Markov model for nuclear power plant under human error, catastrophic failure and its parts failures. The main parts of a nuclear power plant are turbines, steam lines, steam generator, control rods in the reactor, pump for steams and cooling water and a generator for electricity. Although, a nuclear power plant has other components also in the said parts like steam dryers in steam lines, condenser tubes in cooling water systems, moisture separator reheaters in turbines, etc., even so, we have assumed that the main parts of the plant have failed partially due to the minor failure of its components. So, the nuclear power plant can be failed partially due to the failure of turbines, steam lines, steam generator, control rods in the reactor, pump for steams and cooling water and a generator for electricity. As well as plant can fail completely due to the human error and the catastrophic failure. The failure and repair times follow exponential and general time distribution respectively. Using the Laplace transformations and Markov process theory, the reliability indices of the power plant model are determined.

6.1 Introduction

The safe and economic process of a nuclear power plant (NPP) requires that the plant to be connected to an electrical grid system that has a suitable capacity for disseminating the power from nuclear power plant and for providing a reliable

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electrical power supply to the NPP for the safe start up, operation and normal or emergency shutdown of the plant. The NPP generates heat continuously even after reactor shutdown, it is the most important characteristic of the NPP. Presently, NPP delivers approximately 13 % of electrical power worldwide and has developed as a reliable base load source of electricity. The environmental maintainability indicator much affected by the safety of the NPP.

Conventional reliability theory deliberates the suppositions of the probability theory and the binary states of a component or sub-systems of the system as operational or failed. Recently, stochastic process has tremendous growth to model the basic scenario in reliability theory. In order to intensify the efficiency of a system, a unit of the system which has failed is renewed by replacing or repaired. Researchers and practitioners have much attention in modelling the reliability of repairable system. A system is called a repairable system which, after failure to perform at least one of its required operations, can be restored to performing all of its required functions satisfactorily by any method, other than the replacement of the entire system (Achcar and Feingold 1984). High reliability is one of the main goals of the design and the operation of control sub-systems in NPPs.

Many researchers have done a lot of work on nuclear power plant. Lal (1978) extended the formulation for nuclear radiation to study the displacement damage due to different types of radiation environments and recovery rates. A nuclear radiation environment may consist of two types of radiation, viz. electromagnetic waves and particles, and their effects can be broadly classified as displacement effects and ionization which are due to the atomic and electronic processes respectively. Traditional analog-based instrumentation and control systems in NPPs have been replaced with modern digital based instrumentation and control systems. However, the different characteristics of these systems make such assessments very difficult. A key difference between digital and analog systems is in the architecture (Lee et al. 2006). Ozkaynak (1979) presented a nuclear safety system that promises a great reduction in the unavailability of conventional systems of compatible arrangement using four principal design approaches. The first is the employment of solid state devices throughout the system for achieving a better reliability; the second involves the application of sequential redundancy, the third approach employs the concept of cellular automata in failure detection and switching functions and the fourth design approach provides an automatic shift from 2-out-of-3 to 2-out-of-2. Brooks (1984) presented a technique for systematically identifying the areas in which measures to improve plant availability. The task of reliability assessment and improvement for large equipment and systems possess some difficult problems. In the reliability improvement area, a system designer can recommend components that would give higher reliability for the given conditions to assure the reliability of a critical area in a particular design (Hashmi 1978). Volkanovski (2008) developed a method for evaluation of reliability of the power system includes identification of the weak points in the system. The network significance processes the most important elements or group of elements for the power system reliability. Electrical power is needed for most or all safety functions depending on the plant design. The vital safety functions of a nuclear reactor safety system\identified (International Atomic Energy Agency 2000), are control of reactivity; transport of heat from the core; confinement of radioactive materials; control of operational discharges; limitation of accidental releases. The economics of power generation with nuclear power are currently supplying a substantial fraction of power in many countries; increasing attention is being paid to improving the plant availability. Arun Babu et al. (2012) discussed a theoretical approach combining software verification and alteration testing to quantify the software reliability in nuclear safety systems and resulted that the software reliability depends on three factors: the test adequacy, the amount of software verification and the reusability of verified code in the software. Nevertheless, the current licensing procedure for computer based systems is based on deterministic norms. Unlike hardware reliability, the software reliability is not a pure function of time. Software failures are the result of design faults which are often difficult to imagine, categorize, identify, and repair (Lyu 1995).

In this work, the authors have proposed a semi Markov model taking care of the main failures of a NPP. Further, the reliability, availability and expected profit have been analysed to examine the performance of NPP system.

6.2 Assumptions

The following assumptions are associated with the designed model:

(i) Initially, the NPP is in good working condition.
(ii) At any time, the NPP is in any specific states covering good, degraded and failed.
(iii) The NPP may work with reduced efficiency.
(iv) The failure and repair times follow exponential and general distribution respectively (Gupta and Agarwal 1984).
(v) Only one transition is allowed at one time.
(vi) Sufficient repair facilities are available.
(vii) After repair, the NPP works like a new one.

6.3 Notations

The Table 6.1 shows the notations used in the proposed model.

Table 6.1 Notations

t	Time scale
s	Laplace transform variable
$\bar{P}(s)$	Laplace transformation of $P(t)$
$\lambda_R/\lambda_{WP}/\lambda_H/\lambda_C/\lambda_T/\lambda_{SG}/\lambda_G/\lambda_{CR}$	Failure rates of reactor/water pump/human error/catastrophic failure/turbine/steam generator/generator for electricity/condenser
$\mu(x), \xi(x)$	Repair rates for the degraded state and failed state respectively
$P_0(t)$	The probability of the good stage at time t
$P_1(t)$	The probability of the stage at time t when the turbine has been failed
$P_2(t)$	The probability of the stage at time t when the steam generator has been failed
$P_3(t)$	The probability of the stage at time t when generator for electricity has been failed
$P_4(t)$	The probability of the stage at time t when condenser has been failed
$P_5(x, t)$	The probability density function that the NPP is in the state, when reactor of power plant has been failed, at epoch t and has an elapsed repair time of x
$P_6(x, t)$	The probability density function that the NPP is in the state, when water pump has been failed, at epoch t and has an elapsed repair time of x
$P_7(x, t)$	The probability density function that the NPP is in the state, when NPP has been failed due to human error, at epoch t and has an elapsed repair time of x
$P_8(x, t)$	The probability density function that the NPP is in the state, when NPP is failed with catastrophic failure, at epoch t and has an elapsed repair time of x
$P_{up}(t)$	Availability of the NPP
$Rl(t)$	Reliability of the NPP
K_1, K_2	Revenue and service cost per unit time respectively

6.4 System (NPP) Description

In nuclear power technology, India becomes a world trailblazer due to its proficiency in fast reactors and thorium nuclear fuel cycle. A NPP is a thermal station in which nuclear reactors are a heat source. A nuclear reactor is the heart of the nuclear power plant. A nuclear reactor is a device to initiate and control a sustained nuclear chain reaction. In NPPs, different types of reactors, nuclear fuels and cooling circuits and moderators are used. The nuclear reactor most commonly used for the generation of electric energy. The NPPs are the complex system, which produces electrical energy based on the principles of the nuclear fission. Thermal energy produced by nuclear fuel in nuclear reactor transformed into electrical energy by

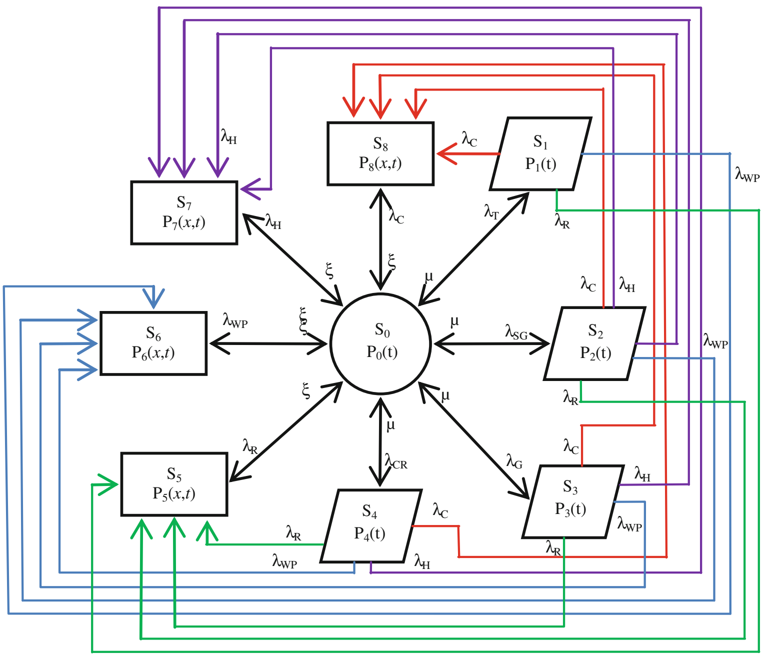

Fig. 6.1 Transition state diagram

steam turbines and generators. A catastrophic failure in such type of systems can exist for software failures. In this research, a complex NPP is modelled which covers three types of states good, degraded and failed. The plant goes to complete failed state with catastrophic failure, human failure, failure of the water pump and failure of the reactor while with the failure of turbine, steam generator, generator for electricity and condenser, it goes to degraded state means that partially failed state (Fig. 6.1).

The state transition diagram and their states described below:

State	Description
S_0	The NPP is in good working condition
S_1	The turbine of the NPP is failed
S_2	The steam generator of the NPP is failed
S_3	The generator for electricity in the NPP is failed
S_4	The condenser of the NPP is failed
S_5	The reactor of the NPP is failed
S_6	The water pump of the NPP is failed
S_7	The NPP is failed due to human error
S_8	The NPP is failed due to catastrophic failure

6.5 Formulation and Solution of the Model

By probability of considerations and continuity arguments, we can obtain the following set of difference differential equations governing the present mathematical model:

$$\left[\frac{\partial}{\partial t} + \lambda_T + \lambda_{SG} + \lambda_G + \lambda_{CR} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C\right] P_0(t) = \mu\{P_1(t) + P_2(t) + P_3(t) + P_4(t)\} + \int_0^\infty \{P_5(x,t) + P_6(x,t) + P_7(x,t) + P_8(x,t)\}\xi(x)dx \tag{6.1}$$

$$\left[\frac{\partial}{\partial t} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu\right] P_1(t) = \lambda_T P_0(t) \tag{6.2}$$

$$\left[\frac{\partial}{\partial t} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu\right] P_2(t) = \lambda_{SG} P_0(t) \tag{6.3}$$

$$\left[\frac{\partial}{\partial t} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu\right] P_3(t) = \lambda_G P_0(t) \tag{6.4}$$

$$\left[\frac{\partial}{\partial t} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu\right] P_4(t) = \lambda_{CR} P_0(t) \tag{6.5}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \xi(x)\right] P_5(x,t) = 0 \tag{6.6}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \xi(x)\right] P_6(x,t) = 0 \tag{6.7}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \xi(x)\right] P_7(x,t) = 0 \tag{6.8}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \xi(x)\right] P_8(x,t) = 0 \tag{6.9}$$

Boundary conditions

$$P_5(0,t) = \lambda_R\{P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t)\} \tag{6.10}$$

$$P_6(0,t) = \lambda_{WP}\{P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t)\} \tag{6.11}$$

$$P_7(0,t) = \lambda_H\{P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t)\} \tag{6.12}$$

$$P_8(0,t) = \lambda_C\{P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t)\} \tag{6.13}$$

Initially, $P_0(0) = 1$ and other state probabilities are zero at $t = 0$. Taking the Laplace transform of Eqs. (6.1)–(6.13)

$$\begin{aligned}&[s + \lambda_T + \lambda_{SG} + \lambda_G + \lambda_{CR} + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C]\overline{P}_0(s)\\ &= 1 + \mu\{\overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s)\}\\ &\quad + \int_0^\infty \{\overline{P}_5(x,s) + \overline{P}_6(x,s) + \overline{P}_7(x,s) + \overline{P}_8(x,s)\}\xi(x)dx\end{aligned} \tag{6.14}$$

$$[s + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu]\overline{P}_1(s) = \lambda_T\overline{P}_0(s) \tag{6.15}$$

$$[s + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu]\overline{P}_2(s) = \lambda_{SG}\overline{P}_0(s) \tag{6.16}$$

$$[s + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu]\overline{P}_3(s) = \lambda_G\overline{P}_0(s) \tag{6.17}$$

$$[s + \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C + \mu]\overline{P}_4(s) = \lambda_{CR}\overline{P}_0(s) \tag{6.18}$$

$$\left[s + \frac{\partial}{\partial x} + \xi(x)\right]\overline{P}_5(x,s) = 0 \tag{6.19}$$

$$\left[s + \frac{\partial}{\partial x} + \xi(x)\right]\overline{P}_6(x,s) = 0 \tag{6.20}$$

$$\left[s + \frac{\partial}{\partial x} + \xi(x)\right]\overline{P}_7(x,s) = 0 \tag{6.21}$$

$$\left[s + \frac{\partial}{\partial x} + \xi(x)\right]\overline{P}_8(x,s) = 0 \tag{6.22}$$

$$\overline{P}_5(0,s) = \lambda_R\{\overline{P}_0(s) + \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s)\} \tag{6.23}$$

$$\overline{P}_6(0,s) = \lambda_{WP}\{\overline{P}_0(s) + \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s)\} \tag{6.24}$$

$$\overline{P}_7(0,s) = \lambda_H\{\overline{P}_0(s) + \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s)\} \tag{6.25}$$

$$\overline{P}_8(0,s) = \lambda_C\{\overline{P}_0(s) + \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s)\} \tag{6.26}$$

After solving Eqs. (6.14)–(6.26), we get the state transition probabilities as

$$\overline{P}_0(s) = \frac{1}{(s + c_1 + c_2) - \frac{\mu c_2}{s+c_1+\mu} - \overline{S}_\xi(s)\left\{\frac{(s+c_1+c_2+\mu)c_1}{(s+c_1+\mu)}\right\}} \tag{6.27}$$

$$\overline{P}_1(s) = \frac{\lambda_T}{(s + c_1 + \mu)}\overline{P}_0(s) \tag{6.28}$$

$$\overline{P}_2(s) = \frac{\lambda_{SG}}{(s + c_1 + \mu)}\overline{P}_0(s) \tag{6.29}$$

$$\overline{P}_3(s) = \frac{\lambda_G}{(s + c_1 + \mu)}\overline{P}_0(s) \tag{6.30}$$

$$\overline{P}_4(s) = \frac{\lambda_{CR}}{(s + c_1 + \mu)}\overline{P}_0(s) \tag{6.31}$$

$$\overline{P}_5(s) = \frac{\lambda_R(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\left(\frac{1 - \overline{S}_\xi(s)}{s}\right)\overline{P}_0(s) \tag{6.32}$$

$$\overline{P}_6(s) = \frac{\lambda_{WP}(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\left(\frac{1 - \overline{S}_\xi(s)}{s}\right)\overline{P}_0(s) \tag{6.33}$$

$$\overline{P}_7(s) = \frac{\lambda_H(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\left(\frac{1 - \overline{S}_\xi(s)}{s}\right)\overline{P}_0(s) \tag{6.34}$$

$$\overline{P}_8(s) = \frac{\lambda_C(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\left(\frac{1 - \overline{S}_\xi(s)}{s}\right)\overline{P}_0(s) \tag{6.35}$$

where

$$c_1 = \lambda_R + \lambda_{WP} + \lambda_H + \lambda_C, \quad c_2 = \lambda_T + \lambda_{SG} + \lambda_G + \lambda_{CR}.$$

State transition probabilities of up state and down state system are

$$\begin{aligned}\overline{P}_{up}(s) &= \overline{P}_0(s) + \overline{P}_1(s) + \overline{P}_2(s) + \overline{P}_3(s) + \overline{P}_4(s) \\ &= \frac{(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\overline{P}_0(s)\end{aligned} \tag{6.36}$$

$$\begin{aligned}\overline{P}_{down}(s) &= \overline{P}_5(x,s) + \overline{P}_6(x,s) + \overline{P}_7(x,s) + \overline{P}_8(x,s) \\ &= \frac{c_1(s + c_1 + c_2 + \mu)}{(s + c_1 + \mu)}\left(\frac{1 - \overline{S}_\xi(s)}{s}\right)\overline{P}_0(s)\end{aligned} \tag{6.37}$$

6.6 Numerical Computation

6.6.1 Availability Analysis

Availability is one of the key metrics that demonstrates the overall performance of the system. Taking the failure rates as $\lambda_R = 0.001$, $\lambda_{WP} = 0.002$, $\lambda_H = 0.003$, $\lambda_C = 0.001$, $\lambda_T = 0.01$, $\lambda_{SG} = 0.02$, $\lambda_G = 0.02$, $\lambda_{CR} = 0.03$, and repair rates as $\mu = 1$, $\xi = 1$, putting all these values in (6.36). After taking the inverse Laplace transform, one can obtain the availability of the NPP system as

$$P_{up}(t) = e^{(-0.5035t)}[\cosh(0.5035t) + 0.9860973188\,\sinh(0.5035t)] \tag{6.38}$$

Now varying the time unit from 0 to 15 years (Hashmi 1978; Basu and Zemdegs 1978; Coudary and Mattei 1984) in (6.38), we get Table 6.2 and correspondingly Fig. 6.2.

6.6.2 Reliability Analysis

The reliability of the system can be interpreted as the probability that no transition occurs from the system success state to the system failure state (Kumar et al. 2009). Consider the repair rates zero and failure rates as $\lambda_R = 0.001$, $\lambda_{WP} = 0.002$, $\lambda_H = 0.003$, $\lambda_C = 0.001$, $\lambda_T = 0.01$, $\lambda_{SG} = 0.02$, $\lambda_G = 0.02$, $\lambda_{CR} = 0.03$. Putting all these values in (6.36) and taking the inverse Laplace transform, one may obtain

Table 6.2 Availability as function of time

Time (t)	Availability $P_{up}(t)$
0	1.00000
1	0.99559
2	0.99398
3	0.99339
4	0.99317
5	0.99309
6	0.99306
7	0.99305
8	0.99305
9	0.99305
10	0.99305
11	0.99305
12	0.99305
13	0.99305
14	0.99305
15	0.99305

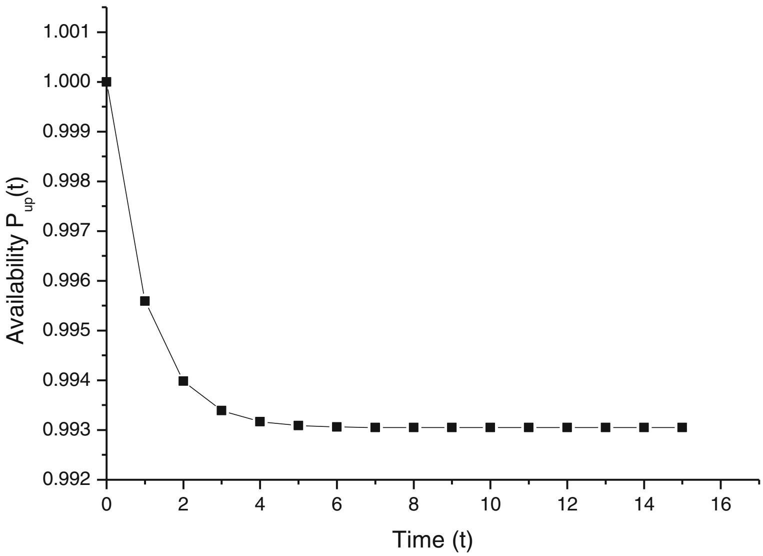

Fig. 6.2 Availability as function of time

$$Rl(t) = e^{(-0.007t)} \tag{6.39}$$

Now varying time unit t from 0 to 15 years (Hashmi 1978; Basu and Zemdegs 1978; Coudary and Mattei 1984) in (6.39), we get Table 6.3 and Fig. 6.3 which shows the reliability with respect to time.

6.6.3 Expected Profit

Expected profit is also much important aspect of reliability for the performance evaluation of the NPP system. Let the service facility be always available. For an industrial point of view, the expected profit during the interval [0, t) is given as:

$$E_P(t) = K_1 \int_0^t P_{up}(t)dt - tK_2 \tag{6.40}$$

Using Eq. (6.38) for a NPP system in (6.40), after integration we get,

$$\begin{aligned} E_P(t) = K_1\{&0.006903019464(\cosh(1.007t) + \sinh(1.007t) + 1) \\ &+ 0.9930486594t\} - tK_2 \end{aligned} \tag{6.41}$$

Table 6.3 Reliability as function of time

Time (t)	Reliability *Rl*(*t*)
0	1.00000
1	0.99302
2	0.98610
3	0.97922
4	0.97239
5	0.96560
6	0.95887
7	0.95218
8	0.94554
9	0.93894
10	0.93239
11	0.92589
12	0.91943
13	0.91302
14	0.90665
15	0.90032

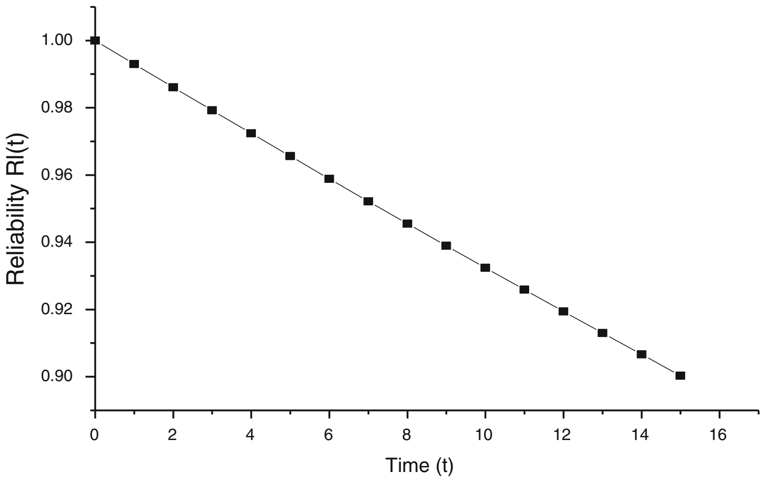

Fig. 6.3 Reliability as function of time

By fixing the value of $K_1 = 1$, and the value of K_2 varies as 0.1, 0.2, 0.3, 0.4 and 0.5 respectively in Eq. (6.41), one obtain Table 6.4 and Fig. 6.4 which represents the graph of expected profit with respect to time (Hashmi 1978; Basu and Zemdegs 1978; Coudary and Mattei 1984).

Table 6.4 Expected profit as function of time

Time (t)	Expected profit $E_p(t)$				
	$K_2 = 0.1$	$K_2 = 0.2$	$K_2 = 0.3$	$K_2 = 0.4$	$K_2 = 0.5$
0	0.00000	0.00000	0.00000	0.00000	0.00000
1	0.89743	0.79743	0.69743	0.59743	0.49743
2	1.79208	1.59208	1.39208	1.19208	0.99208
3	2.68571	2.38571	2.08571	1.78571	1.48571
4	3.57897	3.17897	2.77897	2.37897	1.97897
5	4.47210	3.97210	3.47210	2.97210	2.47210
6	5.36518	4.76518	4.16518	3.56518	2.96518
7	6.25824	5.55824	4.85824	4.15824	3.45824
8	7.15129	6.35129	5.55129	4.75129	3.95129
9	8.04434	7.14434	6.24434	5.34434	4.44434
10	8.93739	7.93739	6.93739	5.93739	4.93739
11	9.83044	8.73044	7.63044	6.53044	5.43044
12	10.72349	9.52349	8.32349	7.12349	5.92349
13	11.61654	10.31654	9.01654	7.71654	6.41654
14	12.50958	11.10958	9.70958	8.30958	6.90958
15	13.40263	11.90263	10.40263	8.90263	7.40263

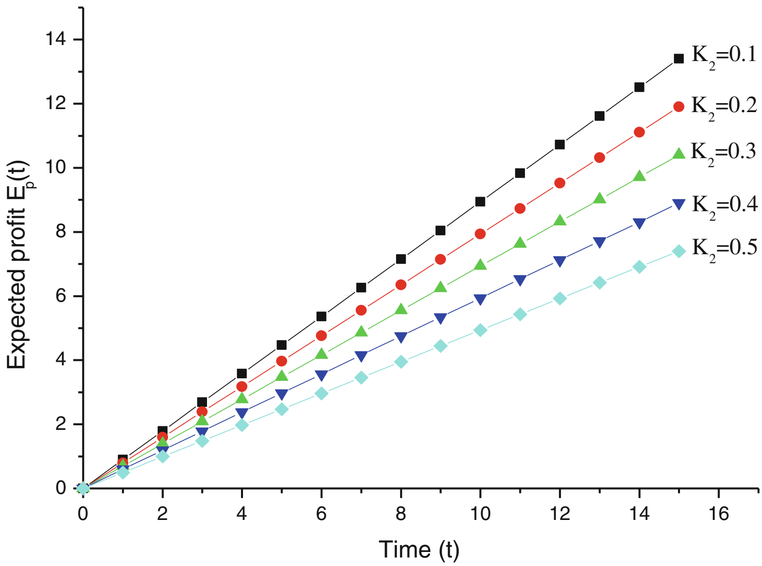

Fig. 6.4 Cost as function of time

6.7 Results Discussion

In this work, the availability, reliability and cost effectiveness of a nuclear power plant by using semi-Markov modelling have been analysed.

Table 6.2 gives the availability of the nuclear power plant with respect to time. Correspondingly Fig. 6.2 shows the graph of availability vs time and shows that availability of the designed NPP system is first decreased rapidly with respect to time, but after some time availability leads with smooth decrement with the increment of time and establishes at the value 0.99305.

From the critical examination of Table 6.3, one has an idea about the reliability of the NPP system. From Fig. 6.3, one can see that the reliability of the nuclear power plant decreases with the passes of time in an even manner and gives the reliability as a line graph.

Table 6.4 yields the expected profit of the nuclear power plant. Keeping the revenue fixed as 1 and varying the service cost as 0.1, 0.2, 0.3, 0.4, 0.5, one can obtain Fig. 6.4. From the graph of expected profit, one can realize that profit of the NPP system decreases as the service cost increases.

6.8 Conclusions

From the above discussion, it is concluded that the availability and reliability of the NPP decreases as time increases and controlling the service cost for attaining high profit is a must. With the help of this diligent reliability model, component or group of components that affect the system, can be recognized precisely. In the future, it is expected that the proposed reliability modelling can seek more applications in reliability engineering of nuclear power plant. Application of this study and results can facilitate a better understating between the parts of NPP system and improve the reliability measure for well performance of the NPP system. Furthermore, the results of this research are very helpful in nuclear power plant problems and useful for engineers or designers in performance related decision.

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Chapter 7
Gas Turbine Assimilation Under Copula-Coverage Approaches

Mangey Ram and Nupur Goyal

Abstract Reliability assessment has a major step towards the development of fault-tolerant system. In different fields of engineering and physical/ailed sciences, researchers or engineers have several reliability approaches for the better performance of the mechanical system. In this research work, the authors focus on the study of reliability of gas turbine. An efficient and reliable gas turbine plays a major role in the power generation as a back-up power plant. In addition to the reliability, authors also determined the mean time to failure subject to the each failure rate. This chapter models a simple gas turbine and formulated with the Markov Process and supplementary variable technique. The effects of failure rates and coverage factor in the performance of gas turbine have been discussed.

7.1 Introduction

Due to advance technology and progressive global demand for electrical energy production in the field of transportation, industry, power generation and other applications, the gas turbine has become an essential and widespread machine. The reliability of a gas turbine is a vital issue in the electrical energy production because it plays a crucial role in this scenario. It also affects the plant's economy because of the need of power, its reliability must but when power is unavailable, it must be generated or purchased, can be very costly (Giacomazzi 2013; Boyce 2012). The reliability of a gas turbine depends on many factors such as their components, human error, common cause failure and catastrophic failure. Gas turbine has some important components such as compressor, combustion, fuel, shaft, rotor and blades. It also depends on the preventive maintenance program, operating condition

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and control system. To achieve the high reliability authors tries to detect all the faults and covered it perfectly or imperfectly, and for the maintenance of gas turbine use Gumble–Hougaard family of the copula. Several authors, including Nelsen (2006) have studied the family of copulas extensively. The Gumbel–Hougaard family copula is defined as:

$$C_\theta(u_1, u_2) = \exp(-((-\log u_1)^\theta + (-\log u_2)^\theta)^{1/\theta}), \quad 1 \le \theta \le \infty$$

For θ = 1 the Gumbel–Hougaard copula models independence, for θ → ∞ it converges to comonotonicity. Ram and Singh (2008) developed a mathematical model of a parallel redundant complex system with two types of failure under a preemptive resume-repair discipline using Gumbel–Hougaard family copula in repair and obtained Laplace transforms of the transition state probabilities and other reliability characteristics of the system.

Research on reliability has a wide history. Many researchers have done a lot of work on reliability and/or gas turbine, using the coverage factor and/or copula, but no one found the reliability of the gas turbine with the consideration of each component and several failures. Tavner et al. (2007) discussed the reliability of modern repairable wind turbine and compared the results from two populations using grouped survey data from wind stats. They also analysed that how these results can be affected by turbine configuration, design, time, weather and maintenance. Watson (2004) studied the two technologies, combined cycle gas turbine and fluidised bed for power generation, and examined the success and failures of these, through economic, institutional and political vicissitudes. Author also demonstrated the benefits of CCGT for industries. Li (2002) introduced the comprehensive study of some methods based on performance analysis for gas turbine. Gas turbine diagnostics made a big breakthrough in the analysis of gas path. Bridgwater (1995) studied the biomass gasification for power generation and explained that how to prepare the gas from biomass and wood for gas turbine or jet engines technically through biomass. Author also discussed the costs and technologies involved in an integrated system for this manufacturer. Yang and Chen (1985) discussed the method to predict the fatigue reliability of gas turbine engine under the consideration service inspection maintenance. They studied about all the uncertainties occur in it, to improve the fatigue reliability.

To attain high reliability, fault coverage has been an essential architectural aspect in many critical applications of nuclear-powered systems (Pham 1993). Arnold (1973) implemented the concept of covered faults and gave the importance of such faults with respect to mean time to failure and mean time to repair. The author found that a very small percentage of uncovered faults may greatly reduce the reliability of a repairable system with one spare module. Bechta Dugan and Trivedi (1989) determined the coverage parameter in fault tolerant system for various models such as Markov, Semi-Markov, non-homogeneous Markov and stochastic Petri net. They also investigated the sensitivity of availability and reliability to the coverage factor, and sensitivity of coverage to various error-handling policies, and concluded that system dependencies are extremely sensitive to the coverage. Xing (2007) introduced methods to obtain the reliability of phased-mission systems (PMS) under the consideration of common-cause failure and coverage factor. The author gave some examples to explain the applications and advantages of these methods.

Goel et al. (1985) discussed the several reliability indices of a repairable man-machine with the supposition that the physical condition of the operator may affect the system's performance. They analysed the reliability measures by taking the human error into account. Human error is defined (Dhillon 1989; Dhillon and Yang 1995; Dhillon and Liu 2006) as the failure to accomplish a precise task that could associate with disturbance of planned procedures or outcome in destructing belongings and gears. There are many reasons for the happening of human errors, such as insufficient lighting in the work area, insufficient guidance or the ability of the manpower involved, deprived gear design, elevated noise levels, insufficient work arrangement, inappropriate tools, inadequately written equipment maintenance and working procedures. Ram et al. (2013) analysed the reliability measures of a two unit system, consisting one unit as standby assimilating the waiting time to repair by supplementary variable technique and Laplace transformation.

7.2 Mathematical Model Details

7.2.1 Notations

The notations used in this proposed work, are shown in Table 7.1.

7.2.2 Assumptions

This research work has the following hypotheses:

(i) Initially, all the components of the gas turbine are working properly.
(ii) The designed gas turbine model has three states, namely good, degraded and failed.
(iii) All the components can be repaired.
(iv) Sufficient repair facilities are available.
(v) Each component is either functional or failed.
(vi) Apiece sub-system has constant and identical failure rate.
(vii) Repair rates follow general and the exponential distribution.

7.2.3 System Description

In this chapter, authors designed a simple gas turbine on the basis of their working, by taking attention of different failures, occur in it. A simple gas turbine is a

Table 7.1 Notations

t/*s*	Time scale/Laplace transform variable
$\bar{P}(s)$	Laplace transformation of $P(t)$
c	Coverage factor
$\lambda_F/\lambda_R/\lambda_B/\lambda_{CT}/\lambda_S/\lambda_H/\lambda_{CC}/\alpha_1/\alpha_2/\beta_1/\beta_2$	Failure rates for fuel/rotor/blades/catastrophic failure/shaft/human error/common cause/compressor/standby of compressor/combustion/standby of combustion
$P_i(t)$	The probability of the state S_i, i = 0, 1, 2, 3, 9
$P_j(x, t)$	The probability density function of the state S_j, at epoch t and has an elapsed repair time of x respectively, j = 10, 11
$P_j(y, t)$	The probability density function of the state S_j, at epoch t and has an elapsed repair time of y respectively, j = 6, 7
$P_j(z, t)$	The probability density function of the state S_j, at epoch t and has an elapsed repair time of z respectively, j = 4, 5
$P_8(r, t)$	The probability density function of the state S_8, at epoch t and has an elapsed repair time of r respectively
$u_1 = e^z$, $u_2 = \eta(z)$	The joint probability (S_i to normal state S_0, i = 2–5) according to Gumbel-Hougaard family is given as: $\exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}}$
$u_1 = e^y$, $u_2 = \psi(y)$	The joint probability (failed state S_6, S_7 to normal state S_0) according to Gumbel-Hougaard family is given as: $\exp[y^\theta + \{\log \psi(y)\}^\theta]^{\frac{1}{\theta}}$
$u_1 = e^x$, $u_2 = \phi(x)$	The joint probability (failed state S_{10}, S_{11} to normal state S_0) according to Gumbel-Hougaard family is given as: $\exp[x^\theta + \{\log \phi(x)\}^\theta]^{\frac{1}{\theta}}$
$\mu(r)$	Repair rate for the states S_1, S_8
Rl(t)	The reliability of the system at time t

machine that converts air into mechanical energy. A gas turbine is divided into three main sections—compressor, combustor and power turbine. In compressor, compressor compressed the inlet air and passed it to the combustor. In the combustion chamber, some fuel is added to the compressed air and burnt it, produced heat is transferred to the power turbine. Power turbine is comprised by blades attached to the rotor. Here with the rotation of the rotor with specific shaped and sized blades, generate mechanical energy [www.massengineers.com]. In this process, gas turbine can be partially failed or completely failed, due to many failures such as equipment failure, standby failure, catastrophic failure, common-cause failure or human error. Authors repaired the partially or completely failed gas turbine by two types, general and exponential distribution. Repair rates are coupled with Gumble–Hougaard family of the copula in this work. The state transition diagram of the simple gas turbine with the failures and repairs is shown in Fig. 7.1 and the configuration diagram of gas turbine at which base state transition diagram is designed, is demonstrated in Fig. 7.2. The states of the gas turbine are described in Table 7.2.

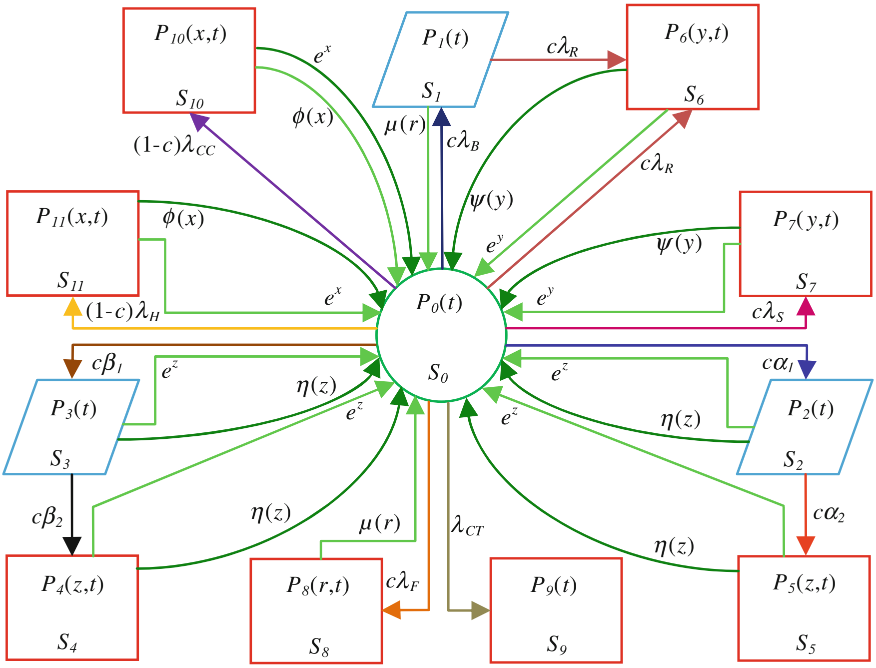

Fig. 7.1 State-transition diagram of gas turbine

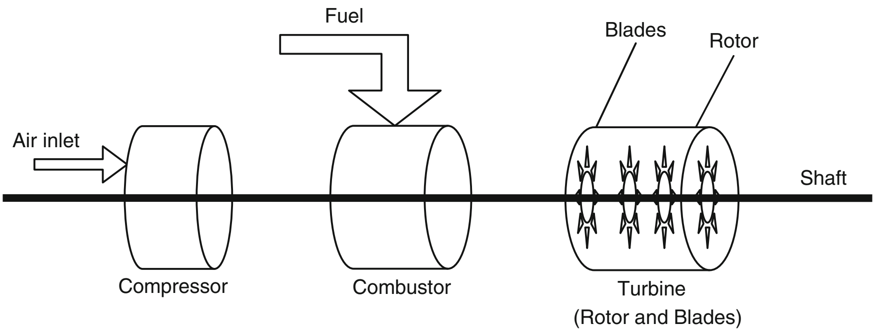

Fig. 7.2 Configuration diagram of gas turbine

7.2.4 Formulation of the Model

By the probability of consideration and continuity of arguments, we can obtain the following set of difference differential equations possesses the present mathematical model.

Table 7.2 State description

S_0	The gas turbine is in good working condition
S_1	The gas turbine is in the degraded state due to failure of the blades
S_2	The gas turbine is in the degraded state due to compressor failure
S_3	The gas turbine is in the degraded state due to combustor failure
S_4	The gas turbine is in the complete failed state due to the failure of standby for the combustor
S_5	The gas turbine is in the complete failed state due to the failure of standby for the compressor
S_6	The gas turbine is in the complete failed state due to rotor failure
S_7	State of the gas turbine when it is completely failed due to the shaft
S_8	State of the gas turbine when it is completely failed due to non-availability of the fuel
S_9	State of the gas turbine when it is completely failed due to catastrophic failure
S_{10}	The gas turbine is in the complete failed state due to common-cause failure
S_{11}	The gas turbine is in the complete failed state due to human failure

$$\begin{aligned}
&\left[\frac{\partial}{\partial t} + c(\beta_1 + \alpha_1 + \lambda_B + \lambda_R + \lambda_S + \lambda_F) + \lambda_{CT} + (1-c)(\lambda_H + \lambda_{CC})\right] P_0(t) \\
&= \mu_1 P_1(t) + \int_0^\infty \mu(r) P_8(r,t)dr + \int_0^\infty \exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}} [P_4(z,t) + P_5(z,t)]dz \\
&+ \int_0^\infty \exp[y^\theta + \{\log \psi(y)\}^\theta]^{\frac{1}{\theta}} [P_6(y,t) + P_7(y,t)]dy \\
&+ \exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}} (P_2(t) + P_3(t)) \\
&+ \int_0^\infty \exp[x^\theta + \{\log \phi(x)\}^\theta]^{\frac{1}{\theta}} [P_{10}(x,t) + P_{10}(x,t)]dx
\end{aligned} \tag{7.1}$$

$$\begin{aligned}
&\left[\frac{\partial}{\partial t} + (1-c)(\lambda_H + \lambda_{CC}) + c\alpha + \xi\right] P_i(t) = c\lambda_B P_0(t); \\
&i = 1,2,3;\ \alpha = \lambda_R, \alpha_2, \beta_2; \\
&\xi = \mu(r), \exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}}, \exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}}
\end{aligned} \tag{7.2}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial z} + \exp[z^\theta + \{\log \eta(z)\}^\theta]^{\frac{1}{\theta}}\right] P_i(z,t) = 0; \quad i = 4,5 \tag{7.3}$$

$$\left[\frac{\partial}{\partial t} + \frac{\partial}{\partial y} + \exp[y^\theta + \{\log \psi(y)\}^\theta]^{\frac{1}{\theta}}\right] P_i(y,t) = 0; \quad i = 6,7 \tag{7.4}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial r}+\mu(r)\right]P_8(r,t)=0 \tag{7.5}$$

$$\frac{\partial}{\partial t}P_9(t)=\lambda_{CT}P_0(t) \tag{7.6}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\exp[x^\theta+\{\log\phi(x)\}^\theta]^{\frac{1}{\theta}}\right]P_i(x,t)=0;\quad i=10,11 \tag{7.7}$$

Boundary conditions

$$P_i(0,t)=\alpha P_j(t);\quad i=4,5,\ldots,8;\ j=3,2,0,0,0;\ \alpha=c\beta_2,c\alpha_2,c\lambda_R,c\lambda_S,c\lambda_F \tag{7.8}$$

$$P_i(0,t)=(1-c)\alpha\sum_{j=0}^{3}P_j(t);\quad i=10,11;\ \alpha=\lambda_{CC},\lambda_H \tag{7.9}$$

Initial condition $P_0(0)=1$ and other state probabilities are zero at t = 0.

7.2.5 Solution of the Model

Taking the Laplace transformation of (7.1)–(7.9), we have

$$\begin{aligned}
&[s+c(\beta_1+\alpha_1+\lambda_B+\lambda_R+\lambda_S+\lambda_F)+\lambda_{CT}+(1-c)(\lambda_H+\lambda_{CC})]\overline{P}_0(s)\\
&\quad=1+\mu_1\overline{P}_1(s)+\int_0^\infty\mu(r)\overline{P}_8(r,s)dr+\exp[z^\theta+\{\log\eta(z)\}^\theta]^{\frac{1}{\theta}}(\overline{P}_2(s)+\overline{P}_3(s))\\
&\qquad+\int_0^\infty\exp[z^\theta+\{\log\eta(z)\}^\theta]^{\frac{1}{\theta}}[\overline{P}_4(z,s)+\overline{P}_5(z,s)]dz\\
&\qquad+\int_0^\infty\exp[x^\theta+\{\log\phi(x)\}^\theta]^{\frac{1}{\theta}}[\overline{P}_{10}(x,s)+\overline{P}_{10}(x,s)]dx\\
&\qquad+\int_0^\infty\exp[y^\theta+\{\log\psi(y)\}^\theta]^{\frac{1}{\theta}}[\overline{P}_6(y,s)+\overline{P}_7(y,s)]dy
\end{aligned} \tag{7.10}$$

$$\begin{aligned}
&[s+(1-c)(\lambda_H+\lambda_{CC})+c\alpha+\xi]\overline{P}_i(s)=c\lambda_B\overline{P}_0(s);\quad i=1,2,3;\ \alpha=\lambda_R,\alpha_2,\beta_2;\\
&\quad\xi=\mu(r),\ \exp[z^\theta+\{\log\eta(z)\}^\theta]^{\frac{1}{\theta}},\ \exp[z^\theta+\{\log\eta(z)\}^\theta]^{\frac{1}{\theta}}
\end{aligned} \tag{7.11}$$

$$\left[s+\frac{\partial}{\partial z}+\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}\right]\overline{P}_i(z,s)=0;\quad i=4,5 \tag{7.12}$$

$$\left[s+\frac{\partial}{\partial y}+\exp[y^{\theta}+\{\log\psi(y)\}^{\theta}]^{\frac{1}{\theta}}\right]\overline{P}_i(y,s)=0;\quad i=6,7 \tag{7.13}$$

$$\left[s+\frac{\partial}{\partial r}+\mu(r)\right]\overline{P}_8(r,s)=0 \tag{7.14}$$

$$sP_9(t)=\lambda_{CT}P_0(t) \tag{7.15}$$

$$\left[s+\frac{\partial}{\partial x}+\exp[x^{\theta}+\{\log\phi(x)\}^{\theta}]^{\frac{1}{\theta}}\right]\overline{P}_i(x,s)=0;\quad i=10,11 \tag{7.16}$$

$$\overline{P}_i(0,s)=\alpha\overline{P}_j(s);\quad i=4,5,\ldots,8;\ j=3,2,0,0,0;\ \alpha=c\beta_2,c\alpha_2,c\lambda_R,c\lambda_S,c\lambda_F \tag{7.17}$$

$$\overline{P}_i(0,s)=(1-c)\alpha\sum_{j=0}^{3}\overline{P}_j(s);\quad i=10,11;\ \alpha=\lambda_{CC},\lambda_H \tag{7.18}$$

After solving Eqs. (7.10)–(7.18), we get the Laplace transformation of state transition probabilities as

$$\overline{P}_0(s)=\frac{1}{D(s)} \tag{7.19}$$

$$\begin{aligned}\overline{P}_i(s)&=\frac{c\alpha}{s+(1-c)(\lambda_{CC}+\lambda_H)+c\beta+\xi}\overline{P}_0(s);\\ &\quad i=1,2,3;\ \alpha=\lambda_B,\alpha_1,\beta_1;\ \beta=\lambda_R,\alpha_2,\beta_2;\\ &\quad \xi=\mu(r),\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}},\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}\end{aligned} \tag{7.20}$$

$$\begin{aligned}\overline{P}_i(s)&=\varsigma\frac{c^2\alpha\beta}{s+(1-c)(\lambda_{CC}+\lambda_H)+c\beta+\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}}\overline{P}_0(s);\\ &\quad i=4,5;\ \alpha=\alpha_1,\beta_1;\ \beta=\alpha_2,\beta_2;\\ \varsigma&=\frac{1-\overline{S}_{\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s}\end{aligned} \tag{7.21}$$

$$\begin{aligned}\overline{P}_i(s)&=c\beta\varsigma\overline{P}_0(s);\quad i=6,7,8;\ \beta=\lambda_R,\lambda_S,\lambda_F;\\ \varsigma&=\frac{1-\overline{S}_{\exp[y^{\theta}+\{\log\psi(y)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s},\frac{1-\overline{S}_{\exp[y^{\theta}+\{\log\psi(y)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s},\frac{1-\overline{S}_{\mu}(s)}{s}\end{aligned} \tag{7.22}$$

$$\overline{P}_9(s) = \frac{\lambda_{CT}}{s}\overline{P}_0(s) \tag{7.23}$$

$$\overline{P}_i(s) = (1-c)\beta\varsigma\sum_{j=0}^{3}\overline{P}_j(s); \quad i = 10, 11;\ \beta = \lambda_{CC}, \lambda_H;$$

$$\varsigma = \frac{1-\overline{S}_{\exp[x^{\theta}+\{\log\phi(x)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s} \tag{7.24}$$

The Laplace transformation of the probability of upstate and downstate system

$$\overline{P}_{up}(s) = \sum_{j=0}^{3}\overline{P}_j(s) = K\overline{P}_0(s); \tag{7.25}$$

$$\begin{aligned}\overline{P}_{down}(s) = \sum_{j=4}^{11}\overline{P}_j(s) = \Bigg[&\left(\frac{1-\overline{S}_{\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s}\right)\\ &\sum_{\substack{\alpha\in\alpha_1,\alpha_2\\ \beta\in\beta_1,\beta_2}}\frac{c^2\alpha\beta}{s+(1-c)(\lambda_{CC}+\lambda_H)+c\beta+\exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}}\\ &+\frac{\lambda_{CT}}{s}+\left(\frac{1-\overline{S}_{\exp[x^{\theta}+\{\log\phi(x)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s}\right)\\ &(1-c)(\lambda_{CC}+\lambda_H)K+c\left(\frac{1-\overline{S}_{\mu}(s)}{s}\right)\lambda_F\\ &+c\left(\frac{1-\overline{S}_{\exp[y^{\theta}+\{\log\psi(y)\}^{\theta}]^{\frac{1}{\theta}}}(s)}{s}\right)(\lambda_R+\lambda_S)\Bigg]\overline{P}_0(s);\end{aligned} \tag{7.26}$$

where,

$$K = 1+\sum\frac{c\alpha}{s+(1-c)(\lambda_{CC}+\lambda_H)+c\beta+\xi}; \quad \alpha = \lambda_B, \alpha_1, \beta_1;\ \beta = \lambda_R, \alpha_2, \beta_2;$$

$$\xi = \mu(r), \exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}, \exp[z^{\theta}+\{\log\eta(z)\}^{\theta}]^{\frac{1}{\theta}}$$

7.3 Particular Cases

7.3.1 Reliability Analysis

System reliability is one of the fundamental quality characteristics which deal with the behaviour of each apparatus of the system. Reliability represents the probability of non-failure components, sub-systems and system to perform their required functions for a particular time period in specified environmental condition. Reliability does not account for any repair actions that may take place (Ram 2013; Avizienis et al. 2004). So, to determine the reliability of gas turbine, repair rates must be considered zero and setting the failure rates as $\lambda_F = 0.006$, $\lambda_R = 0.028$, $\lambda_{CT} = 0.015$, $\lambda_H = 0.015$, $\lambda_B = 0.042$, $\lambda_S = 0.005$, $\lambda_{CC} = 0.032$, $\alpha_1 = 0.045$, $\alpha_2 = 0.050$, $\beta_1 = 0.011$, $\beta_2 = 0.025$ in Eq. (7.25), by taking the inverse Laplace transformation, one obtains the reliability of the gas turbine as

$$\begin{aligned} Rl(t) = {} & \frac{15c}{29c+5} e^{(-0.001(47+3c)t)} + \frac{11c}{112c+15} e^{(-0.001(47+22c)t)} \\ & + \frac{(1125 + 54880c^2 - 275c^3 + 15750c)}{(29c+5)(112c+15)(15+109c)} e^{(-0.002(45c+31)t)} \\ & + \frac{42c}{109c+15} e^{(-0.001(47+19c)t)} \end{aligned} \tag{7.27}$$

After varying the time t from 0 to 100 and coverage factor c from 0.1 to 0.1.0, one can see the behavior of reliability with 3D graph in Fig. 7.3. Notations in Fig. 7.3 are considered as t represents time and c represents coverage factor.

7.3.2 Mean Time to Failure Analysis

Mean time to failure (MTTF) is the calculated elapsed time between natural failures of a system during operation. MTTF can be measured as the average time between

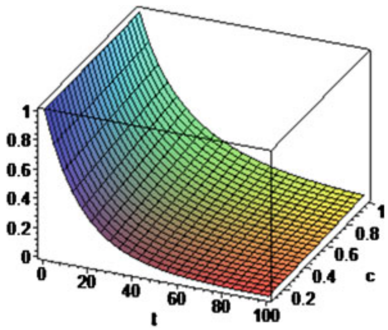

Fig. 7.3 Reliability with respect to t and c

failures of a gas turbine. Consider that the repair facility is not available, putting each repair rate zero and taking the limits of s tends to zero in Eq. (7.25), we can evaluate the mean time to failure of the gas turbine as

$$\begin{aligned} MTTF &= \lim_{s \to 0} \overline{P}_{up}(s) \\ &= \frac{1 + \sum \frac{c\alpha}{(1-c)(\lambda_H + \lambda_{CC}) + c\beta}}{c(\lambda_F + \lambda_R + \lambda_S + \lambda_B + \alpha_1 + \beta_1) + \lambda_{CT} + (1-c)(\lambda_{CC} + \lambda_H)}; \\ &\alpha = \lambda_B, \alpha_1, \beta_1;\ \beta = \lambda_R, \alpha_2, \beta_2 \end{aligned} \tag{7.28}$$

Now varying input parameters one by one at 0.01, 0.02, …, 0.09 respectively and setting the other failure rates as $\lambda_F = 0.006$, $\lambda_R = 0.028$, $\lambda_{CT} = 0.015$, $\lambda_H = 0.015$, $\lambda_B = 0.042$, $\lambda_S = 0.005$, $\lambda_{CC} = 0.032$, $\alpha_1 = 0.045$, $\alpha_2 = 0.050$, $\beta_1 = 0.011$, $\beta_2 = 0.025$, in (7.28), we can acquire the MTTF with respect to the variation of failure rates and coverage factor that signify by graphical representation shown in Fig. 7.4. Notations in Fig. 7.4 are considered as a represents λ_{CC}, b represents λ_H, $c1$ represents λ_R, f represents λ_B, g represents λ_S, $a1$ represents α_1, $a2$ represents α_2, $b1$ represents β_1, $b2$ represents β_2, h represents λ_F, l represents λ_{CT} and c represents coverage parameter.

7.4 Results Discussion

In this section, the authors debate the results of our prediction of reliability and mean time to failure for the designed gas turbine. The outcomes of our predictions are as follows:

The critical examination of Fig. 7.3 gives us an idea about the reliability of the gas turbine. This study tells us that the reliability of the gas turbine decreases continuously with the increment in time but due to fault coverage, the reliability of the gas turbine increases as coverage factor increases. The graphs demonstrated in Fig. 7.4, show the behaviour of MTTF of gas turbines with respect to each failure rate and coverage parameter. From the critical study of these graphs, authors conclude that MTTF of the gas turbine decreases with respect to each failure rate except the failure of blades, compressor and combustor while the MTTF of the gas turbine increases with respect to coverage parameter. Mean time to failure for gas turbine is approximately constant in case of failure of the compressor, combustor and their standby.

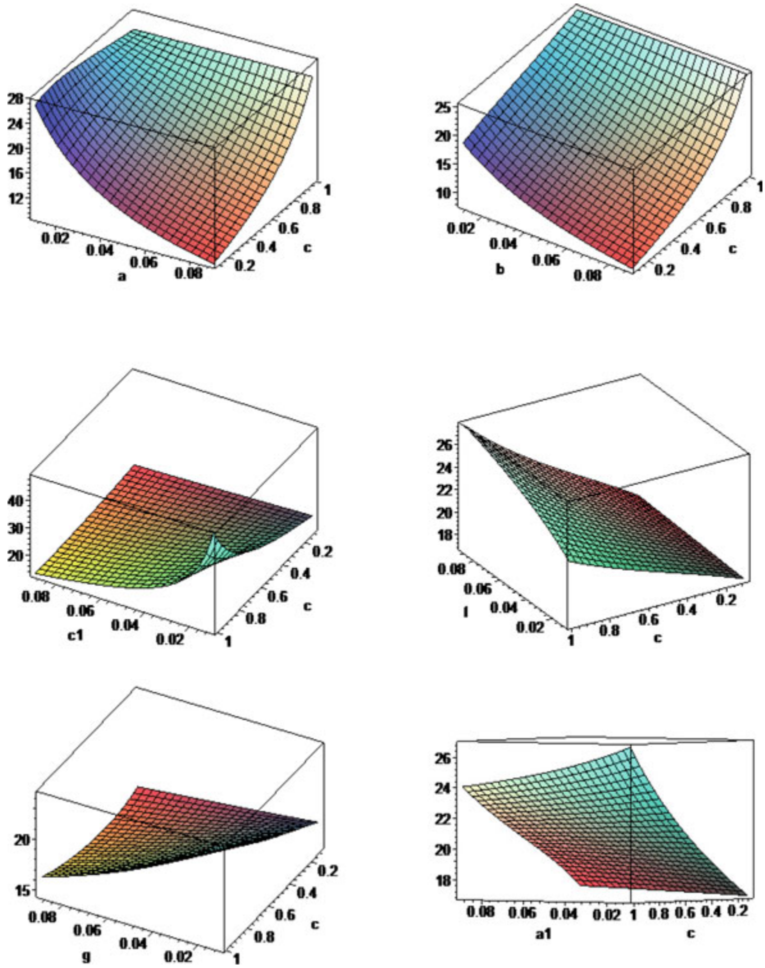

Fig. 7.4 MTTF with variation in failure rates and c

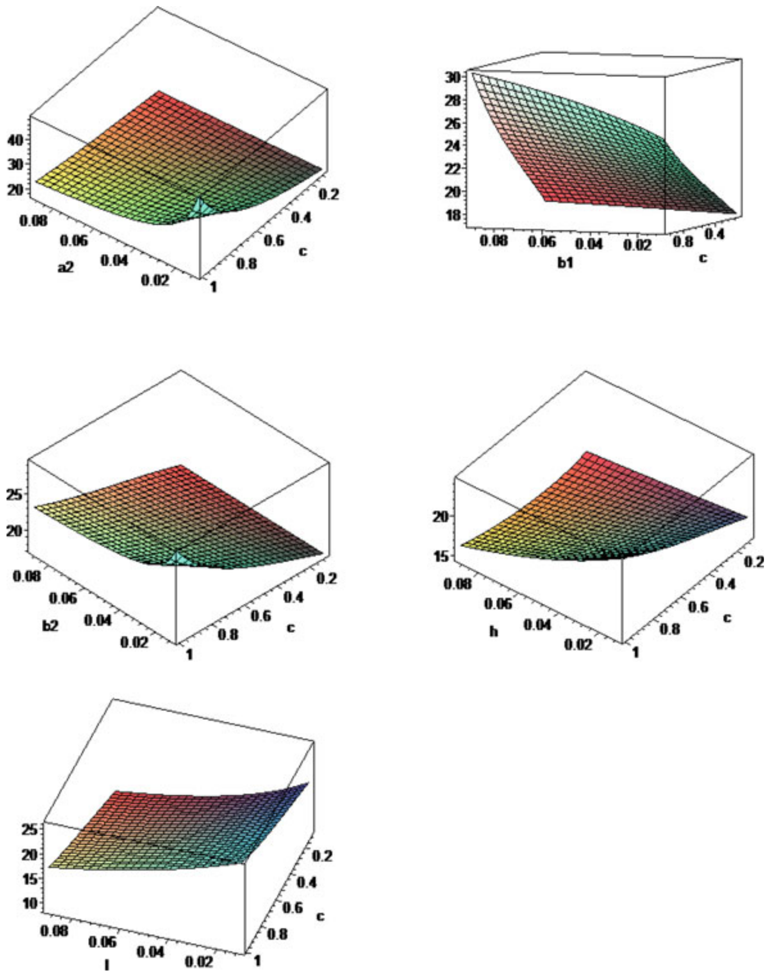

Fig. 7.4 (continued)

7.5 Conclusion

The authors summarise their study on gas turbine in this segment. In this chapter, authors emphasis on reliability evaluation of gas turbine because it affects the turbine's performance. The preliminary investigation is carried out to accomplish the reliability and MTTF of designed gas turbine system. The advantage of the proposed methodologies covered faults and Gumble–Hougaard family of copula are most significant in the reliability analysis of gas turbine. Under the consideration of these methodologies, one can attain a highly reliable gas turbine. To achieve a high reliable and available gas turbine, the designers and engineers must keep in mind many factors, some of the more important considerations which govern the design are shaped and size of blades, shaft, rotor, compressor, combustor and type of fuel. Furthermore, this study will be very helpful for designers and engineers to enhance the reliability of gas turbine.

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