Designing a support system for aerospace maintenance supply chains

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Abstract

Purpose – To develop a systems strategy for supply chain management in aerospace maintenance, repair and overhaul (MRO).

Design/methodology/approach – A standard systems development methodology has been followed to produce a process model (i.e. the AMSCR model); an information model (i.e. business rules) and a computerised information management capability (i.e. automated optimisation).

Findings – The proof of concept for this web-based MRO supply chain system has been established through collaboration with a sample of the different types of supply chain members. The proven benefits comprise new potential to minimise the stock holding costs of the whole supply chain whilst also minimising non-flying time of the aircraft that the supply chain supports.

Research limitations/implications – The scale of change needed to successfully model and automate the supply chain is vast. This research is a limited-scale experiment intended to show the power of process analysis and automation, coupled with strategic use of management science techniques, to derive tangible business benefit.

Practical implications – This type of system is now vital in an industry that has continuously decreasing profit margins; which in turn means pressure to reduce servicing times and increase the mean time between them.

Originality/value – Original work has been conducted at several levels: process, information and automation. The proof-of-concept system has been applied to an aircraft MRO supply chain. This is an area of research that has been neglected, and as a result is not well served by current systems solutions.

Keywords Maintenance, Supply chain management, Inventory, Aerospace industry

Paper type Research paper

Industrial research motivation

Three major changes should be taken into account when considering how to manage an airline fleet: business models, aircraft technology and supporting information processing technology. These are outlined below.

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Firstly, business models developed recently include point-to-point low fare carriers, which aim to eliminate complex ticketing agreements and sell direct to the consumer, offering value over comfort. To achieve this, low fare carriers tend to favour streamlined operations, with a single aircraft type to maximise efficiencies in purchasing power, maintenance and crew utilisation (Fiorino, 2005).

Secondly, aircraft technology has changed since the 1980s and maintenance, in particular where engines are concerned, has a lower fixed-schedule component (i.e. planned preventative) and a greater diagnosed or measured performance element (referred to as on-condition scheduling). As newer aircraft employ more solid-state systems with fewer mechanical instruments and controls and improved material and system design, their overall maintenance needs are less. A drop in demand has reduced new aircraft prices by as much as 50 per cent (*OnBusiness*, 2002) and leasing rates have come down; thus many older generation aircraft have been retired over the past few years. Therefore, while a five-year-old airplane performs the same task as a 30-year old, lower ownership costs, lower maintenance costs and lower fuel costs have led to a demographic shift to younger fleet in recent years. Coupled with a drop in aircraft utilisation, the consequence for maintenance costs has been pronounced, and the value of the aircraft maintenance, repair and overhaul (MRO) market has fallen to US$34.6bn in 2003 from US$43bn in 2001 (*Back Aviation*, 2003). There is continuing consolidation in the market, with constant pressure to innovate and create competitive advantage.

Thirdly, major environmental changes have come into play. In particular, inventory management of aircraft spare parts is different to the conventional "produce and discard" view of ERP systems since parts are typically maintained and re-stocked – these are referred to as *rotable* inventory units. Additionally, the business environment gives increasing pressure to link information systems within cross-company business processes (Luftman and Brier, 1999), despite many still being only deployable within single organisations.

Key questions that have arisen from action research and motivate this work are:

RQ1. What is the composition of the aircraft MRO supply chain?

RQ2. What factors inhibit transactional exchange between different companies in MRO supply chains, and what can be done to minimise them?

RQ3. Which factors best serve as optimisation objectives for MRO supply chains, and why?

Purpose and scope of the research

In general, the purpose of the work is to promote the increased use of computer-based systems to automate, communicate and optimise business information processes in the aircraft maintenance industry. This is in response to the perception that the industry lags others in its adoption of technology, and that the scope to apply technology is large and offers huge potential benefits (*Airline Business*, 2000).

The systems development approach described in the next section aims to move from the general to the specific in three steps: starting with a structured mapping of the supply chain (a "business process model"), moving to the automation of transactions between members of the supply chain ("the information model" level), and finally performing complex optimisation on extensive operational data used within one of the firm types in the supply chain (the "computerised information management" level).

The first step described (mapping the supply chain) aims to span the industry with a generic model of organisation types and their processes. The second step (building an e-commerce exchange) covers the governing transactions between a repair service provider and their maintenance agency customer. The third step (inventory optimisation) is yet more specific and detailed, applying a mathematical solution to a well-defined and large-scale resource-planning problem. This three-step approach corresponds to the conventional organisational view (strategic-tactical-operational) (Laudon and Laudon, 2000), requiring greater detail and understanding at each descending level.

Methodology: systems development

This work uses a standard information modelling approach (Stevens *et al.*, 1998) as shown in Figure 1. The "use-case scenarios" were developed from an airline (Aer Arann) and a primary maintenance provider (Shannon MRO).

The "process level" of development has been used to define the business process deliverables (e.g. inventory management process for cost and downtime minimisation). This model is referred to in this paper as the "Aircraft maintenance supply chain reference (AMSCR) model" and is intended to coordinate with other standard models such as the Society of British Aerospace Companies supply chain relationships in action model (SBAC, 1999) and the supply chain operations reference model framework (Stephens, 2001).

The "information-level" model is an e-commerce exchange demonstrator. This facilitates the simulation of real business processes in a computer-based system by allowing transactions between organisations in the MRO supply chain. The model encompasses the principle of demand driven management; this requires close integration between providers and consumers of goods and services, and a high level of e-commerce capability (Williams *et al.*, 2002).

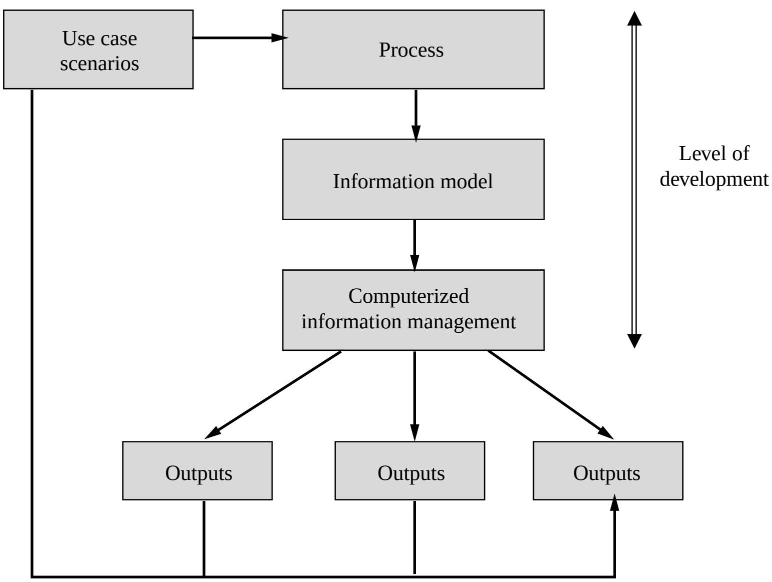

Figure 1.
Derivation of the system

The "computerised information management level" embodies algorithms for dynamic inventory control that are embedded in the e-commerce exchange demonstrator; inputs are taken from back-end MRO inventory management ERP systems. The outputs were then validated against the original use-case scenarios to create off-line MRO SCM simulations.

Each of these levels is now described in greater detail.

Process level: the AMSCR model

This section addresses *RQ1*: what is the composition of the aircraft MRO supply chain?

Central to this research is the application of business process modelling techniques and frameworks to well-known actions and information flows (Kugeler and Vieting, 2003; Melão and Pidd, 2000). A business process can be defined as the transformation of inputs (resources, information and requirements) into outputs (products and results) in order to add value (Adesola and Baines, 2005). Typically, these tend to focus on the internal structure and operation of organisations. However, the anticipated breakthroughs in this research are sought in the information flows that connect firms. The process view extending beyond single firms is useful to understanding how supply chain work is performed and presents a different view of the problem environment; where organisational boundaries and information flows are less clear (O'Brien, 2004).

This research has produced a detailed series of process maps to record the activities and material flows of a small airline (Aer Arann), a primary maintenance provider (Shannon MRO), a sub-contract repair facility (PWAI) and a parts trader (Magellan). It has been built using a top-down, high-level viewpoint and is shown in Figure 2. There are two process constituencies: internal (many of which are included within ERP applications) and external (the domain of e-commerce).

Core supply chain processes were identified, mapped and refined between four of these organisations (as demonstrated by the shaded area in Figure 2).

It is important to note that most of these processes were either performed manually or were served poorly by incumbent systems that had neither been well

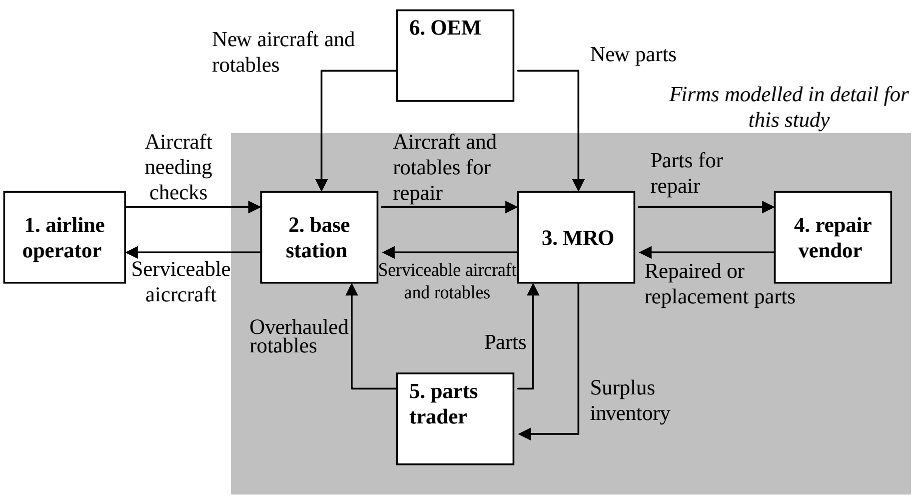

Figure 2.
The aircraft MRO supply chain reference model – physical flows

defined nor standardised. Mapping each organisation in detail took an average of six person weeks in-house per company. From the high-level reference model (Figure 2) a series of more detailed process maps was produced.

The system shown in Figure 2 shows an industry where demand drives inter-organisational transactions, so that the supply chain is better referred to as a demand chain (Rainbird, 2004). However, as this research is focused upon MRO activities extra complexity is introduced by the fact that flow of material takes place in two directions.

It is a key feature of aircraft MRO supply chains that movement of material occurs in both directions: this is in contrast to standard supply chain models of "consumable products" where there is a predominantly one-way flow of materials toward the customer. Physical flows in the opposite direction towards the supplier (often referred to as reverse logistics) are considered exceptional in "consumable product" supply chains. However, in the MRO scenario, there is an even flow of serviceable items from customer to supplier, with maintained (or re-manufactured) items flowing in the conventional downstream direction. Thus, there is a closed loop supply chain, allowing the movement of rotable items (Hayek *et al.*, 2005).

Information level: e-commerce demonstrator

This section addresses *RQ2* in greater depth: what factors inhibit transactional exchange between different companies in MRO supply chains, and what can be done to minimise them?

Developments in technology in recent years offer potential for firms to increase their use of automated systems to perform routine supply chain operations (Sexton, 2003; Singh, 2003). A database with a web-based interface was designed to allow suppliers and customers to transact business over a common e-business exchange, where each could log in and manage orders. The motivation for this was the lack of automation in managing the MRO supply chain: despite a diverse range of internal systems in operation within the different organisations there are often scant resources to connect these systems and develop common transaction standards.

Often, standard ERP applications envisage the purchasing process between customer and supplier in a "consumable product" supply chain to be a well-defined sequence of transactions; this can be shown as a timed sequence of events from 1 to 7 as in Figure 3.

However, the nature of MRO transactions is different: while some materials are purchased, many operations involve sending an item for repair; other items may be recycled or disposed of altogether. Current ERP systems often do not reflect this process accurately in their informational relationships and use the standard

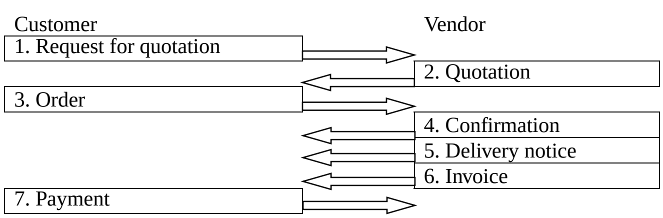

Figure 3.
Transactions for the consumable PO process

"consumable product" purchase order (PO) model as an approximation. This gives rise to two major factors that hinder transactional exchange between companies:

(1) The repair order process needs to be managed manually or the ERP application modified; which often happens incrementally by trial and error.

(2) If customers' and suppliers' ERP systems are not interconnected, it is not possible to perform automatic transactions or optimisations between organisations.

In response to these problems the repair order process was observed and modelled, as shown in Figure 4 (in time order from 1 to 8) and implemented in an e-commerce exchange demonstrator that allows transactions between firms.

The MRO process is seen here to have greater complexity and uncertainty, with a possible repeating loop (between steps 4 and 5) that requires a more flexible database structure to manage the informational transactions.

Figure 4 shows the core MRO process that this research has used as a basis to conduct an e-commerce exchange using event rules to streamline the transactions between customer and vendor. Before this process is initiated, the customer sends unserviceable items (in the aviation industry, the terms "serviceable" and "unserviceable" are understood to mean "fit for use" and "out of order", respectively) to the vendor without a PO, the vendor generates a sales order (if appropriate), the customer responds with a PO and the transaction begins. As the work progresses, work orders (WOs) are generated by the vendor and attached to the sales order, these changes are communicated to the customer and may be used to amend their original PO. Some examples of optimisation objectives are shown as business rules in Table I.

Table I shows typical examples of business rules agreed between customer and vendor in order to minimise cost and simplify decisions. Formulation of these rules requires collaborative planning between the respective organisations and may be included in the terms and conditions in commercial contracts between them (forming part of the repeating loop in steps 4 and 5 of Figure 4). The e-commerce demonstrator can:

- control the business process and facilitate appropriate transactions; and
- apply different business rules dependent on the business conditions to enforce customer and supplier policies.

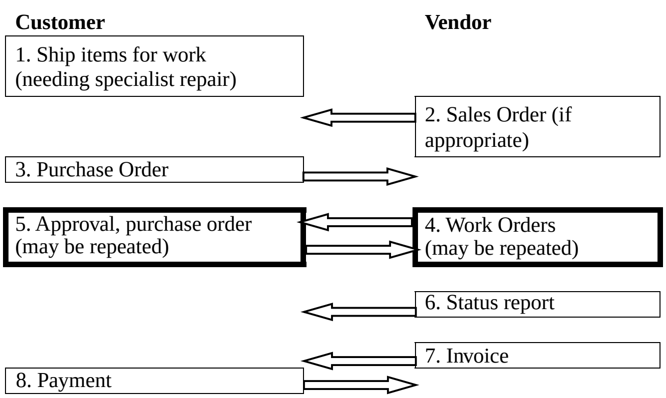

Figure 4.
Transactions for the MRO PO process

Example (e.g. jet engine parts)	Rules	Transaction handling benefit
A set of 48 matching blades from a jet engine is sent for repair	IF fewer than ten are scrapped, replace scrapped items with new ELSE IF between 10 and 20 are scrapped, replace with reconditioned parts and reduce the status of the set ELSE IF more than 20 are scrapped, overhaul and retain the remainder for spares	Delays in consulting the customer can be reduced by having well-defined rules Inappropriate repair decisions can be avoided – sometimes parts may be repaired but cannot be matched so will not be used
A combustion chamber liner is sent for repair	IF the liner has been overhauled before, do not overhaul ELSE IF welds above a certain total length are needed, do not overhaul	Individual airlines have difference overhaul policies, which can be applied as appropriate
A disk is sent for overhaul	IF the remaining life of the disk is below the minimum build standard for the airline, offer for sale on the open market without overhauling	Different airlines build engines for different lengths of service, so residual value may be obtained for redundant parts

Table I.
Heuristics included in the transaction exchange e-commerce demonstrator

This requires data from separate ERP systems, which should be linked through the e-commerce exchange. This is a neglected area of research, which the authors are investigating.

Figure 5 shows the functionality of the MRO exchange for customers. Importantly, the system allows the customer to create and manage event rules, so that their policies will be applied to all future orders. The WO is created by the supplier, and authorised by the customer (e.g. the MRO in Figure 2) creating a PO. This differs from the

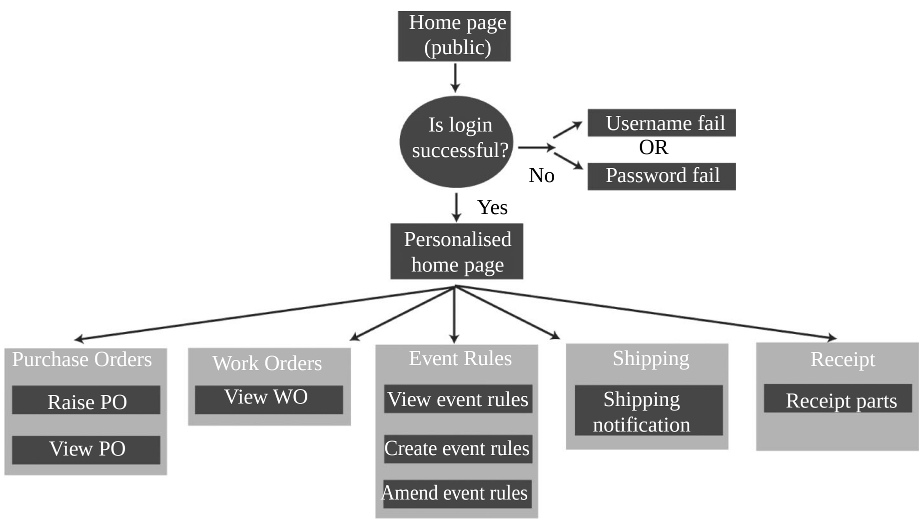

Figure 5.
Customer functionality delivered by the e-commerce demonstrator

conventional purchasing transaction, as the buyer (the company with items to repair) does not know whether they will actually be buying (or for how much) until the vendor (the company with repair capabilities) has reviewed the delivered parts and proposed work.

Figure 6 shows the functionality of the MRO exchange for the vendor (e.g. the repair vendor in Figure 2). The vendor proposes work, for acceptance by the customer, so that transactions are created and advanced only as necessary. Thus, the process is primarily "pushed" by the seller, which does not correspond with purchasing activity for "consumable items" as typically modelled in ERP systems.

The main difference between the supplier and vendor functionality in the MRO exchange is that the customer controls the business rules, whilst the vendor controls the generation of WOs within the ERP system.

The e-commerce exchange outlined here concentrates on the relationship between repair vendor and customer. For example, the transactions from airline operator to airline base station and from the airline base station to the MRO provider, as shown in Figure 2. In addition to purchasing transactions, there is also a need to manage technical records between organisations: for instance when an aircraft is sent for maintenance, it is accompanied by a detailed status pack about the maintenance level and history for all major components and a list of required upgrades and modifications as called for by the airline, aircraft manufacturer and regulatory authorities. There is thus ample scope for further work to model and prototype systems for the automation of commercial transactions between the various members of the whole MRO supply chain.

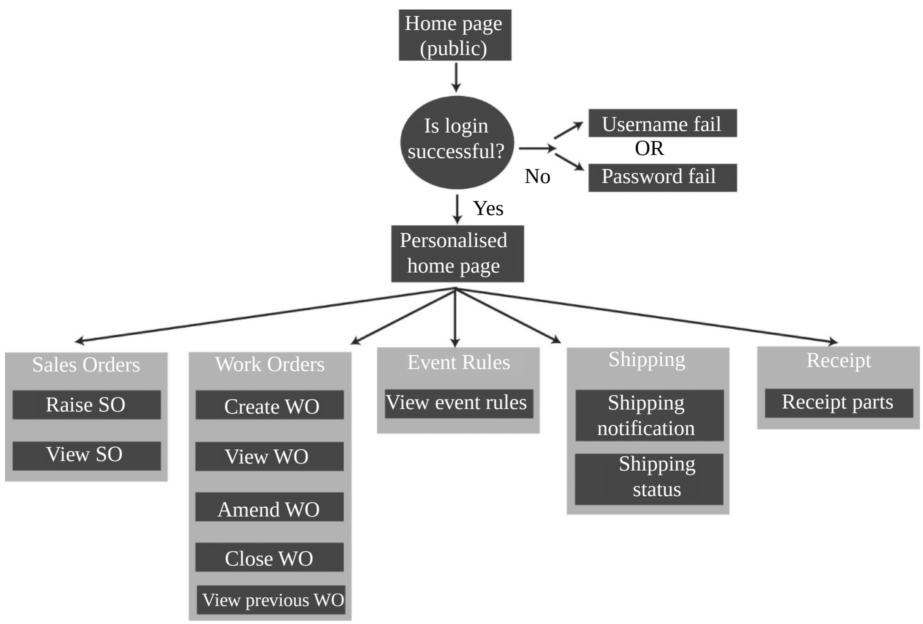

Figure 6.
Vendor functionality delivered by the e-commerce demonstrator

Computerised information management level: optimisation for forecasting spare part inventory

This section proposes solutions for *RQ3* identified earlier: which factors best serve as optimisation objectives for MRO supply chains, and why?

One of the major MRO supply chain partners (FLS Aerospace) expressed concern that excessive inventory existed due to the lack of systemic forecasting. An airline's main inventory investment is the line items that are maintained and re-used (i.e. non-consumables); these are referred to as rotable (as they rotate through inventory and are not consumed). Rotable stock needs to be managed differently to consumable material. While there have been some systems developed for this problem, usually looking at the problem of dividing inventory around several airports (Tedone, 1989), specialist solutions are not in widespread use in the industry (*Aircraft Technology Engineering and Maintenance*, 2001). The standard model followed by ERP inventory systems takes manufacturer's guideline reliability data for each part number and makes a calculation based on several factors. The calculation is performed using proprietary solutions, the example below is from FLS Aerospace and is produced by their Visicalc application, which uses an iterative probability calculation (Kearney, 2003):

Recommended holding for part 763810-1 $= f$ (MTBR, TAT, QPA, FleetUtil, SL) $= 8$
where:

- MTBR $=$ 2,314 hours – manufacturer's mean time between removals figure
- TAT $=$ 30 days – turn around time: time taken to route, maintain and replace item 763810-1 in inventory
- QPA $=$ 1 – quantity per aircraft
- FleetUtil $=$ 53,229 hours in the past 365 days – total hours flown by the total number of aircraft of the same type (e.g. Boeing 737-800) in a fixed period
- SL $=$ 95 per cent target service level: the probability of the part being available)

The calculated number will be a quantity of a given part number: for example, the recommended holding level for a cabin pressure controller (part number 763810-1) is 8, to satisfy 95 per cent of requests for part number 763810-1. Note that no account is taken of the time taken to order a new item as the items are maintained as opposed to consumed. This means that ordering costs and economic ordering cost quantities are not needed in this calculation, since they have no bearing on the number of items needed to support operations.

Since, the actual time at which a part is needed is stochastic, a probability distribution is used to determine a realistic holding. The service level (SL) is the probability of a part being available: a SL of 95 per cent means that there is a 95 per cent probability of the part being available at any time, given the stated utilisation parameters. To guarantee 100 per cent SL would require a full duplication of all items in service, which is excessively costly. In practice, a target SL of 95 per cent is used for essential items (parts without which the aircraft cannot operate, and are referred to as "no go"). There are lower SLs for "go if" items (e.g. one radio may be unserviceable if two others are working) and "go" items (e.g. galley equipment, which the aircraft can operate safely without).

It was proposed that the conventional approach was deficient in its analysis since it considered individual line items (stock keeping units/part numbers) without regard to the other items. This highlights two major factors when considering MRO supply chain optimisation:

(1) *The relative cost of parts*. It is more acceptable to delay the despatch of an aircraft for a US$100,000 part than for a US$100 part. Typically inventory-planning calculations take no account of relative cost and impact on availability. However, it makes sense from an operational perspective to manually manage low stock levels of very expensive items, while providing greater levels of safety stock for less costly items.

(2) *The relative failure rates of parts*. Rather than calculate failure rates at the individual part level, the real business problem is to maximise the number of requests satisfied for spares, regardless of the part number. In other words, each time a request is made to stores, there is a required probability of 95 per cent that it be fulfilled. This is quite different to the traditional objective of having a given part available 95 per cent of the times that it is requested.

Thus, the objective of the inventory planning function changes as shown in Table II (where I is a part and there are n parts).

The traditional calculation comprises a sum of simple calculations; the new approach requires a large-scale linear programming solution to achieve the objective function.

Taking the relative rates at which parts are required, it was observed that the prototype system gave large reductions in required inventory levels for many items, compared to actual holdings based on line-by-line forecasts.

This is useful in planning asset reduction, as it allows the company to ask questions such as: "if we cut our inventory value by US$100M, what is the resultant SL?" The optimisation skews its recommendation by value (lower-value parts are covered first): the most valuable parts will run out first, giving the greatest saving and causing the smallest number of items to fall short, making it easier to respond manually case by case. In contrast, existing practice does not focus on managing shortages of more expensive items.

Prototype: systems results and industrial implications

Three levels of research outputs have been prototyped: the AMSCR model (process level), a repair order e-commerce exchange prototype (information level), and a rotable inventory optimisation system (automation level). Each different level of development within this research has illuminated new issues in aircraft MRO supply chain management.

The AMSCR model achieved several outcomes:

- Participants in the building of models gained clarity and consensus on their own processes.

Table II. Objective functions for part-level and fleet-level optimisation

From: the sum of minima for each item of inventory	
Total inventory cost $= \sum_{i=1}^{n} \min(\cos t_i)$ subject to i attaining target SL	The sum of all items with cost minimised to achieve a target SL
To: the minimal sum for all items	
Total inventory cost $= \min \sum_{i=1}^{n} \cos t_i$ subject to I attaining target SL, where I is the set of all i from 1 to n	The minimal sum of the cost of all items attaining a fleet-wide SL

- They also came to better understand their place in the industry.
- The model serves as a basis for devising supply chain solutions.

It is intended to continue development of the AMSCRM to tie into the Lean enterprise model developed by the Lean Aircraft initiative programme at the Massachusetts Institute of Technology (http://lean.mit.edu).

The e-commerce exchange has been validated with a MRO operator, a component trading company and a specialist repair vendor. The observable strengths were that:

- The e-commerce system accurately captures the process beyond the capability of available ERP solutions, as it focuses on external transactions.
- The automation of the process is helpful in standardising procedures and reducing error and uncertainty in inter-organisational communication.
- There is greater visibility of WO status by customers (this may be a cause for concern, as vendors have less control over managing customer expectations).

However, the downsides of such systems are that:

- Participants have a high degree of mistrust in the e-commerce exchange model – even though it is an efficient method for gathering and communicating information – for confidentiality reasons live critical data is reluctantly given to external intermediaries.
- Integrating an e-commerce exchange into internal ERP systems would be expensive and difficult: the economic benefit must be clearly evident.

The opportunities that such systems provide include:

- E-commerce exchanges are of greater benefit to customers than vendors, as they enhance the ability for customers to track vendors' status reporting. Also, at present, vendors provide status information in a range of formats and reports are not as regular as customers would like.
- Greater transparency and speed of communication should facilitate reduction in inventory levels through faster repair cycle turn-around times.

The development of such systems is currently threatened by:

- Little interest in e-commerce initiatives, as most companies have been party to failed projects and have been exposed to extensive negative publicity.
- The immature state of middleware technologies, solutions and service management. Few companies will entrust critical data to service providers. In particular, there is a lack of standards at the data format level, which has long been a problem with web-based EDI initiatives.
- There is a strategic problem with the idea of e-commerce exchanges. For example, at the "Eye for Aero" conference in 2000, Airbus announced that all customers would have to use their site in future to purchase MRO parts. In the following presentation, Air France announced their own e-commerce initiative, whereby all of their MRO parts purchasing would be conducted on their new web site. This created an immediate stalemate, resulting in the failure of the airline's project and a low initial uptake of the supplier's service.

The rotable inventory optimisation system was prototyped with a small number of parts, giving forecast reduction in inventory of 40 per cent with no consequent loss of service. On the strength of these prototype results, the company collaborating in the research provided resources to build a full-scale enterprise application, drawing data from a range of sources, including ERP for material holding, cost and mean-time-between-failure (MTBR) figures, and engineering databases for aircraft utilisation rates. The results of the first test on a limited range of data gave similar cost reduction: a group of parts valued at US$8M could be reduced to US$5M without affecting the SLs.

The system is now undergoing integration for full fleets and parts listings, where it will be used on a pool of inventory valued at US$250M. It is expected that savings of 20 per cent will result in the system use (if the company acts on recommendations and sells off excess inventory). In addition to reducing current holdings, the application permits better forecasting at the provisioning stage, when fleet purchase is being considered. Furthermore, the owner of the inventory can increase its return on these assets by selling inventory support to other operators of the same fleet: if you hold spares to support 25 aircraft, the additional investment to support several more aircraft is negligible. To date, over six man-years of development effort have been put into developing this system (implemented in a Java environment and linking it to an Oracle Enterprise database).

The prototype provides the potential to achieve target SLs whilst substantially reducing the total value of inventory required (MacDonnell and Clegg, 2004) which is essential for efficient MRO supply chain management (Piplani and Yonghui, 2005)

Summary

This project has been driven by three research questions:

RQ1. What is the composition of the aircraft MRO supply chain?

RQ2. What factors inhbit transactional exchange between different companies in MRO supply chains, and what can be done to minimise them?

RQ3. Which factors best serve as optimisation objectives for MRO supply chains, and why?

To investigate these research questions this project has developed a proof-of-concept system at three levels: first at a high level by relating to industry reference models and mapping cross-company process touch points (at the "process level"), second by establishing electronic connectivity and facilitating transactions based upon these processes in an e-commerce demonstrator (at the "information model level"), and then by developing cross-company dynamic forecasting algorithms to optimise stock holding costs and availability trade-offs within the e-commerce demonstrator (at the "computerised information management level").

A further potential step would be to build a simulation of supply chain operations within the sector to assess performance of the "as-is" and "to-be" processes (Jain *et al.*, 2001); this may be planned as a large-scale project for future exploration.

This prototype system is gaining maturity and is a timely development with trends such as "tracking and tracing" of individual items in the supply chain; and increasing legislation that is forcing more and more "consumable" type products into those that should be maintained, repaired or overhauled and so this type of concept will have a growing applicability outside of the aircraft maintenance sector.

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