TITLE:

“The development of e-enabled MRO-maintenance, repair and operations in the global air transport industry for optimizing airplane utilization through minimising downtime: An application case study”.

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**ABSTRACT:**
The objective of this research is to propose the development of new e-enabled systems for controlling MRO-maintenance, repair and operations or overhaul in global aerospace supply chains. Current methods of managing MRO in civil airplane operations are limited due to their inherent legacy structures, resulting in restricted visibility and reactive modes of operation, leading to excessive operating costs. Such costs account for lost revenue when measured in terms of airplane “downtime”. MRO organisations strive to limit costs associated with “downtime” but are constrained by the nature of the business model under which they operate. This is particularly true for MRO operations in vertical sectors such as aerospace, which are process-intensive and controlled at all levels of the product life cycle, from cradle to grave in order to meet robust certification requirements. Such requirements involve verification of supply and operational information, both at the airplane and component levels. This paper describes an e-MRO system development for a civil aircraft operator in the air-cargo sector of the industry. The aircraft are based in the UK and support the movement of freight in global markets. The aircraft are classed as out-of-production aircraft, typical of many freighter aircraft currently operating and are subject to ageing aircraft status. As a result most data remains in paper format and has not been digitised.

**Introduction**
Maintenance, repair and operations is an area which offers opportunities for creating new MRO business models by optimising processes through e-enablement, particularly in sectors requiring global presence and execution. Requirements for certification involve the verification of supply, manufacturing and operational information, including generating detailed technical records both at the aircraft operational level as well as component level. In addition, for those parts classified as being critical to safety, e.g. engines including their internal parts such as compressors, the monitoring of MRO operations constitutes a legal requirement under Civil Aviation Authority regulations. For categorization purposes aircraft are sub-divided into 3 main areas, namely: airframe and associated structures, power-plants and components. Each area is typically controlled by 3 key elements, namely: by flight hours, flight cycles and by calendar limitations, i.e. by date and/or age. MRO operations ensure such limitations are maintained within safe and acceptable margins, in accordance with manufacturer specifications, general airworthiness practices and aviation authority directives. To achieve the above, MRO companies need to continuously monitor operations in order to generate periodic inspection requirements, which require the aircraft, its components and equipment undergo routine and preventative maintenance in accordance with certified schedules.

**Literature review**
The review of MRO activities and inspections, as required for continued airworthiness verification, is addressed herein from both a systems development/integration as well operations management perspective. Typical MRO applications, their modules and functionality are addressed both within the literature section as well as at the e-analysis stage, for comparison purposes.
**MRO History and Background Studies**

Commercial aircraft maintenance activities form an important part of airworthiness operations. Such activities consist of servicing, repair, modification, overhaul, inspection and determination of condition. These tasks involve a variety of operations which are targeted at restoring parts to meet strict serviceable condition levels. Broadly, there are two types of MRO inspection requirements or checks which are needed to be carried out on commercial aircraft, refer to Figure 1:

1. **Corrective maintenance**, which includes such actions performed as a result of failure in order to restore a part to satisfactory levels. In general it is about verifying and replacing faults and includes unscheduled maintenance, and

2. **Preventive maintenance**, which involves maintaining the parts and items in a serviceable condition through systematic inspections and checks. This type of maintenance is termed scheduled maintenance as it is carried out at pre-appointed times in an aircraft's life and may be controlled either by calendar, flight hours or/and flight cycles (Wu et al, 2004).

![Figure 1: Scheduled versus un-scheduled checks, Komorowski (2003)](image)

Direct maintenance costs (DMC) are defined as the labor and material costs directly expended in performing maintenance activities on an aircraft or related equipment. The labor and material expenses are not included in DMC costs. According to Knotts (1999) the key influential factors on DMC are the maintenance man-hours on and off the aircraft as well as labor rates and material costs. This could be shown as follows:

\[
DMC = (MMHon + MMHoff) LR + MC
\]

Where \(MMHon\) is maintenance man-hours on aircraft, \(MMHoff\) is maintenance man-hours off aircraft, \(LR\) is labor rate, and \(MC\) is material costs (Knotts, 1999).

One goal of operations management addressing MRO is to achieve a balance pattern of scheduling maintenance inspections and flight hours so that the results would meet the FAA regulations as well as airline internal operating policies. In order to achieve this, maintenance inspections need to be scheduled based on the given flight schedules. According to Sriram and Haghani (2003), the frequency of scheduled
checks also depends on combination of factors such as flight hours, landing, and take-off cycles. The four major types of check that are mandated by the FAA for each type of aircraft are listed below:

**A Check:** This is the first check that occurs in the region of every 65 flight-hours. It covers the inspection of all the major systems such as landing gear, engines, and control surfaces.

**B Check:** This is the second check that usually takes place in the region of every 300-600 flight-hours. It involves a detailed visual inspection as well as lubrication of all the moving parts of the aircraft.

**C and D Checks:** These two major checks are usually scheduled in the region of once every one to four years respectively, both requiring about a month of work on the aircraft (Clarke et al, 1997)

One of the main purposes of having an MRO application is to enable accurate maintenance scheduling and facilitate demand utilization. According to Brio (1992) however, such systems are not capable of facilitating such work from start-to-end and suggests human knowledge and experience still play an important role in the accuracy and efficiency of such operations. Furthermore, intervention and interaction still appear to be necessary on the part of users for the purposes of overriding or providing decision support to the application where needed, such as solving maintenance-scheduling conflicts. Although such activities are often classed as system monitoring, they highlight the limitations of such systems and the importance of the human control element.

**Maintenance scheduling**

Maintenance scheduling involves the arranging of the sequences in which the work orders and tasks will be done and deciding who will be in charge of completing the tasks. Factors to be considered are job duration, required skills, job priorities, availability of required spare parts, appropriately skilled workers, special tooling and status of equipment maintenance (Pintelon et al, 1999). Due to complexities associated with such arrangements and interactions, MRO systems are required to assist in overcoming many diverse challenges in an efficient manner. Such systems would facilitate the decision making process by taking all the above factors into account during the process. Complete automation is not considered possible or desirable and maintenance scheduling, similar with any other managerial interaction or decision tool, will often require human judgment to address some of the finer issues. In other words the aim here is not so much to automate decisions, but to enable users to make correct and fast decisions based on accurate and most current information available. The system responsible for providing such information will be robust and reliable enough to integrate a number of complex IT systems and applications (Sherwin, 2000), whilst concurrently providing interfaces for complex operational associations, both within the organisation as well as with its suppliers or service provides. Such MRO applications would need to be developed around expert or knowledge-base system models, in order to facilitate the required automation and decision making features.
**Knowledge-based systems**

Knowledge based systems assist organisations and MRO providers to improve turnaround times by proposing proven solutions to previously known problems on hand or probable solutions to unknown problems on hand. According to Mustapha et al (2004), a knowledge-based or expert system (KBS) comprises of computerized knowledge of an expert in a particular subject domain. Knowledge-based systems are capable of providing fast and easily accessible knowledge based information in a useful and practical manner. The software is designed to capture and use domain-specific knowledge expertise in order to facilitate decision-making or problem solving tasks (Mustapha et al, 2004), see Figure 2.

![Figure 2: Knowledge-based or expert system (KBS), Mustapha et al, (2004)](image)

Knowledge-based systems have the capability to offer a direct rectification course of action whilst reducing actual time spent on trouble-shooting and minimizing the involvement of experienced maintenance personnel handling MRO activities (Mustapha et al, 2004). The full version of the proposed e-MRO system incorporates such features in order to assist the maintenance personnel reduce time taken to address known problems. This also results in minimising aircraft downtime.

**Aircraft downtime and associated costs**

Since much aircraft downtime is directly attributed to rectifying or finding the cause of problems, reducing it is significant due to the knock-on effect it potentially may have on the supply of parts required for rectification. This effect happens because organisations are usually reliant on existing stocks to cover such occasional parts failures, as lead-time prior to actual demand does not exist. Downtime on such occasions translates to lost time for the MRO facility, since no direct man-hours are booked whilst waiting for spare parts and also lost time for the aircraft operators, since their aircraft remains grounded. Lost time accrues costs to MRO facilities and aircraft operators alike, which are neither directly recoverable nor contribute to the progress status of the aircraft.

Controlling the costs associated with these types of checks remains a challenge for commercial MRO providers. The objective is to provide fully serviceable aircraft when required by an airline at minimum cost and minimum down time. According to a study by Maple (2001) maintenance costs typically account for 10-20 per cent of
aircraft-related operating costs. A significant part of that figure is directly attributed to downtime. It is widely accepted that maintenance costs of a commercial aircraft make a significant contribution to an aircraft’s cost of ownership. The majority of MRO providers use some method or application in order to achieve higher productivity rates and lower operation costs whether they are direct or indirect maintenance costs.

**Case study: system overview**

The case study presented herein addresses the need for development of suitable e-MRO systems, the purpose of which is to enable the current or facilitate the future effects of growth projections in the aerospace sector in an efficient and empowered way.

**System capabilities**

The e-MRO application was developed as a technology demonstrator, rather than a commercial system. Its development was based on the RAD-rapid application development principle. This prototype application uses mathematical algorithms to identify and generate both general inspection requirements for aircraft and components, as well as specific task checks on a scheduled or unscheduled basis. It has the capability to resource operations by assigning employees to each task within their job group category, such as avionics or electrical, whilst allowing both the supervisor and the employee to monitor their hours worked or view progress at any time against given benchmarks for that specific operation. The supervisors may call-up work cards and confirm, after viewing the details of the card and checking for technician’s signature and notes, that such work has indeed been carried out in accordance with approved processes and procedures prior to closing-off that work card. This feature enables operations to be completed both efficiently and within controlled guidelines, whilst at the same time assuring the safety and integrity of the checks by re-affirming task status at any time.

Furthermore, the system has the ability to track aircraft operations through the imputing or recording of flight hour and flight cycle information for all life-controlled associated parts and structure. In effect, scheduling and resources allocation takes place through this interface and results in the system maintaining an important health-monitoring baseline for the aircraft. The parts supply interface is also enabled at this level, as well as at the planning and task execution level. In other words, the parts monitoring interface enables advance tracking of replacement components or scheduling of associated services, such as workshop slots for overhaul, prior to the planned removal dates. This results in parts, plans or tools being available at the time when required without incurring delays leading to downtime. Since this feature also has the capability to track log-book entry items, many un-scheduled item replacements are also identified prior to requirement thus facilitating technical operations.

**System implementation**

Implementation of such systems increases competitiveness in the marketplace, as the potential exists to achieve better turnover figures partly due to reduced task completion times. This efficiency gain has the potential to directly affect man-hour rates, as MRO-associated tasks are more often billed as such, i.e. per man-hour rather than on fixed-price contract.
Currently most MRO providers and airlines are adopting or have already adopted some type or method for the control of their MRO processes and operations. Although the aircraft industry is considered as inherently traditional in its approach to systems implementation, many companies in this sector are keenly observing or reviewing developments including the technologies driving them. Harmon et al (2001) state that regardless of a company’s strategy it has to realize the need to adapt to the new business environment, which has been created by the Internet and the web in order to stay competitive in the industry.

**Case study Methodology**

To meet this requirement a 3-stage methodology was adopted, namely: e-proposition, e-prototyping and e-analysis, based of research by the DOMAIN Group at the University of Liverpool, U.K. The first stage addresses the value proposition and involves the identification of new e-enabled MRO models, classification of supply/service networks and action based mapping of technical task requirements and material information flows affecting operational and/or business processes. The second stage addresses the prototype application development and involves client and server-side development, application hosting and networking and systems integration map. The third stage addresses the value analysis and involves review of the new e-MRO model key elements and comparison/qualitative analysis of e-MRO model benefits over the traditional MRO model, see Figure 3.

![Methodology Diagram](image-url)

**e-Proposition**
- Identify new e-enabled business model
- Action based mapping of resources, information flows and business processes

**e-Development**
- Rapid Application Development – RAD toolset
- Application hosting and networking, client and server-side development
- Systems integration map

**e-Analysis**
- Comparison analysis of previous business model to e-enabled business model
- Qualitative analysis of business benefits
- Revisit key questions raised

Figure 3: The DOMAIN project research methodology map, Michaelides et al, (2003).

**e-Proposition**
Current MRO systems are based on methods traditionally designed to support all the relevant maintenance phases for the operator’s fleet of aircraft. However, the emphasis of newer methods of managing MRO operations is deep rooted in economies and maintaining competitive margins in a wider spectrum of activities
which include suppliers and service providers. From an operations management perspective, this translates to enabling better turn-around times to be achieved, thus minimising aircraft downtime, which is inherently associated with losses in gainful revenue. This can only be realised through accrued efficiency gains as a result of allowing system users to better manage resources which are directly and indirectly associated with the maintenance operation as a whole rather than just the task on hand. More significantly, the objective is to realign traditional MRO operations and to establish and foster a culture of pro-activity on an ongoing basis rather than allow actions to be based on a reactive event such as upcoming inspection intervals. By optimizing schedules and integrating the maintenance function with real-time check status and progress information, incidents of unplanned maintenance tasks and inspections may be significantly reduced.

Thus, by utilizing the e-MRO system all persons involved in the overall task of supporting the aircraft on an ongoing basis, such as parts suppliers and route planners, (not only technical staff such as supervisors, mechanics, technicians, and engineers) will all be knowledge powered and be able to better contribute to the reduction of maintenance downtimes without compromising safety. In order to better achieve this, the e-MRO system may be integrated with ERP systems, such as SAP or other modules such as SCM-supply chain management or CRM-customer relations management or best-of-breed systems such as APS-advance planning and scheduling, see Figure 4.

![Figure 4 e-MRO system integration](image)

It is proposed that new e-MRO models are developed, based on shared information structures and transparency of the overall activity through utilisation of concepts such as Internet presentation layers (IPL), see Michaelides (2003). This will be supported by suitable e-business technologies as well as operational structures based on collaborative methods.

**e-Development**

The e-MRO system comprises of a front-end interface with a robust MySQL back-end database. APM (Apache, PHP, and MySQL) open source technologies were used to develop the system. Information and data originate and end at the browser. Such flows invoke the PHP engine through the web server and query or update the database through the MySQL Server interface. Informational and transactional data flows are shown in Figure 5.
Figure 5  Sequential data flows in web database application (Welling and Thompson 2003).

The e-MRO system architecture enables integration with other systems. This integration could be at the ERP-enterprise resources planning system module-level, such as HR-human resources, SCM-supplier management system, or MM-material management. It is possible to further integrate the core system application directly with the TR-technical records module and IFPM-integrated flight parameter monitoring module, although the latter is currently under separate development. See Figure 6 for e-MRO system high-level schema indicating data-centric tier for A and B Checks. C Checks were incorporated into the version 1 production release.

Figure 6  e-MRO system high-level schema

In designing the prototype system, rapid application development (RAD) toolsets were used. This ensured minimum time elapsed between prototype version development and production version release. When developing such dynamic applications there are broadly two different methods:

1. client-side dynamic pages, or
2. server-side active pages.

In designing the e-MRO prototype system the second method was adopted using PHP as a server side scripting language. Typical e-MRO system components are shown in Figure 7.
Dynamic content is linked directly to the MySQL Version 4.1.11 database using Apache server technologies. Specifically, Apache HTTP server was used as the web server for the application and PHP Version 5.0.4 was used as a server side scripting language. PHP is short for hypertext pre-processor and is an open source product scripting language designed specially for the web. Each time an HTML page is visited the embedded PHP code will be executed. The combined use of PHP with Apache web server ensured the system could handle large amounts of traffic. According to Williams and Lane (2004), “PHP is an open source project of the Apache Software Foundation and it’s the most popular Apache web server add-on module, with around 53 per cent of the Apache HTTP servers having PHP capabilities”. The system architecture for the e-MRO system is shown in Figure 8.

User and data Interface

The e-MRO System eliminates the need for most of the paper documents and procedures that are required. Digital records and documents are stored within the system and backed up regularly on incorporated or independent storage devices.
From a user perspective, it is easier for personnel to carry out their duties while spending less time searching for related documents and instructions.

The legacy data, such as maintenance schedules, task job cards, manuals and instructions were converted from the scanned paper versions to HTML and PHP files. Using OTS-off the shelf commercially available OCR-optical character reading software the data was transformed from .TIF image format to editable word documents, whilst ensuring the accuracy and integrity of the data was maintained. Furthermore, all technical documentation from the regulatory authorities and aircraft manufacturers, such as release to service certificates were electronically uploaded into the system. Using this method of data storage and retrieval enables records to be available for indexing and searching by the users, with the objective of enhancing the productivity of engineers and technicians.

Supervisors and inspectors manage both work completion status and approvals activities on line. These electronic signatures indicating release, approval or verification are stored in the database for further review and for maintaining the audit trail. This also addresses the issue of maintaining credible technical records, either historical or current, which constitutes a legal requirement for both operators and MRO providers alike. This may be graphically viewed with the aid of a use case diagram, see Figure 9.

![Figure 9](image)

Figure 9 Use case diagrams for supervisor activities.

The use case indicates the sequence of actions that are carried out by the system and its actors (Bennett et al, 2001), as graphically represented by the supervisors and other systems that interact with the MRO system. The preceding activity diagram shows step by step details of the actions that a power user, such as a supervisor would adapt in the e-MRO system. All activities are enabled once the user signs into the system. A
separate activity diagram exists for various levels of users. Varying privilege levels are set in place to control/manage the extent of users’ involvement, according to nature/level of tasks or operations. For example, work card tasks are classified according to:

1. nature, associated with users trade, such as electrical or avionic, and/or
2. operations, based on either:
   a. approval level, such as inspector, or
   b. seniority, such as supervisor or operator.

**Front-end user interface**

Users are able to access latest information associated with their assigned maintenance tasks at any stage of the MRO process, see Figure 10.

![Assigned job list interface](image)

**Figure 10** Assigned job list interface

Furthermore, by using either fixed or mobile devices users may access, review and update job status information pertaining to any task on an ongoing basis. Part status or similar supply information may also be dynamically viewed when waiting for urgent deliveries, such as parts classified as AOG-aircraft on ground. Finally, inspection status is updated on an ongoing basis and allows for accurate progress reviews to be carried out.

The *Job List Management* application within the system allows the supervisors to assign employee identification numbers to tasks and also to sign off work cards after technicians complete the task. The supervisors are able to use the specific interface to assign a particular technician to a task. The technician will be able to access his/her personal job list after the supervisor had assigned then a task and save the job in the system as completed once cleared. There are types of jobs, which may be assigned to a work group rather than an individual. In that case the system will authorise all the technicians within that specific work group to access the job list, view the jobs, and if required assign a task to themselves. The e-MRO system will recognize the tasks that have been assigned to a work group. The system shall generate a list of remaining jobs which need to be allocated within that assigned task group. When a technician starts working on a specific job that specific task shall become inactive for all
members within the same group until the technician finishes the job and signs off the job list. This is aimed at preventing duplication of assigned tasks. However, the task in question may remain active in another task group, for example with a different trade, such as avionics, in order to allow for concurrent task execution.

After each task has been signed by the technician or the engineer responsible for completing the job, the supervisor is responsible for final release of the completed work card. Work cards will remain open until every single element on the card has been carried out, approved or electronically released by the supervisor. The status of a work card may be complete but the full inspection will remain unreleased until the supervisor has confirmed all work cards have been carried out, inspected where appropriate and are accounted for, see Figure 11.

![Work card detail interface](image)

Figure 11 Work card detail interface

In order to better manage the task on hand, supervisors are afforded visibility of the complete task including all work-in-progress. The system generates tables containing all the Job List information for WIP jobs. At any given time should a technician be faced with a challenge or require assistance they may send an instant message to a supervisor through the e-MRO system. Supervisors will receive such messages either as B2B on-line screen alerts or as email messages to their account. Response times are monitored in order to reduce any possibility or extent of downtimes arising as a result of WIP delays.

**e-Analysis**

The generation of MRO requirements is dependent on both historic records and current technical/operational requirements. The multi-disciplinary nature in which such records are processed currently results in disparate methods of MRO control and execution, many of which remain paper-based to date. Furthermore, due to the traditional manner in which such records have been generated and maintained in the past, migration from such methods to more advanced electronic formats of e-MRO constitutes a significant change and necessitates the development of more suitable business models. These models are largely driven by integrative initiatives across
disparate information and process domains. By adapting such models to e-MRO operations, these domains are further extended to include networks of suppliers and service providers, thus facilitating the creation of proactive rather than reactive systems. Such systems are based on the notion of improving visibility through the incorporation of next generation Internet technologies. The scope of such e-MRO applications extends beyond traditional linear process execution thus facilitating concurrent networks and collaborative models, which are underpinned by suitable integrative technologies. Subsequently, the practical implications of this research are realised through the development of e-MRO systems with global application.

The need to develop next generation e-MRO systems may be described as being driven by a 2-tier requirement. The first requirement is associated with market dynamics and the ongoing need to develop optimum methods of delivering value in the highly competitive airline operations area, including airfreight sector. According to industry statistics for global commercial aviation presented by the International Air Transport Association (IATA, 2005), this is viewed as an area of high growth potential. The second area addresses the effects of such growth from a regulatory perspective, in ensuring mechanisms reinforcing safety standards and certification are not only maintained but improved upon in order to counteract the potential negative effects associated with rapid sector growth. The International Civil Aviation Organization (ICAO, 2005) predicts the magnitude of such growth to result in doubling in numbers of aircraft expected to enter service within a decade and tripling in some areas such as the Gulf region (Flight International, 2006a). According to The Seattle Times (2006) the whole focus of the aerospace industry has shifted eastward in recent years to the Middle East and Far East. In order to meet the challenges associated with the above projections, MRO facilities need to develop new methods of operating more effectively whilst incorporating the latest advances in Internet tools and information technologies, which would facilitate the global sharing of related MRO data.

**Future work**

The MRO system is currently capable of providing limited reporting functionality on some aspects of the captured data within the database. Future system enhancements however are planned to extend this capability by including forecasting information based on current fleet utilization figures from current operations, both at organisational as well as manufacturer levels, as well as from historical data that has been preserved within the e-MRO system database, see Figure 12.

![Figure 12 Future information and process flows](image)
Future e-MRO versions shall incorporate the IFPM-integrated flight parameter monitoring module. This module allows for on-line management of flight parameters, such as flight hours, flight cycles and calendar limitations. The application is designed to monitor the airframe, its engines (including controlled internal parts) and components by tracking the following individual as well combined factors: flight hours, landing, and take-off cycles. Frequency of scheduled checks depends on such monitoring (Sriram and Haghani, 2003). The IFPM-integrated flight parameter monitoring module is currently been developed independently and is not automatically uploaded into the e-MRO system.

Conclusions

MRO remains a highly competitive area which is subject to many challenges associated with socio-economic and socio-political fluctuations. Over the recent years such drivers have initiated new opportunities and shifted the focus of competitive markets eastwards (Flight International, 2006b), where high growth figures appear promising in sustaining global expansion plans. However, the aerospace sector is inherently highly volatile and remains one which is affected to its core by an ever increasing list of current and potential factors, from terrorism to SARS and avian flu. The very nature of some such factors is unpredictable as they have the ability to both fuel and constrain the growth rate of an industry, already hard hit and only recently showing signs of recovery. As a result, this industry can ill afford to have failures or losses in areas such as MRO, where they are relying on effective and efficient systems to support their existing business models and maintain some semblance of stability and security in their operations. Such a sense of stability could be enhanced within ones immediate operating environment through the reliance on effective and robust solutions. This would allow companies to focus on other areas, such as pursue new business or expansive ventures. With many new MRO ventures widely planned and expansion plans existing for many others (Read, 2006), maintaining a competitive edge in the market remains challenging.

This paper has reviewed systems used for managing existing MRO operations in the civil aircraft sector and has discussed the problems/constraints inherently present in carrying out such operations under current socio-economic conditions. The paper has discussed the role of e-business tools and technologies in enabling and supporting next generation business applications. A case study was presented describing the development of an e-MRO system for a UK based cargo aircraft operator. Utilisation of the e-MRO system has enabled improved visibility of the MRO task and afforded better optimisation through advance scheduling operations. Furthermore, the system allows a more proactive approach to the MRO requirement and enables advance sourcing and monitoring of supplies and service requirements. Finally, future work was presented outlining the need to incorporate the forecasting functionality as well as the IFPM-integrated flight parameter monitoring module.
REFERENCES:


