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Product lifecycle management in aviation maintenance, repair and overhaul

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Abstract

This publication discusses the evolution of CAD, CAM, and CAE tools through product data management systems into today's product lifecycle management (PLM), followed by a review of the characteristics and benefits of PLM. Current practices and potential applications of PLM in aviation maintenance, repair and overhaul (MRO) are discussed through case studies, two of which were from the authors' experience.

Keywords: Product lifecycle management; Maintenance, repair and overhaul; Enterprise management; PDM; CAD/CAM

1. Introduction

Modern day enterprises are confronted by challenges arising from continuous innovations, global collaborations, and complex risk management. Intellectual assets in the form of product and process data must be accessible to anyone in the value chain. To address these issues, product lifecycle management (PLM) is proposed in recent years as a business approach integrating people, processes, business systems and information to manage the complete life cycle of a product across enterprises. PLM enables the collaborative creation, management, dissemination, and use of product definition and process operation information across the extended enterprise from market concept to product retirement.

As the life span of an aircraft is over 30 years, opportunities abound for the application of PLM in aviation maintenance, repair and overhaul (MRO). Yet, the use of PLM in the support phase is not as widespread in the aviation industry as the design phase. The aim of this paper is to study the opportunities, advantages and caveats of implementing PLM in the aircraft MRO industry.

This report consists of three sections including this introduction. The second section surveys the realm of PLM. The third section discusses the opportunities and advantages of applying PLM in the aviation MRO industry through case studies.

2. An overview of PLM

2.1. The evolution of PLM

Product lifecycle management (PLM) originated from two roots. One is enterprise management, which can be further subdivided into material resource planning (MRP), enterprise resource planning (ERP), customer relationship management (CRM), and supply chain management (SCM). Because of the visibility across the complete lifecycle of a product, the attendant risks can be estimated. In this sense, PLM serves as a decision support tool.

The other root is the management of product information throughout the entire lifecycle of the product [1]. In this context, system integration facilitates the collaboration among virtual enterprises. Computer-Aided Design and Manufacturing (CAD/CAM) and product data management (PDM) systems [2] play a major role here. CAD systems emerged in the early 1980s and enabled designers to create geometric models of the product more easily than on paper. Such digital designs can be more easily manipulated and reused. With time, the volume of product information created by authoring Computer-Aided Design, Manufacturing and Engineering

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(CAD/CAM/CAE) tools threatened to get out of control. As a result, product data management (PDM) systems appeared in the 1980s [2].

PDM provided easy, quick and secure access to data created during product design. First generation PDM systems were effective in the engineering domain, but failed to address non-engineering activities such as sales, marketing and supply change management as well as entities external to a company like customers and suppliers. Further expansion of PDM was hindered in two ways:

1. The information managed by early systems was limited to engineering information such as geometric models, bills of material and finite element analysis models.
2. The use of PDM systems required engineering knowledge.

With the advent of the Internet, web-based PDM systems became more accessible to suppliers and other parties outside of the enterprise. However, PDM was still confined to engineering information but not other aspects of the product's lifecycle [2].

Product lifecycle management (PLM) appeared later in the 1990s with the aim of moving beyond mere engineering aspects of an enterprise. PLM seeks to manage information throughout all the stages of a product's lifecycle such as design, manufacturing, marketing, sales and after-sales service. As such, ERP, CRM and SCM are integral parts of PLM [2]. These applications focus on specific processes during a product's lifecycle and depend on product and process information. PLM extends PDM beyond engineering and manufacturing into more strategic areas like marketing, finance, and after-sales service throughout the lifecycle of the product [3]. Clearly, the information resident in PLM systems exceeds the engineering data provided by PDM systems. Ideally, each time a product model is modified, the change is propagated throughout the lifecycle of the product and its real impact becomes measurable. Compared to this, PDM systems only notify other engineering applications of any changes [4]. To the authors' best understanding, no comprehensive PLM system exists as of today and so PLM remains very much in the research domain.

2.2. What PLM entails

CIMdata [5] defines PLM as a strategic business approach that applies a consistent set of business solutions in support of collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, from concept to end-of-life, integrating people, processes, business systems, and information [1]. During the life of a product, a large amount of data is generated. This includes CAD data, specifications, quality documents, bill of materials, engineering simulations, etc., which are shared throughout the extended enterprise [1]. PLM applications form the product information backbone for a company and its extended enterprise [5,6]. CIMdata defines three major considerations in any product lifecycle: product definition, production definition, operational support [5]. Product definition encompasses information about how the product is designed, manufactured, operated or used, serviced, and then retired. This data is continually updated throughout a product's lifecycle [5]. Production definition focuses on all activities associated with the production and the distribution of a product. Operational support focuses on managing the enterprise's core resources, i.e., its people, finances, and other resources required to support the enterprise [5].

Ameri and Dutta [2] define PLM as a knowledge management solution for product lifecycles within the extended enterprise. They define knowledge as organized, validated information that can be used purposefully in problem solving. From a manufacturer's point of view, the lifecycle of a product comprises five phases: imagination, definition, realization, support, and retirement [1,7]. During the imagination phase, the market requirements are determined and a product design concept is realized. The definition phase consists of the detailed design of the product, the planning of the manufacturing process and the development of a prototype. The actual production and the subsequent warehousing take place in the realization phase. During the support (or use) phase the manufacturer is responsible for the maintenance of the product. When the product is retired, it is disposed or recycled.

PLM has three fundamental concepts [1,5]:

1. A universal, secure, managed access and use of *product definition information*.
2. A persistent integrity of product definitions and related information throughout the life of the product.
3. The management and maintenance of *business processes* that create, manage, disseminate, share and use product information.

To achieve a universal product and process model, Thimm et al. proposed a semantically and graphically explicit description of product lifecycle stages using the Unified Markup Language (UML) [8]. To realize the information integration between knowledge based system and CAD/CAPP systems, Chen et al. [9,10] enhanced their interaction mechanisms through associative features [11], which are modeled based on intelligent design patterns. Different application feature types are unified with a generic definition [12]. Dynamic change propagation across different applications has also been explored [10]. Such research efforts advance the attractiveness of PLM by bridging declarative decision making modules and product/process oriented engineering applications.

2.3. Benefits of PLM

Generally, many benefits accrue from the adoption of PLM. It

- helps to deliver more innovative products and services in a shorter time[1,5],
- is able to shorten time-to-market [1,3,5],
- establishes a more comprehensive and collaborative relationship with customers, suppliers, and business partners [5],

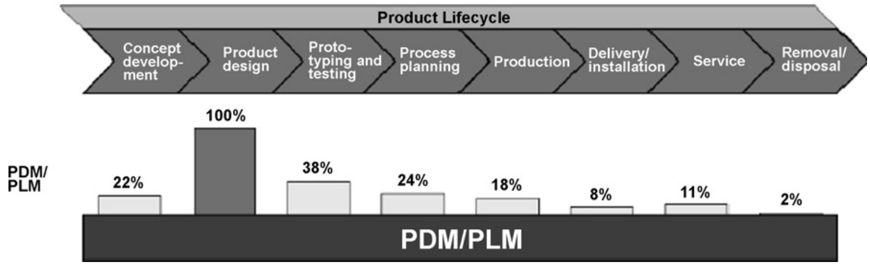

Fig. 1. Usage of PDM and PLM throughout a product's lifecycle; normalized to the product design phase (from [8]).

- improves communication among departments [3],
- improves the success rate of newly introduced products [3], and
- reduces costs by taking advantage of the efficiencies and effectiveness that come from improved market intelligence and business collaboration [1].

2.4. Adoption of PLM in industry

Today, PLM is primarily used in the automotive and aerospace industry, followed by the machinery industry [13]. Several vendors, including SAP, IBM, Dassault Systems, and UGS offer PLM solutions. Although PLM is meant to manage product information throughout the entire lifecycle of a product, an international study revealed that the adoption of PLM is still mainly limited to product design (see Fig. 1) [13]. The figure shows the relative intensities of PLM and PDM adoption in several stages of the product's lifecycle. It can be seen that PLM is used nearly 10 times less frequently in the service phase than in product design and that the use of PLM and PDM in the retirement phases is insignificant.

According to Abramovici et al., today's PLM applications are more than 5 years behind state of the art solutions. The trend in the next few years is expected to focus on product lifecycle stages in general and an improved support of engineering collaboration functionality [13].

3. PLM in the aviation industry

3.1. Aircraft design

As mentioned earlier, the automotive and aerospace industries are the biggest adopters of PLM. The high degree of penetration of PLM in the aerospace industry is due to the fact that their products have long lifecycles, are very complex and have nearly no possibility of physical prototyping [13–15].

In general, PLM has a major positive impact on business:

- IBM-Dassault's PLM Solution, ENOVIA VPM, enabled Dassault Aviation and its 27 partners in North America and Europe to collaboratively design the Falcon 7X business jet. Furthermore, 7 months were sufficient to assemble the aircraft instead the usual 16 for comparable aircrafts [16].
- UGS PLM solution's was deployed in the development of the Boeing 7X7 series of commercial aircraft and the F-35 Joint Strike Fighter (JSF). A Lockheed Martin-led coalition of military aircraft manufacturers and suppliers around the world designed as many as 5000 aircraft using Teamcenter™ with just three design variants to satisfy the operational needs of the USAF and RAF at the lowest cost of sustainment for a 30-year life of fleet. Lockheed Martin reported a 35 percent cycle time reduction and anticipates the manufacturing time to be reduced by 66 percent [17]. Lockheed has two primary partners, Northrop Grumman and BAE Systems, plus up to 1000 suppliers in 30 countries.
- Pratt & Whitney used Tecnomatix solutions in order to limit the development of its engines to within 3 years which was considered competitive. Besides that, the design is service friendly and minimizes downtimes by making maintenance operations as simple as possible [18]. The engines were designed such that no other components need to be removed for a line-replicable component to be replaced. During development, maintainability issues were addressed *via* 3D visualization and since there was no need for a physical mock-up development time and costs were significantly reduced [18].

3.2. Aviation maintenance, repair and overhaul

In the aviation industry, capital equipment and products with long service lives and complex configurations are a challenge. The profitability of the industry is not from the sale of aircraft, but from maintaining them for an anticipated thirty-plus year lifespan [5]. Aviation MRO companies, with assets in service for many years, need to focus on persistent product performance. Today, the global commercial aviation fleet includes more than 17,000 active aircraft. The 2005 operating budget for MRO exceeded US$38 billion and an inventory of spare parts is estimated at US$50 billion [19]. Furthermore, analysts expect a growth in operating budgets to nearly US$46 billion in 2010, exceeding US$54 billion by 2015 [19].

The main stakeholders in the use phase of an aircraft are: the operator of the aircraft, the aircraft manufacturer, part manufacturers, and the company that maintains, repairs and overhauls the aircraft. The objective of the aircraft operator is to ensure safe operation at minimal operating costs. Confining service to only those parts of the aircraft that require it, as opposed to servicing all units, increases profitability. In particular, PLM application goals are reducing the time that an aircraft is under maintenance, curbing actual maintenance costs, and lengthening the time between service. Aircraft manufacturers and part manufacturers want products that are safe and easy to maintain. MRO companies strive to minimize maintenance costs and turn-around time to maximize revenue for the owner.

Maintenance can be defined as the process of ensuring that a system continually performs its intended function at its designed-in level of reliability and safety. There are two types of maintenance: *scheduled maintenance* and *unscheduled maintenance* [20]. The former is a preventive form of maintenance conducted at pre-set intervals to ensure that the aircraft is air-worthy. Unscheduled maintenance is needed in the event of a breakdown. Such maintenance actions are more definitive, requiring extensive testing, adjusting and often a replacement or overhaul of parts or subsystems [20].

Scheduled maintenance and inspections consists of a battery of checks, depending on the number of flight hours elapsed: transit, 48 h, "A," "B," "C," and "D" checks [20]. The transit check is performed at each transit stop of the aircraft. 48 h checks are performed once every 48 h, and are more detailed than transit checks. The intervals for a Boeing 747–400 of "A", "B", "C" and "D" checks are 600, 1200, 5000 and 25,000 flight hours, respectively.

Maintenance is further classified as *on-* or *off-aircraft* [20]. On-aircraft maintenance is performed on or in the aircraft itself. On-aircraft maintenance can be done with or without taking the aircraft out of service. The former is called line maintenance and the latter hanger maintenance. Line maintenance entails work associated with, for example, transit, 48-h, "A," and "B" checks. Examples of such inspections include checking the brakes, oil levels, the condition of cargo door seals and the wing surfaces for obvious damage or oil leakage. Hanger maintenance entails scheduled checks, modifications of the aircraft or aircraft systems by an airworthiness directive or engineering order, special inspections mandated by the airline, the FAA or other regulations, painting of the aircraft and aircraft interior modifications. During hangar maintenance, the aircraft is out-of-service.

Off-aircraft maintenance entails the overhaul of systems removed from the aircraft which can be temporarily put out of service if substitute systems are not deployed. Aircraft availability can be measured as (MTBF/(MTBF+MTTR)) [21,22], where MTBF denotes *mean time between failures* and MTTR denotes *mean time to repair*. To increase aircraft availability either the MTBF needs to be increased or the MTTR decreased. These issues can be addressed in the product design phase. By improving the quality of the maintenance, the MTBF can be increased, and an improved turn-around-time equals a decrease of MTTR. More recently, due to high fuel cost, aviation operators have shifted the MRO responsibility to MRO companies, such as Honeywell, for integrated service solutions and asset availability [23].

3.3. PLM and aviation MRO

In order to ascertain the opportunities for PLM applications in a particular sector, its objectives need first to be identified. The objectives of aviation MRO are [20]:

1. To ensure or restore safety and reliability of the equipment.
2. To obtain the product and process information necessary to optimize maintenance when these inherent safety and reliability levels are not met.
3. To obtain the information necessary for component repair and tooling design for those items to be fully repaired or replaced during the overhaul process.
4. To accomplish these objectives within the required time limits and at a minimum total cost, including the costs of maintenance and the cost of residual failures.

The first objective can be realized by scheduled and unscheduled maintenance. The key technical information for any maintenance job is the component maintenance manual (CMM), which is supplied by the original equipment manufacturer (OEM), such as Boeing. Due to the complexity of the system, automated information retrieval, associative inspection and maintenance procedures and tools, product structure information, fault detection and isolation tools, and even 3D viewing and mark-up tools should be provided by the OEM *via* a PLM system. Currently, the processes are independent and largely manual. Further more, the ideal PLM system should be able to record, check and manage inspection and maintenance records, such as the replacement of certain parts after repair. Fig. 2 shows a typical high-pressure blade before and after repair [24]. Portal services tracking the lifespan and the inspection results can extend valuable air-time and improve time in service by applying integrated service systems. At Tinker Air Force Base in Oklahoma City, staff members use portable devices developed by UGS and Intel for wireless access to maintenance records and technical manuals where and when these are needed. Each item that needs repair is displayed as an image or 3D CAD model. This reduces the time personnel spend searching paper files, fill out (paper) forms and search through maintenance manuals. The system can also search for historic data on similar maintenance issues and their resolution [25]. Aside from maintenance, another way to reduce costs is to minimize waste in the value chain. With PLM, paperwork is reduced, thus allowing staff more time to perform value-adding tasks.

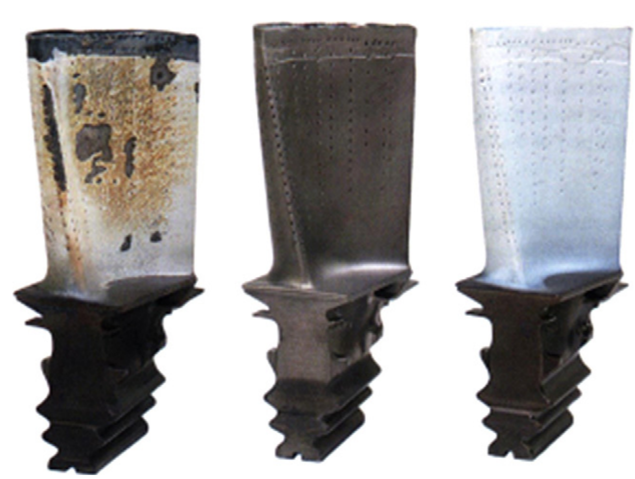

Fig. 2. A high pressure blade before and after rejuvenation repair [27].

Clearly, every airline operator seeks cost-effective and reliable MRO vendors for their regular maintenance contracts. An evaluation of maintenance tasks including whether to repair or to replace items is the common task of both the operator and the vendors. Here, detailed product engineering knowledge and procedures involved in any repair are necessary. Future PLM systems should be able to offer more than the current hard copy standard service bulletins or rough experience-based estimations. Fig. 3 shows the inner skin of an outer carbon cover after removal from the honeycomb core, the damaged honeycomb core on the inner skin, and the repaired panel. Integrated product and process information play an important role in timely and efficient repair. Furthermore, OEM and MRO companies have to exchange information such as the bid price, part numbers, references to standard service bulletins, procedures, the repair schedule, inspection results, and the final agreed repair plan. Clearly, collaborative information sharing reduces overall maintenance costs and time.

The impact of PLM also lies in the feedback, either within an enterprise, an extended enterprise, or across lifecycle stages of the product. The PLM collaborative management function is especially helpful for service quality assurance. Vendor service quality can be evaluated by an investigation into why safety and reliability levels are inadequate. Reasons may include maintenance or parts of low quality, inadequate maintenance processes and procedures, or unsuitable maintenance intervals. Immediate improvement measures should be implemented and, if necessary, new vendors should be appointed. Through such feedback, the maintenance schedule can be revised and optimized, realizing the third objective of maintenance. Research revealed that 40% of the replacements of engine-driven air compressors on the Navy P-3 Maritime Patrol aircraft were unnecessary [21]. PLM can potentially lower maintenance to a level that meets safety and reliability standards. For example, a European airline achieved a 15% drop in unscheduled downtime and a 25% reduction in overall MRO costs by using PLM [26]. An Asian airline even reported a 40% decrease in unplanned maintenance [26].

Such feedback to the OEMs potentially improves the design of aircraft of the same or different model, thereby realizing the close loop of design for maintenance and service. Because PLM can be pervasive throughout the extended enterprise, such systems will lead to not only an active change in the design and manufacturing phases but also in business activities like ERP and SCM.

In the case of off-aircraft repair or overhaul, a PLM solution can really be deployed in a pervasive manner in order to achieve the third and fourth objectives given at the beginning of this section. Feature-based information integration on product and process models is one such approach as illustrated in the case study of the next section.

Last but not least, PLM can play a role in the optimization of inventory. By having the right part at the right place at the right time, there is no need for expensive back-order. Carrying costs can be minimized and turn-around time for an overhaul project can be reduced. Shorter turn-around time means increased revenue for the airline operator.

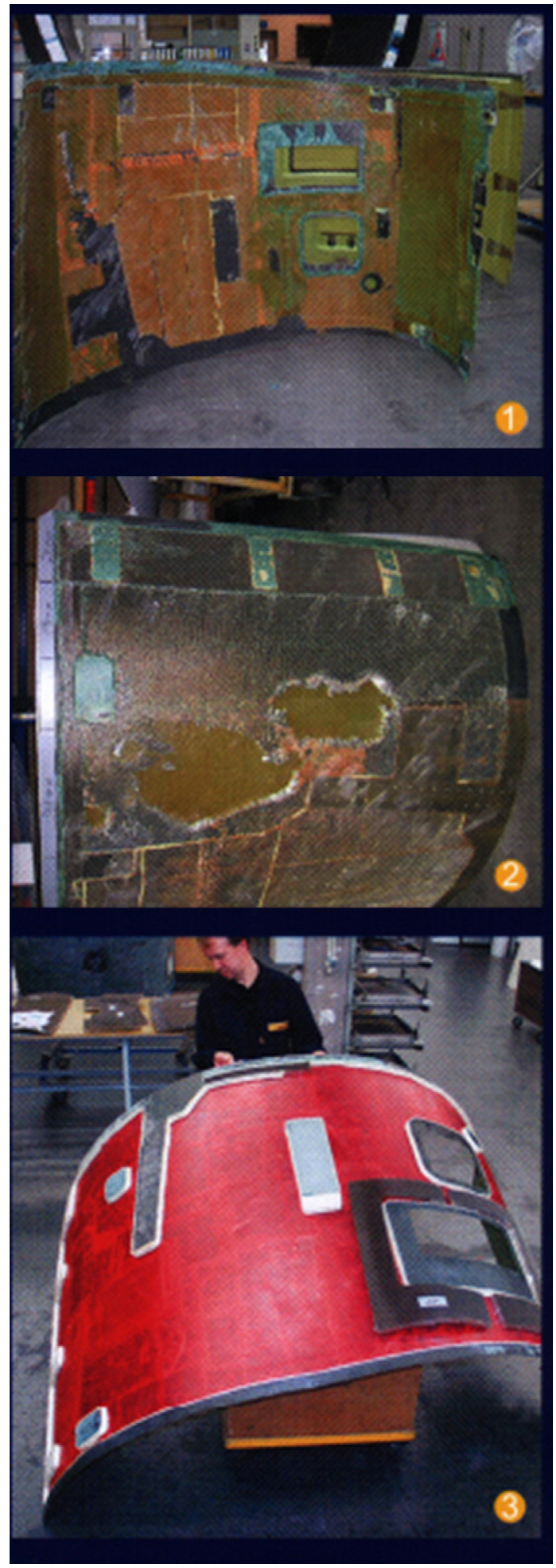

Fig. 3. Outer cover panel repaired [27].

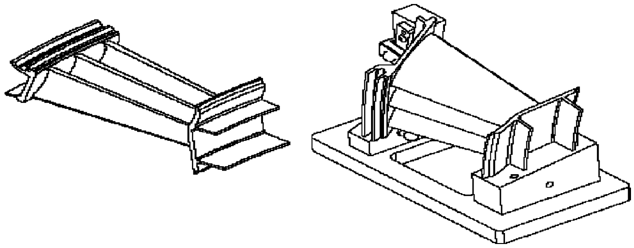

Fig. 4. Feature level product information sharing across design and repair stages.

Thus, it can be seen that the impact of PLM on aviation MRO is considerable.

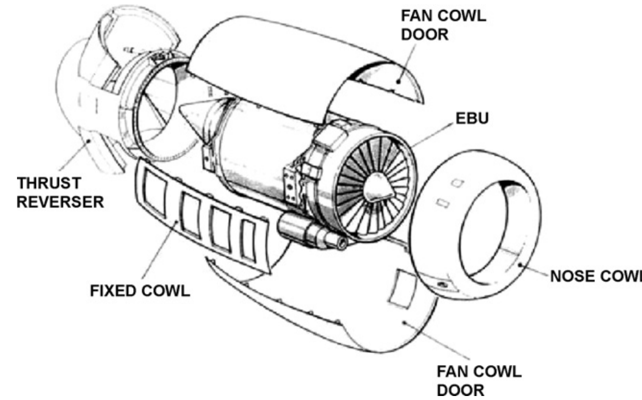

Fig. 5. A typical aircraft nacelle assembly.

3.4. Case study

Two case studies involving two MRO companies in Singapore will be discussed.

The first company repairs turbine blades (see Fig. 4). Damaged blades are usually cleaned, inspected for damage, and the craters filled with qualified material by welding. The repaired blade is then machined back to its original shape. It was a surprise to the authors that the part definition data was derived by reverse engineering from coordinate measurements, which are of limited accuracy. The part geometry is then reconstructed in CAD, and then the repair fixtures and jigs for EDM machining, milling polishing, etc., are designed based on these reconstructed CAD models. Because the CAD models were not the original design but re-constructed from measured profiles, the repair fixtures that were designed based on the reconstructed CAD models are inaccurate. This could have been averted if the repair fixtures were designed based on the original product model. Furthermore, the original datum, axes and origins can be referenced for quality checks, rather than those chosen by the repair engineers based on their experience. Such breakdown of information flow between the OEM and

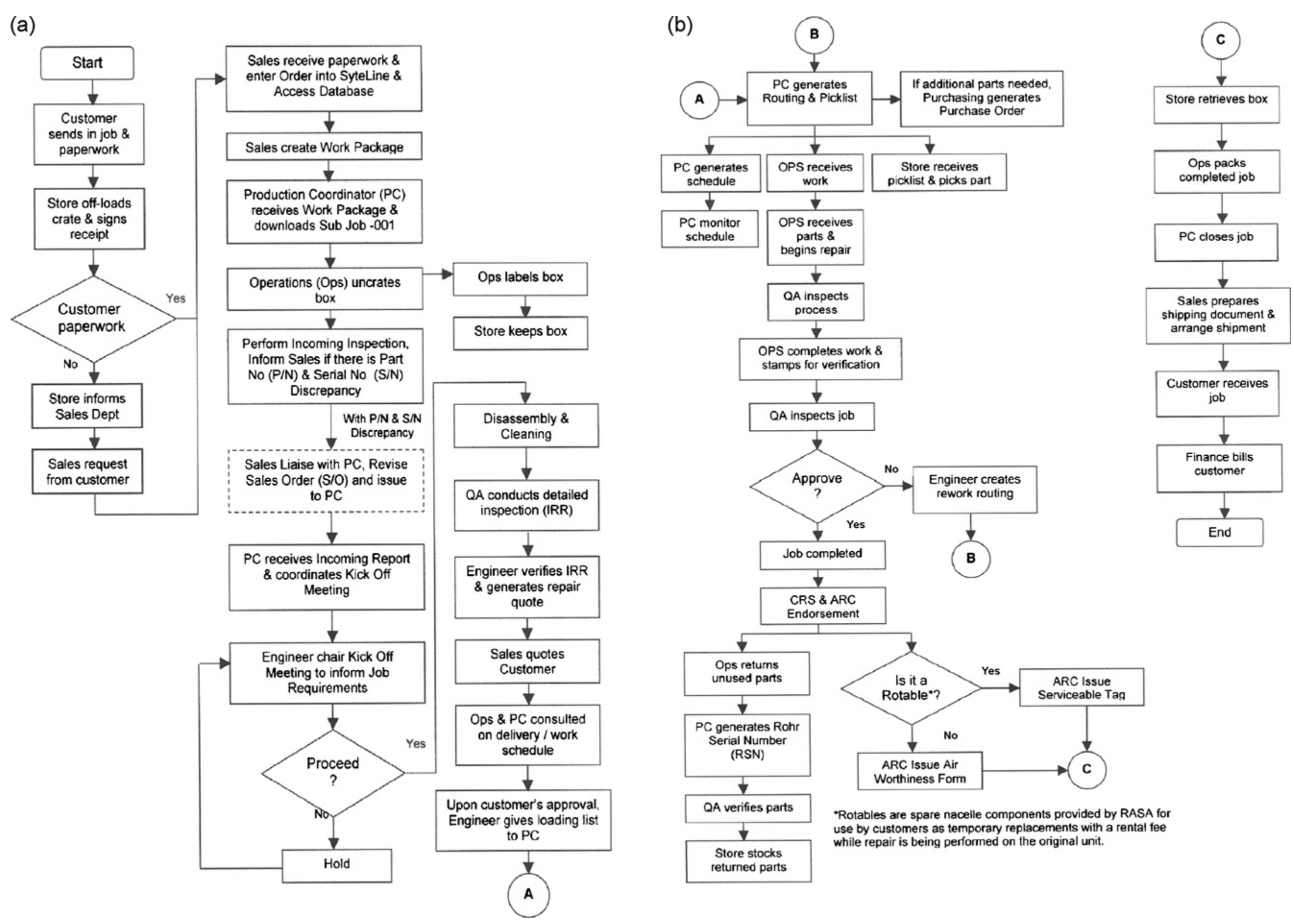

Fig. 6. Repair work flow procedure.

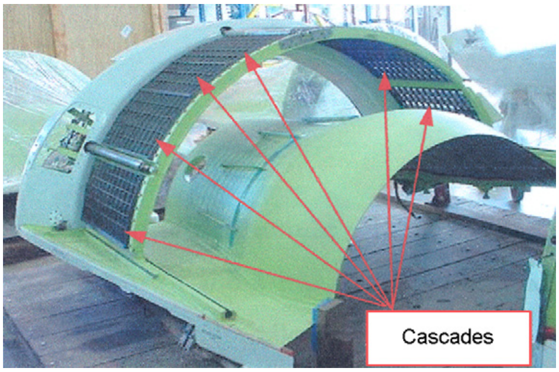

Fig. 7. The engine core cowl and the thrust reverse cascades (by courtesy of Goodrich Singapore Pte. Ltd.).

Fig. 9. A typical tool used to repair core cowl composite layers (http://www.aerostructures.goodrich.com/html/rd_nonmetals.asp).

down stream part repair companies is very common and disruptive.

In a PLM set-up, the OEM can easily share product definition data with the MRO vendors without affecting the OEM's intellectual property rights. In this way, the MRO vendor can repair all kinds of parts and the quality of repair can be expected to be much higher.

The second MRO case study involves the overhaul of the aircraft nacelle system. A typical nacelle assembly is illustrated in Fig. 5.

As shown in Fig. 6(a) and (b), the business processes start with the customer sending in the job, ending with three possible scenarios: (1) customer rejects quotation due to disagreement with price, delivery time, or other issues; (2) overhaul completed to the customer's satisfaction; or (3) the job encountered delays because of technical or other issues. Due to stringent qualifications, the MRO operations are recorded in detail every step of the way. In addition, procedural compliance to standards is mandated. In the company mentioned, an in-house process management system was adopted.

Clearly, the MRO vendor did not synchronize its system with the OEM's product management system, giving rise to discrepancies in information such as part numbers, document numbers, reference procedures, working bill of material, etc.

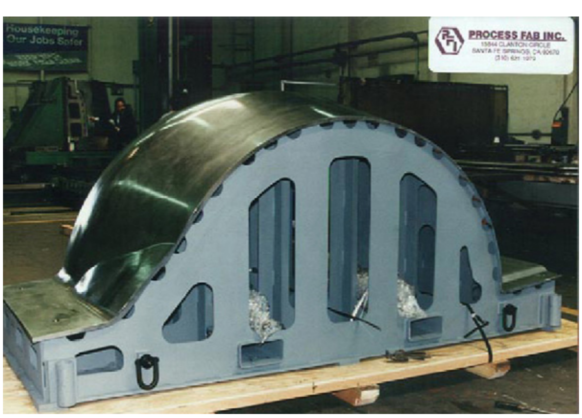

Fig. 8. An example core cowl lay-off tool (http://www.processfab.com/imx/part11.jpg).

Since the original design data such as the shape of the cowl was not accessible, to maintain the original shape of the cowls after disassembly (see Fig. 7), lay off tools like the one shown in Fig. 8 are first used to mount them before repair began. In addition, for the composite cowl repair work, convex tools such as that shown in Fig. 9 are required. Again, the features of the repair tool are mapped from the surfaces of the product. It is therefore necessary for the PLM system to support feature-based information sharing and representation [9–11]. In fact, if product data is available, the tools need not be procured from overseas since they can be manufactured locally more economically. However, as it is, the MRO company has to rent such tools from the OEM at considerable cost. Cost aside, considerable delays are often encountered.

It can be appreciated that PLM applications in the MRO industry have many similarities with collaborative virtual enterprises in upstream aircraft manufacturing. In both situations, product and process data are merged, through unified features. In the case of PLM, it is imperative that data is associative and integrated throughout the entire lifecycle of the product, subject to constraints. Because of the dynamically changing environment, it is necessary to identify, predict and manage risks.

4. Concluding remarks

Presently, PLM is mainly adopted in the design phase of aircrafts with impressive results. However, in comparison with the design of aircraft, PLM is used nearly 10 times less frequently in maintenance, repair and overhaul. Because of the long lifespan of aircrafts, this means that the potential of PLM in aviation MRO activities has not been realized.

The potential impact of PLM on aviation MRO is great as the two case studies show. However, much research is still needed in data and constraint management although a few successful initiatives have been reported. Ideally, PLM provides reliable and accurate feedback among partners in an extended enterprise and among the various lifecycle stages of a product; it could optimize inventory levels and improve the efficiency of scheduled or unscheduled maintenance by cutting down on non-value add tasks.

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