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THE MANAGEMENT OF MANUFACTURING PROCESSES USING COMPLEMENTARY INFORMATION STRUCTURES

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ABSTRACT

The reality of manufacturing planning is very different from the one of engineering design. Whereas the former must manage variables of an extrinsic nature (time, cost and quality), the latter manages the form, fit and function of the product, variables of an intrinsic nature. Information coherency between the product definition, the process plan and manufacturing resources must be maintained at all times. Complementary product structures have therefore been proposed as an alternative to the unified multi-view product models developed in earlier research. They allow users to create customized product structures which are linked together at the component level and can be managed separately. Ensuring consistency between these structures relies only on managing the links rather than attempting to maintain a unified product model. The Complementary Information Structures paradigm is fully illustrated through the example of an aircraft pylon design, where the step by step development of its manufacturing Bill of Materials is detailed.

Keywords: Complementary Information Structures, Product Lifecycle Management Solutions, Manufacturing Process Management, Lean Thinking.

1 INTRODUCTION

The Lean philosophy applied to both product development and production activities has pragmatized the general approach to efficient engineering and manufacturing work. The lean principles essentially promote the reduction of waste; waste in terms of knowledge during the product development phase or waste in terms of quality and time during the production phase [1]. Toyota Motor Corp. is widely recognized as the founder of everything and anything “lean” in the manufacturing industry. The set-based design process used at Toyota relies on the generation of an unusually high number of concepts, which are followed through in parallel up until the production of scaled down prototypes [2]. As a consequence Digital Mock-Up (DMU) technologies, effectively enabled by Product Lifecycle Management (PLM) software, have been called upon in order to reduce the costly physical prototyping activities. In the light of Information Technologies, Lean principles are therefore influencing the design of new information systems that support product lifecycle activities.

In simple terms, PLM is about integrating the various data management solutions developed for the different stages of the life of a product (CAD, CAM, PDM, MRP, ERP, CRM, etc.) in a comprehensive platform destined to improve the information and data share between partners, clients, and suppliers in a virtual product development environment [3]. Nevertheless, PLM systems, in comparison to their CAD or ERP fathers, are still in a state of relative infancy and research is ongoing. Although most commercial PLM solutions propose a similar variety of functions and applications, they are based on different information structure backbones. These essentially dictate information flow and communication between the different modules used by the various stakeholders involved in the lifecycle of the product. Within this context, this paper presents the innovative concept of “complementary information structures”, and illustrates its use via the interaction between the PDM and Manufacturing Process Management (MPM) modules of a PLM platform. A real use case of the development of an aircraft pylon is presented and offers the reader a step by step example of how engineering and manufacturing data can be efficiently synchronized using the complementary information structures approach.

2 MANUFACTURING PROCESS MANAGEMENT

Vandevelde and Van Dierdonck [4] conducted studies on the integration mechanisms in place between design and manufacturing. From these studies, barriers to the effective exchange of information between design and manufacturing were highlighted, i.e. physical barriers, organizational barriers and technical language barriers. Twigg [5] came to the same conclusion while studying the design and manufacturing interface across firms. Both authors concur on the fact that formalization of information exchanges is needed to improve the integration of design and manufacturing.

This section will first describe the differences between manufacturing and design realities and the requirements this places on the creation and organization of product related information from the point of view of various actors.

2.1 Manufacturing planning and engineering design

Design engineering defines what the product must be, starting from the requirements and finishing with the complete detailed product definition. The form, fit and function characteristics of the product, which are essentially of an intrinsic nature [6], are thus the key elements in this domain. Manufacturing realities must be taken into account to define the manufacturing strategy and the complete set of process plans. The former includes a range of activities that are carried out within a dynamic process where constant changes happen. Information coherency between the product definition, the process plan and manufacturing resources must be maintained at all times. The manufacturing planning activities essentially start at the strategic planning phase of the product development with tasks such as plant selection, innovation in manufacturing processes and supply chain strategy. The manufacturing planning phase terminates at the end of the production ramp-up process, the point where production stability is reached. Hence, the goal of the process-planning task is to completely define the processes required to realise a product, given its specification and available manufacturing resources. To fulfil their tasks, process-planning engineers need access to plant resources such as the available equipment and manufacturing processes defined by the company. They define how the concept will be transformed into the final product. The reality of manufacturing planning, where motivations are related to variables of an extrinsic nature (time, cost and quality), is very different from the one of design engineering.

2.2 Functional requirements and constraints of an MPM solution

The role of MPM is to cover all activities of the manufacturing planning function within the product development activities. It essentially starts with the strategic planning of the product development and finishes when the production ramp-up process is completed (the point in time where production stability is reached) [7]. This is a difficult task but must be done properly to remove the numerous inconsistencies, which induce errors in the product development cycle. An MPM system prepares information for production scheduling, but does not replace any Manufacturing Resource Planning (MRP), Manufacturing Execution System (MES) or Enterprise Resource Planning (ERP) system. It is rather an interactive platform that transfers the data from the virtual 3D product definition environment to the manufacturing systems. Figure 1 summarizes the various functions and constraints that need to be met by an MPM solution [7].

It must be pointed out that the goal is to maintain a complete synchronisation of the information between engineering and manufacturing definitions at all times. As shown in Figure 1 the system needs a real-time interface with CAD and PDM systems in order to track changes and offer a continuous workflow with the engineering system. This workflow, with the proper business rules in place to control the maturity of information, can create an effective pull of the product design data from engineering to manufacturing. The platform must be powerful enough to manage the complete 3D manufacturing mockup, which can include all the instances of parts and sub-assemblies with a proper revision status. Emphasis must therefore be placed on ensuring the product/manufacturing process data integrity within an interactive platform with access to a number of libraries as shown at the bottom of Figure 1. A powerful search engine is needed to identify the required information based on the existing relationships between these various entities. Once the manufacturing information has been designed and approved, it is released to production pending a version control. In this case also, synchronisation must be maintained between the production and manufacturing planning information sources. Clear definitions of all information authorships must be maintained. Quality feedback from the shop floor can also be used to track the performance of previous manufacturing plans.

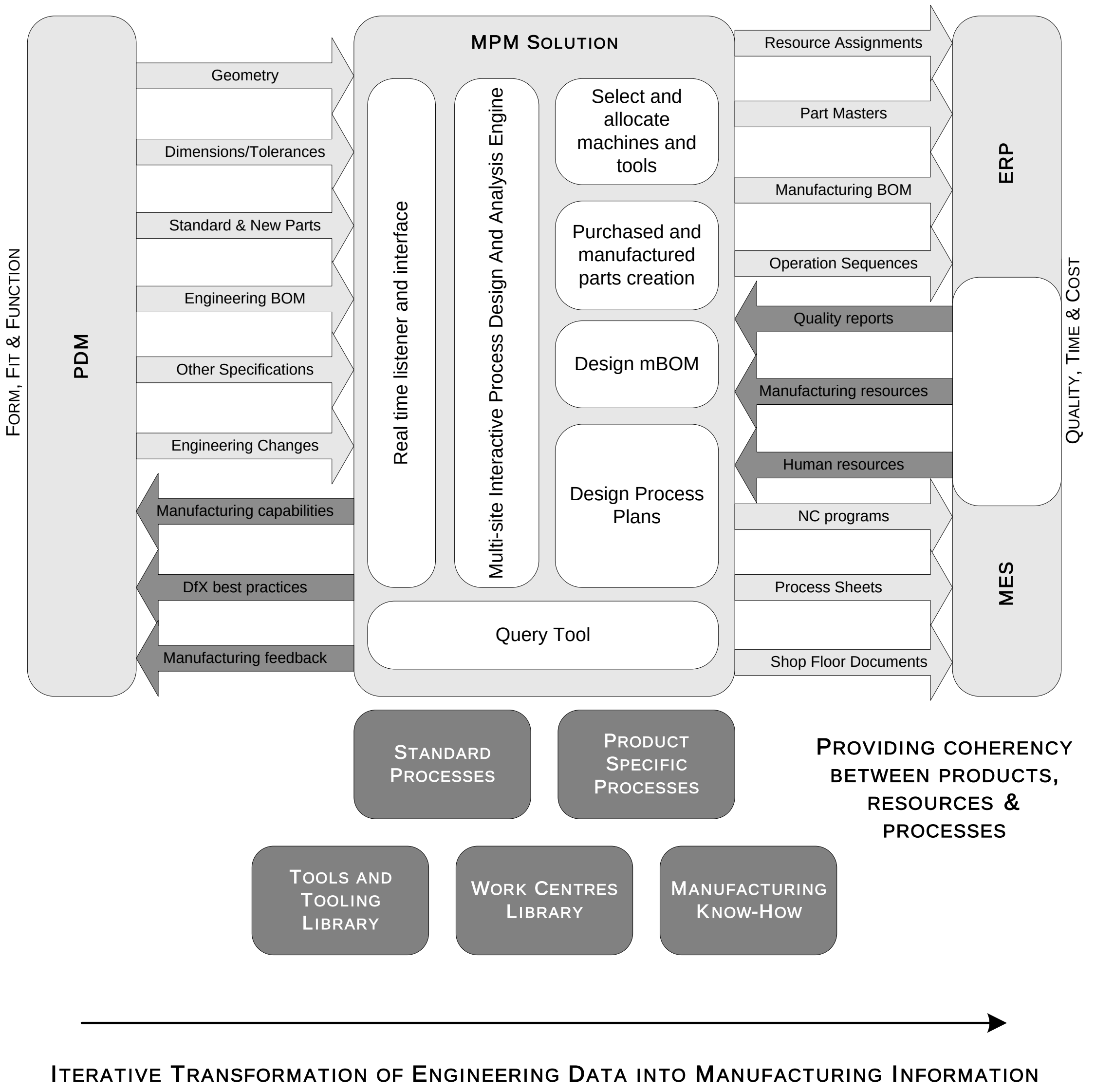


Figure 1. Functional requirements of a Manufacturing Process Management system [7]

Finally, one of the core activities involved in the development of products is the management of changes for both the product and its corresponding manufacturing plan [8]. An engineering change will always have an impact on the manufacturing process definition of the product. The same is also true, when a modification is initiated on the manufacturing planning side; this change will always have an impact on the production but not necessarily on the product definition. A genuine MPM system must support the standard change and configuration management methodologies such as the one proposed by the Configuration Management Institute, the CMII model [9].

2.1 Research in the field of Manufacturing Process Management

The different requirements of design and manufacturing engineers have long been recognized by researchers. However it is only within the last 20 years that efforts have begun to develop systematic methods enabling these differences to be reflected in the information technology tools used by the various actors throughout the product lifecycle. On one level, this has been enabled by the development of CAD/CAM systems and the integration of CAPP software into the development process. However, it has also been widely recognized that these efforts must be extended to fully support the differing informational needs of manufacturing and engineering [7] [10] [11] [12]. The varied experience and fields of expertise of the different actors involved in product development creates a need for organizing and presenting product information in a way that can be understood and fully leveraged by all involved.

While this field of research is still not widely treated in the literature [12], various strategies have been developed in order to enable customized representations of the product information. Zimmerman *et* *al.* [12] have proposed a system of linking engineering objects, known as Universal Linking of Engineering Objects (ULEO), in order to map features from the design view of a product model to the manufacturing view while maintaining links to ensure coherency of the information. Tichkiewitch & Veron [10] also proposed a system which uses a product model to link the data model and the knowledge model used in a product development process. The individual users can customize their view of the product model based on their role within the product development team. This has been implemented to a certain degree within a system known as CoDemo.

Both ULEO and CoDemo are built on the philosophy of providing different views of a large, unified product model, known as the multi-view model. In other words, while the features or engineering objects within the product model are mapped onto different views, the links between these objects are created and maintained within the unified model. While this allows for a certain level of granularity which can facilitate the previously mentioned attempts at automation, in practice such unified product models can quickly become unwieldy and difficult to maintain [7].

3 THE “COMPLEMENTARY INFORMATION STRUCTURES” PARADIGM

A standard method of structuring information within engineering domains is by means of association with a product structure, a hierarchical breakdown of a product into its constituent sub-assemblies and parts. In order to cater to the varied experience of actors, it is proposed that separate yet complementary structures can be used according to the needs of the stakeholder. These complementary product structures may be identical, or they could vary depending on the needs of the stakeholders. In contrast with the unified product model approaches discussed previously, complementary product structures allow users to create customized product structures which are linked together at the component level (i.e. part or assembly). The individual product structures can then be managed separately, for example within the separate modules of a PLM solution, an example of which will be presented in section 4.

As suggested above, the product structures are kept consistent by means of links. As such, it is not a question of maintaining a unified product model, but that of maintaining the links between several product structures. It is also important to understand that the nature of the links between two product structures will differ from one interface to another.

Here, the authors will focus on the underlying relationships between design and manufacturing discussed previously in section 2. In the case of design and manufacturing activities, the product structures can be referred to as ‘as designed’ and ‘as planned’ respectively. Hence, according to the complementary structures approach, the team in charge of the process planning manages *as-planned* structures, also known as manufacturing Bill of Material (mBOM). These manufacturing product structures result from the manufacturing strategies and are rarely identical to the *as-designed* structure, also known as the engineering Bill of Material (eBOM). However, the structures remain interconnected through the MPM module, which uses 3 types of links:

- equivalence link to relate a part iteration in the manufacturing BOM to the equivalent part in the engineering BOM and thus ensures conformity and traceability;
- occurrence link to relate the position of equivalent parts within the engineering and manufacturing BOMs and thus enable the view of the identical mock-up;
- Reference link to propagate change when part iteration on the manufacturing side doesn’t have a strict equivalent on the engineering one.

As a result, a component that a designer views as a single part may be considered to be an assembly by the manufacturing department due to the necessary fabrication method. While the parts may be organized in different subassemblies in the eBOM and mBOM, the 3D positioning of the parts within the mock-up is retained between the two BOMs. This ensures that the mock-up as viewed by both design and manufacturing engineers remains identical.

The existing complementarities between both engineering and manufacturing product information structures described above support complex change process mechanisms. For example, any change to the design of a product will entail a change to the manufacturing process, as this implies a change to, for example, the geometry, tolerances or materials. Furthermore, changes to the product become more and more formalized as the design progresses.

4 MPM IN ACTION: THE RETROFIT OF AN AIRCRAFT ENGINE

This section details a practical example consisting of a cross-functional parallelisation of tasks between a design and a manufacturing team. The use case is drawn from the Virtual Environment student Project held each year at Ecole Polytechnique de Montreal [13]. This case study features a development team involved in a significant engineering change consisting of the design of a new pylon to install the PW305A engine from Pratt & Whitney Canada on a Bombardier Aerospace CRJ-700 regional jet. The retrofit provides a new variant of the aircraft and the change necessitates re-establishing compliance with aviation regulations. This basically means carrying certification tests and presenting analysis reports concerning the main subassemblies, along with the bleed air, fire extinguishing, fuel, hydraulic and electrical systems. For the purpose of the case study detailed in this paper, the development of the forward engine mount has been chosen.

4.1 The as-design product strcture (eBOM)

The *as-designed* forward engine mount assembly (eBOM) and its respective DMU representation are displayed in Fig. 2. The front mount is a core assembly within the pylon structural design and is to withstand severe loads, vibrations and eventually fire. It is the link between the engine and the fuselage frame. The connection to the engine has to be as flexible as possible to ease engine installation and to sustain slight movements during specific flight stages.

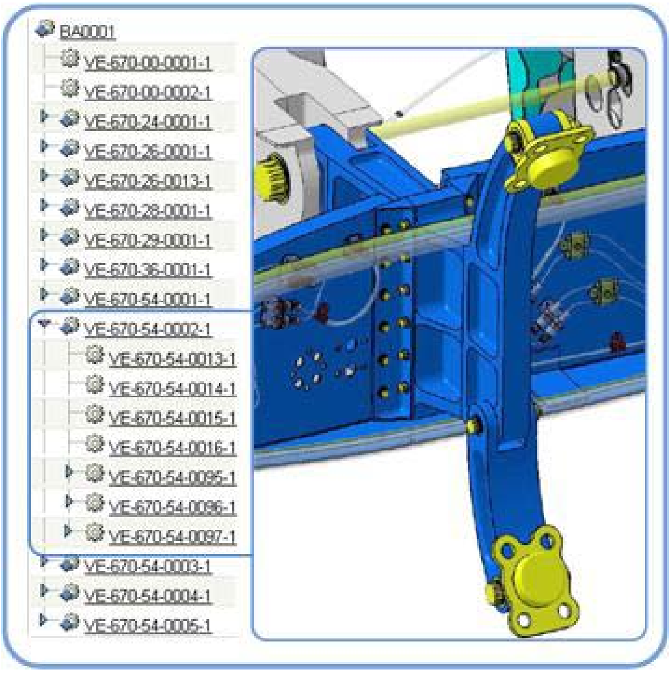


Figure 2. Aircraft pylon forward engine mount eBOM and corresponding DMU.

Fig. 3 contains a 3D wireframe view of the front mount assembly and its representative eBOM. While for the sake of clarity the eBOMs presented in Figs. 2 & 3 do not expand subassemblies B, C, and G, the wireframe in Fig. 3 demonstrates how subassembly C is composed of three other subassemblies, namely C1, C2 and C3. Each of these subassemblies contain the hardware necessary for assembling the front engine mount such as bearings to allow pivoting movements, as well as titanium fasteners to strengthen the connections.

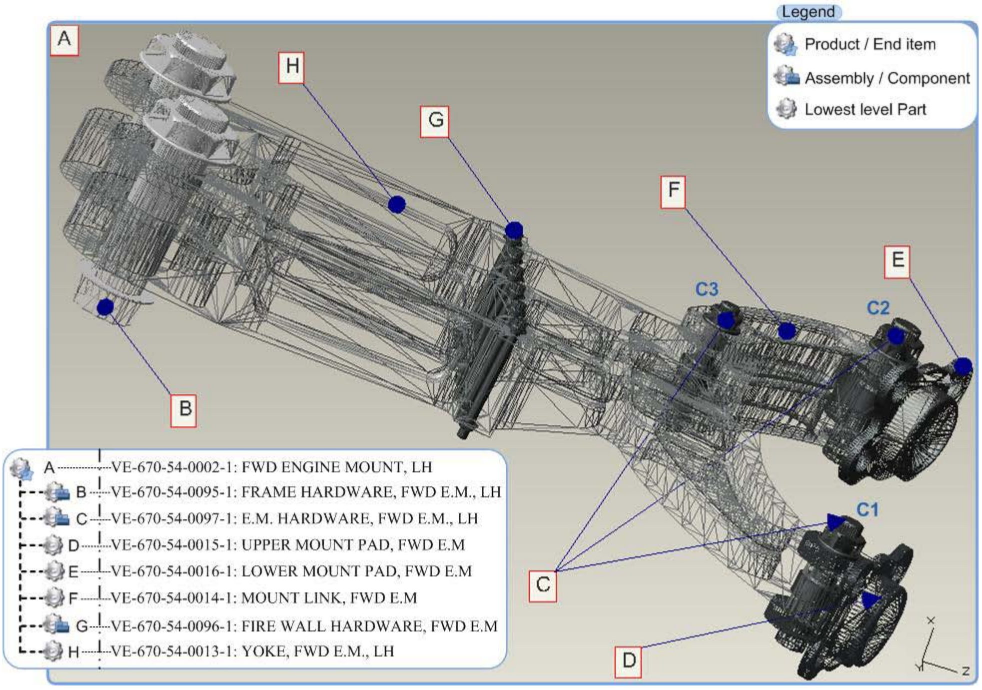


Figure 3. A 3D wireframe view of the forward engine mount

The eBOMs shown in Fig. 2 and Fig. 3 were provided by designers in conformity with the functional view of this specific end-item. In parallel to the design team, the team in charge of the process planning manages the mBOM. Relying on the equivalence, occurrence, and reference links embedded in the MPM module, the steps through which a manufacturing structure is built and maintained are described in the next sub-section. It will be seen that the functional arrangement presented above stands in contrast to the manufacturing arrangement of the mBOM presented in section 4.2.

4.2 Building and maintaining a manufacturing complementary structure

The manufacturing activities start with an access to partial design data. While having access to the same functional views as the designers, the manufacturing engineers have to use their expertise to actually deploy strategies to build, assemble and eventually test the artefact based on the shop floor resources and constraints. The manufacturing product structure results from the manufacturing strategies and is rarely identical to the *as-designed* structure.

Regarding the forward engine mount, its manufacture has been found to necessitate quite a different breakdown structure from the *as-designed* one. This mBOM needs to follow a strict chronology of operations to end-up with a mechanism that can be manufactured and assembled. The processes required are as follows:

(1) The assembly of the Upper Mount Pad (D in Fig. 3) to the Yoke (H) by means of the joining hardware (C1). This consists of various operations such as the press fitting of bearings into the yoke, the placement of washers and the tightening of nuts onto a bolt at required torques.

(2) The assembly of the Lower Mount Pad (E) to the Mount Link (F) by means of the joining hardware (C2) by means of similar processes as detailed in (1).

(3) The assembly of the newly completed sub-assemblies using the joining hardware (C3) in order to complete the main structure of the Forward Engine Mount (A).

When attaching the mount to the fuselage frame and the firewall, all the other components (i.e. B and G in Fig. 3) are installed and the physical assembly of the mount with the aircraft is therefore considered achieved.

In order to reflect the chronology of these operations in the mBOM, the manufacturing product structure includes *MFG-ASSY-001*, which contains the Upper Mount Pad (D), the Yoke (H) and the necessary joining hardware (C1) for the Forward Engine Mount. Similarly *MFG-ASSY-002* is made up of the Lower Mount Pad (E), the Mount Link (F) and the joining hardware (C2). This is different from the eBOM prepared by designers, where C1, C2 and C3 were included in a subassembly C. Fig. 4 exhibits the resulting mBOM and eBOM.

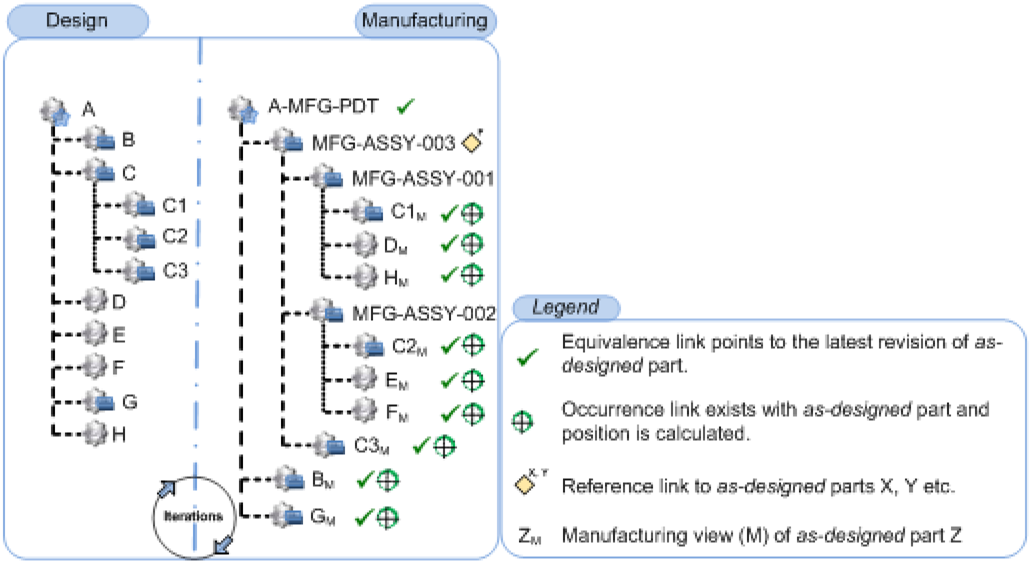
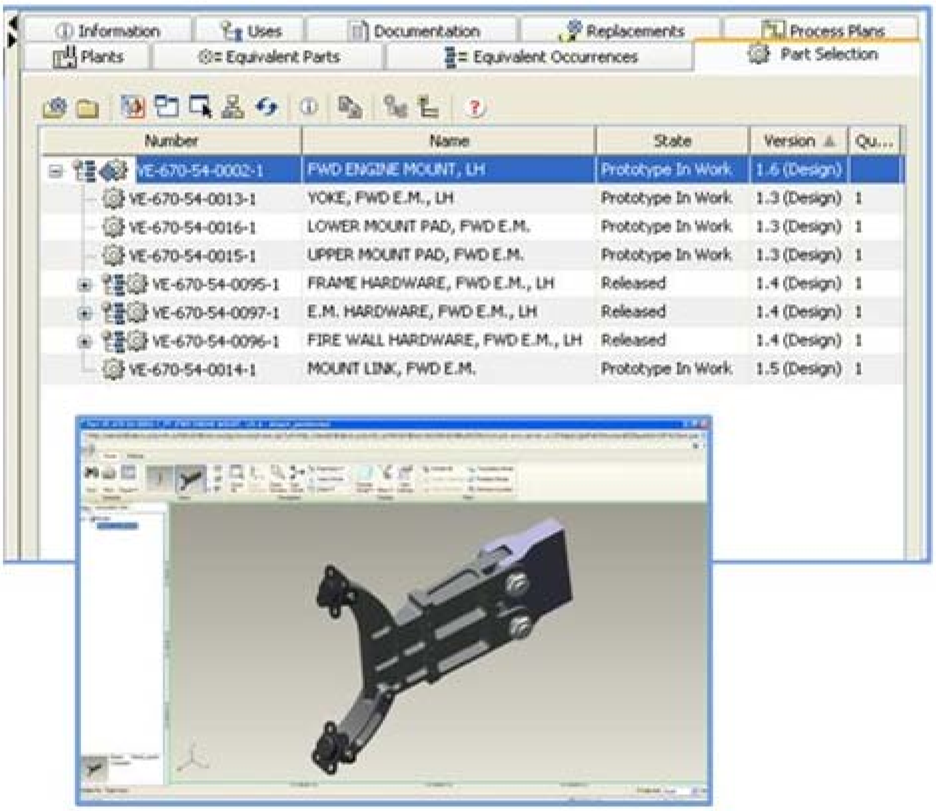


Figure 4. Design and manufacturing complementary information structures and links for the forward engine mount

The complementary information structure links are maintained throughout the design and manufacturing iterations. In fact, the described links are not static but rather dynamic and are effectively updated, when necessary, to keep stakeholders informed. As shown in the screenshot example provided in Fig. 5, a full CAD visualisation tool is necessary to obtain 3D representations and mock-ups either being from the eBOM or the mBOM. The visualisation tool is further used to identify the right occurrences of the parts, when multiple, and reciprocally select them within the BOMs. Finally, annotations can be added to the process sheets which populate the mBOM along with the resources and time allocation tables (visible in the upper right tabs in Fig. 5).



Number	Name	State	Version	Qu...
VE-670-54-0002-1	FWD ENGINE MOUNT, LH	Prototype In Work	1.6 (Design)	
VE-670-54-0013-1	YOKE, FWD E.M., LH	Prototype In Work	1.3 (Design)	1
VE-670-54-0016-1	LOWER MOUNT PAD, FWD E.M.	Prototype In Work	1.3 (Design)	1
VE-670-54-0015-1	UPPER MOUNT PAD, FWD E.M.	Prototype In Work	1.3 (Design)	1
VE-670-54-0095-1	FRAME HARDWARE, FWD E.M., LH	Released	1.4 (Design)	1
VE-670-54-0097-1	E.M. HARDWARE, FWD E.M., LH	Released	1.4 (Design)	1
VE-670-54-0096-1	FIRE WALL HARDWARE, FWD E.M., LH	Released	1.4 (Design)	1
VE-670-54-0014-1	MOUNT LINK, FWD E.M.	Prototype In Work	1.5 (Design)	1

Figure 5. An MPM user interface - Courtesy of PTC [14]

4.3 Configuration management

An important point to discuss is the configuration management, which serves to capture, as snapshots, the evolving items at certain levels of maturity. A prototype could be, for example, built and tested from a specific configuration of the end-item while design iterations are still running continuing. To do so, instances of the parts are generated from the captured configuration and identified by their serial numbers or lot numbers as provided by the suppliers or the shop-floor. An instance, not to be confused with an occurrence, corresponds to the materialization of an artefact and therefore identifies a unique physical part, whereas the occurrence identifies the presence and unique position of a part within the digital mock-up.

Instances are therefore incorporated to form the complementary structure (*as-built*) mirroring the physically assembled prototype. Since the structure remains linked to its *as-designed* version, the traceability regarding all the approximations made while prototyping and testing is enabled. Hence, because the manufacturing serial and lot numbers are identified, the physical parts are also tracked. Of course this methodology could also be applied when all parts and documents have reached the release status. This is to say each produced and delivered instance of the end-item is fully traceable by the preceding means.

5 THE SUCCESS OF MPM

The concepts and technologies described earlier were first developed at a research laboratory of the École Polytechnique de Montréal. They led to the start-up of Polyplan Technologies Inc., which further extended the research results to a standalone industrial application tested on a series of PDPs. While fully implemented in a production environment for the development of a very complex product that included some 100,000 parts manufactured in two different plants, the Polyplan/PTC application [14] and associated business processes demonstrated significant product development improvements. The MPM strategy satisfactorily supported a large engineering process and created a powerful information pull system that helped reduce the product development cycle to first product delivery by 8 weeks (this represented a time reduction of 15% of that part of the PDP). Figures on the improvements related to the end of the production ramp-up are not available yet. The number of errors and the quantity of rework were also reduced significantly; this improvement in product quality was due to two main factors. First, the use of 3D product data in the manufacturing engineering and on the shop floor reduced the number of interpretation errors. Second, the coherency of the product and manufacturing data reduced the number of errors by ensuring that the proper version numbers of the product and of its manufacturing plans were always used.

The information exchange between engineering and manufacturing engineering departments was, overall, notably improved due to the data synchronisation maintained throughout the project. This created a smoother business relationship between the two most critical stakeholders in the product development cycle: engineering and production. With right methodologies in place, the system also demonstrated its ability to structure the manufacturing know-how across all the different manufacturing processes and plans of a given company.

6 THE FUTURE OF COMPLEMENTARY INFORMATION STRUCTURES

Expanding the reach of complementary information structures is being pursued into other areas of the product lifecycle; prototyping and in-service activities are currently the focus of industry funded research projects.

Prototyping and testing activities fulfill several needs within product development, from preliminary proof of concept to testing of complex functionality. These activities carry high costs and are resource intensive, and therefore as much information and knowledge as possible must be extracted and retained from each design-build-test cycle. As prototypes are developed iteratively and in parallel with the design, tracking the various configurations can be a difficult process. It has been proposed that the application of complementary product structures, using a similar methodology to that explained in this paper, could allow designers to create robust links between the ‘as-tested’ product structures (i.e. prototypes) and the ‘as-designed’ structure [15].

Another problematic being researched is the mitigation of late stage changes to the design, in particular those which must be implemented post-certification in the aircraft industry. Changes to a product once it has been put into service carry heavy costs to manufacturers, especially in the field of aircraft engine manufacturers where companies are increasingly moving towards performance based contracts (e.g. Rolls Royce's Power by the Hour^{TM} program). It is therefore important to identify means for reducing these costs, either by eliminating possible cost drivers early in development or enabling more efficient cost reduction initiatives after entry into service. To facilitate this cost reduction, processes must be developed for sharing reliable, complete and timely information between stakeholders of the design and development phase and those of the in-service phase. Recent research has identified the information required by designers of aircraft engines [16], and work is in progress to develop a method for identifying in-service cost drivers based on preliminary information from development testing. It is expected that the use of complementary product structures will facilitate the required information sharing between in-service personnel and those involved in earlier product development phases.

By enabling complementary information structures throughout the product lifecycle, stakeholders will be able to share knowledge and information by means of a common reference, the product, but within a context appropriate to their role and activities. Based on current research, it is believed that these complementary structures and the robust links which connect them can be enabled within future Product Lifecycle Management systems. This will further the progression towards true Lean engineering, where, through efficient knowledge and information capture and reuse, waste is reduced at all stages of product development.

REFERENCES

[1] Ward, A.C., *Lean product and process development*, 2007 (The Lean Enterprise Institute, Cambridge, MA, USA)

[2] Sobek, II D.K., and Ward, A.C, Principles from Toyota's set-based concurrent engineering process, in the *Proceedings of the ASME DETC/CIE Conference*, Irvine, CA, USA, August 1996.

[3] Grieves, M.W., Product lifecycle management: the new paradigm for enterprises, in the *International Journal of Product Development*, 2 (1/2), 2005, pp.71-84.

[4] Vandevelde, A., and Van Dierdonck, R., Managing the design-manufacturing interface, in the *International Journal of Operations & Production Management*, 23 (11), 2003, pp.1326-1348.

[5] Twigg, D., Managing the design/manufacturing interface across firms, in *Integrated Manufacturing Systems*, 13 (4), 2002, pp. 212-221.

[6] Evans, B., Simultaneous Engineering, in *Mechanical Engineering*, 110 (2), 1988, pp. 38-39.

[7] Fortin, C., and Huet, G. Manufacturing Process Management: iterative synchronisation of engineering data with manufacturing realities, in the *International Journal of Product Development*, 4 (3/4), 2007, pp. 280-295.

[8] Jarratt, T., Clarkson, P.J., and Eckert, C.M., Engineering Change, in P.J. Clarkson and C.M. Eckert (eds.): *Design Process Improvement – a review of current practice*, 2005, pp. 262-285 (Springer-Verlag, London).

[9] Guess, V. C., *CMII for Business Process Infrastructure*, 2002 (Holly Publishing, Scottsdale, AZ)

[10] Tichkiewitch, S., and Véron, M.,. Methodology and Product Model for Integrated Design Using a Multiview System, in *CIRP Annals - Manufacturing Technology*, 46 (1), 1997, pp. 81-84.

[11] Brissaud, D., and Tichkiewitch, S. Innovation and manufacturability analysis in an integrated design context, in *Computers in Industry*, 43 (2), 2000, pp. 111-121.

[12] Zimmermann, J. U., Haasis, S., and Van Houten, F., ULEO-Universal linking of engineering objects, in *CIRP Annals-Manufacturing Technology*, 51 (1), 2002, 99-102.

[13] Fortin, C., Huet, G., Sanschagrin, B., and Gagné, S., The CAMAQ project: a virtual immersion in aerospace industry practices, in the *World Transactions on Engineering and Technology Education*, 5 (2), 2006, pp. 287-290.

[14] PTC, (2010), Parametric Technology Corporation, http://www.ptc.com/products/windchill/

[15] Toche, B., Huet, G., McSorley, G., and Fortin, C., A Product Lifecycle Management Framework to Support the Exchange of Prototyping and Testing Information, in the *Proceedings of the 2010 ASME IDETC/CIE Conference*, Montreal, Canada, August 2010.

[16] McSorley, G., Huet, G., and Fortin, C., In-Service Information For Aeroengine Designers: A Survey, in the *Proceedings of the 2010 ASME IDETC/CIE Conference*, Montreal, Canada, August 2010.