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Assessing the challenges of managing product design change through-life

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ABSTRACT
Whole-life support for complex products requires coordinated action. Existing shortcomings of the design change management process currently operated within key UK engineering sectors are identified and discussed. The challenges that must be met in order to better satisfy the need for accurate product information across an integrated supply chain are presented. The role that information technology must play in achieving greater efficiency is developed. Recommendations are made in the form of 10 requirements to guide future design change management strategies. It is intended that implementation of these requirements will enable and improve the provision of product-related information so that it more accurately reflects the current configured status of the products. The aim is to facilitate and support enhanced product maintenance, effectiveness and utilisation.

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1. Introduction

In a period of rapid technological development, the designs of complex, high-value products will often change. In this paper the term complex is applied to individual products such as aircraft, ships and trains and to configured systems such as power generation plants. These changes may often be made on an individual basis, meaning that the make-up of each product will diverge. This can continue to occur throughout the product's lifecycle, resulting in a proliferation of product variants.

The original equipment manufacturers (OEMs), owners and end users of these products may, therefore, be required to manage ever-changing resources. Most OEMs have a structured approach to managing their own internal product design change process. Many experience real challenges when managing change information to support their businesses and customers. This process requires a more coordinated approach and there is a need to provide clarity on the issues that have to be addressed. It is proposed here-in that this need can be best met using a common design change management strategy.

While the responsibility for managing the design changes of their end product rests with the manufacturer, it may be that the majority of design change is undertaken by their suppliers. Thus, the design change process can span the domains of a number of

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organisations and involve significant volumes of information. The full specification of the challenges of communicating information about product design changes within and between organisations must be better understood.

Design integrity may be defined in terms of the reliability, availability, maintainability and safety of a product. The product can be deemed to be fit for purpose as long as it meets the criteria specified under each of these four categories. Many organisations, particularly in safety critical industries, are required to maintain extremely high levels of design integrity. Doing so requires that the information associated with the design also retains its integrity, again measured against the same four criteria. This means the accurate control of details embedded within catalogues, bills of materials, inventory, assembly and maintenance instructions. All such information must be updated where required.

Product change management practices need to evolve. The design information management and change control methods used in the past are unsuited to complex products. To improve the management of product change, working practices, business and information models need to adapt to support future ways of operating. This requires that researchers should work to identify areas that will benefit from a systematic approach with a view to bringing them together under a more unified process model. These points support the intention and methodology proposed in this paper.

1.1. *Research priorities and motivation*

The concept of Smart Manufacturing aims to create organisations that are able to quickly respond to customers, while minimising energy and material usage and maximising economic competitiveness (SMLC). The scope and challenges that this embodies can be defined in the context of the ARTEMIS programme. This article set out to support the development of novel technical solutions to address the extreme complexity of new systems. It has explored the use of reference designs and architectures, seamless connectivity, middleware, design methods, implementation and tools (ARTEMIS 2013). This includes increasing industrial integration support the flow of products from the smallest suppliers to the largest prime contractors (Gerritsen et al. 2011).

International research priorities recognise that there must be a change from the largely static network of embedded systems to integrated systems-of-systems which are highly dynamic, evolving and that are never down (Grimm 2011). An approach for sharing of product knowledge considered that much of the information may be already dispersed in the different enterprise information systems. However, to enable this to be fused into existing product lifecycle management (PLM) systems, further research and standardisation are required (Jun, Kiritsis, and Xirouchakis 2007; Quentin and Szodruch 2011).

The current industry trend points to the integration of various software point solutions into one monolithic coherent enterprise architecture that links various stages of the product design, production and support processes. The barrier to progress would seem to be the development of new business models and standards that will enable the development of knowledge-sharing platforms on a global level (Rachuri et al. 2008). These will be based on an open architecture framework for products, processes and services (Chandrasegaran et al. 2013). It is, therefore, vital for new innovative business models to take this trend into account. Trends in design practice have clearly resulted in greater emphasis on the need for effective information management (Srinivasan 2011). The goals include enhanced after-sale-support services and enterprise asset management (Millson and Wilemon 2002). There is at present no central process for standardisation and consequently independent organisations have assumed important roles in developing and maintaining modern PLM standards (Barki and Pinsonneault 2005). It is a challenge just to keep track of these developments and the authors suggest that this trend will only increase.

This paper is concerned with the management of design change and the information it engenders. The intention is to provide a platform for future research based upon an initial assessment of the current practices embedded within and the perceived needs of industry. Section 2 of this paper reviews previous research in order to better define the challenges to be met. It considers current design change management practices and assesses the challenges remaining.

Section 3 offers two case studies from the transport sector together with the findings of an industry survey to illustrate from an industrial context the challenges faced in managing design integrity through-life. This survey involved a series of one-to-one activities conducted by the authors with practicing design engineers within some prominent organisations engaged in this area. Direct collaboration within the organisations acknowledged at the end of this paper allowed the capture of current perceptions and practices.

Finally, the paper considers future needs of design change management systems in order to provide clarity on the issues that must be addressed. To underpin this, 10 requirements are proposed to guide future strategies and to promote the development of enhanced practice in this vital area. These are very much seen as an integrated set of requirements, rather than a simple sequence of individual points.

2. A review of current design change management challenges

A review of engineering change in the late 1990s determined that research was being aimed at the management of post-production changes to a product from the manufacturing perspective, but not into the impacts on the product user or owner (Wright 1997). This work correctly identified that business process improvements were required to enable a company to maximise the advantages available from better managed change processes in complex product design. Little further work has been reported in this field, despite an increasing awareness of how the accumulative effect of small levels of discrepancies in product information can have a disproportionate cost impact and degrade employee effectiveness (Guess 2009).

There is no consensus on what constitutes best practice for the management of engineering change in this context. There is, however, clear evidence for the need to define and implement such methods (Eckert et al. 2009). A survey conducted in 2010 identified that there are many challenges to be overcome (Heisig et al. 2010). This was reflected in a comprehensive review of the available literature that focussed on design change but did not fully consider the logistical aspects of the change process (Jarratt et al. 2011). Ultimately, it is clear that accurate information is critical to maximise the efficiency of change-related product services as inconsistencies can have significant operational and cost implications (Redman 2008).

Research has considered the social dimension of design change, part of which will require the implementation of a product-wide platform to enable collaboration (Siddiqi et al. 2011). However, the effects of change propagation were not included. A further comprehensive review of design research themes placed emphasis on information management over long timescales (McMahon 2012). It also noted a relative absence of research into product service issues and suggested that design researchers should work to identify areas that will benefit from a systematic approach with a view to bringing approaches together under a more unified process model.

A recent paper considered why change propagation was a problem and suggested a way forward based upon a tool for knowledge capture and reuse (Ahmad, Wynn, and Clarkson 2013). It was reported that, in the context of components that are not directly connected, no commercial solution could be identified. The application of this change impact assessment method to a jet engine was considered, but this was deemed to be too complex at this stage of the development, supporting the premise that more research is needed. Stating the obvious, a jet engine is only part of the complex product that constitutes an airplane. It is possible to see that product data management (PDM) can assist in synchronising design change information within and between organisations. But the provision of greater compatibility between PDM systems remains a challenge (Rahmani and Thomson 2011). In the context of new product development, little research was found in the area of product interface management. What has been reported seems not to be capable of tracking changes automatically. This review indicates the relative scarcity of research supporting engineering change management between companies and confirms that there is a need for a framework that can support the development of a new generation of engineering change tools (Rouibah and Caskey 2003). A number of factors that will influence design change management practice can now be identified and considered.

2.1. *Through-life design change*

Complex products, such as aeroplanes or helicopters, are often refitted with state-of-the-art technology once they have been in service for several years. This may be necessary to meet new needs or to refresh the product's existing technology. The need to assure sustained performance means that such retrofits are even more constrained than incremental developments. It also places great demands on the recording of updated product configurations and changes (Ariyo, Eckert, and Clarkson 2009).

Managing changes during life is a challenging process (Vianello and Ahmed-Kristensen 2012). For example, the design of each airplane within a fleet of new aircraft will gradually diverge during operational service as maintenance and part replacement activities are exercised on an individual basis. Management of this change process requires the coordination of many activities spanning design, procurement, production, marketing, sales and support. All are reliant on accurate product information and with the unending drive to improve efficiency, there is a declining tolerance to error. The safety critical nature of some industries adds a further dimension to this process in that all changes must be compliant with rules set down and monitored by a design authority.

The design authority concept seeks to provide greater coherence and control of a product's design (Atasu and Subramanian 2012). This requires two qualities: the technical knowledge to manage the design combined with the organisational power or governance to provide authority. The execution of the control necessary to maintain design integrity may be undertaken by an organisation or by a group of organisations that are acting as a design authority collaborating to ensure a design is effectively controlled. The ability of a design authority to exert control depends on the existence of a wider management or regulatory system. The role and responsibility that a design authority plays in maintaining design integrity vary according to specific product circumstances. Even when a design authority is established, it is important to recognise that it represents one component of a wider system that is responsible for maintaining and ensuring design integrity.

2.2. *Extended product support*

Further pressure to change design practices is inevitable as businesses extend their services to cover the whole lifecycle up to and including end-of-life. Organisations are increasingly deriving revenue from product-related activities through innovations in the area of leased purchasing as well as after-sale services and extended product support. More producer responsibilities are being introduced by environmental legislation. This concept emerged in the early 1990s and acceptance of environmental responsibilities by manufacturers is developing (ElBaradei 2003).

It is clear that many of the engineering management practices that are synonymous with concurrent engineering have found a close empathy with more recent supply chain management techniques. They both seek to integrate many aspects of product design, manufacture, operation and disposal. An approach for the sharing of product knowledge considered that much of the required information may be already dispersed in the different enterprise information systems. However, to enable this to be fused into existing PLM systems, further research and standardisation are required (Ouertani et al. 2011).

2.3. *Management of product data integrity*

To respond to market demands means that a close relationship between business strategy and product strategy is required. The way that products are managed, designed, manufactured and used shapes the structure of the world's economies (Colfer and Baldwin 2010). However, while the need for effective change management is recognised, there are obstacles preventing the deployment of the required systems (Burgess, McKee, and Kidd 2005). The efforts to integrate change management systems within and across organisations are considered to be fragmented despite the apparent capability of PDM systems to tackle this. The paper suggests that companies seem to view the engineering change process as a compliance issue rather than a potential source of competitive advantage (Burgess, McKee, and Kidd 2005). However, to make an adjustment to this status quo would require a change of mind set towards proactive collaboration and partnership.

A further indication of the challenges faced in understanding engineering change behaviour was presented and applied within the context of a diesel engine, which is again only one part of a complex product. The current approach was confined within the product domain, but the paper recognises that this needs to extend into the organisational domain (Hamraz, Caldwell, and Clarkson 2012). This will need the type and level of inter-organisational collaboration proposed later in this paper.

Despite significant investment in the development of product data exchange standards, current software and systems are still unable to fully take account of business process flows. This is exhibited in part by the lack of a common vocabulary which can result in non-standardised implementations that bring with them high organisational costs. In identifying a pathway to resolve this issue, it has been suggested that synchronisation may be preferable to homogeneity across an enterprise (Rangan et al. 2005). It is recognised that changes can propagate with associated impacts on product configuration. Mapping these changes and monitoring the effect that they have within an organisation are recognised as being a challenging but nevertheless a worthwhile research topic.

2.4. *The growth of embedded software and sensors*

Closed-loop PLM is an evolving concept that describes how intelligent products can provide feedback to manufacturers as they are being used (Kiritsis 2011). This feedback enables designers to implement design change and product revisions more quickly in response to reported product performance. In many respects this concept is similar to personal computers that already report problems direct to software vendors. It is a challenge just to keep track of these developments.

Existing design approaches need to be substantially adjusted to manage and truly benefit from innovations such as embedded software (Henzinger and Sifakis 2006). As an example of the complexities of developing embedded software, modern cars can contain more than 2 million lines of code, distributed over 80 nodes and using 5 different networks (Patil and Kapaleshwari 2010). Producing and maintaining this facility in new and existing vehicles are a huge task.

The challenges faced in regard to design change within an automotive context in cross-enterprise communication are not confined to data alone, but also to format and semantics. The industry deals with multiple engineering change management systems with multiple formats and multiple definitions. Their use will contribute to losses due to lost man hours and delays with factors such as the use of alternatives for replacement parts (Wasmer, Staub, and Vroom 2011). There is a need for knowledge-level communication within distributed computational resources that enables designers to access information in a simple and meaningful way. The requirement of providing design knowledge in a usable form using different systems was identified as being one of the most challenging to meet (Wang et al. 2002). It has been suggested that part of the resolution of this requirement can be found with the adoption of a standardised data model to provide a common understanding of the underlying business process between various stakeholders (Corella, Rosalen, and Simarro 2013; Wasmer, Staub, and Vroom 2011).

The analysis of change propagation within a complex sensor system over eight years is said to have realised some 40,000 plus change requests (Giffin et al. 2009). This showed that changes can propagate between areas that do not seem to be directly connected, particularly with electro-mechanical and software contexts. This raises the requirement for collaboration between different information systems, with the view being taken that access to proprietary information will be critical and that standardised information systems will be necessary.

The following sections of this paper make an important contribution to this increasingly critical area. There is an opportunity, by working collaboratively, to achieve improved control for less cost. Design integrity for many organisations can be the foundation of their business reputation or brand and often underpins product safety. Better managed and executed design change procedures are, therefore, potentially of great benefit to such companies.

3. Managing design integrity through-life: rail and aerospace

All organisations with responsibility for managing products and assets have a need to maintain design integrity. They must ensure that the purpose of the product is realised during manufacture, maintained during use and increasingly that end-of-life considerations are met. Figure 1 illustrates prominent enterprise processes found within an organisation. It depicts the range of activities that must be integrated if an organisation is to operate effectively. It can be observed that product-related information is a feature of many of the identified process areas. As such these areas will require access to and knowledge of product information and will thus feel the impact of design changes. The purpose of this section is to explore how these responsibilities are being discharged in two sectors providing and operating complex products: rail and aerospace.

3.1. *The UK rail industry*

In 1993 British Rail was privatised and the management of UK rail vehicles moved to a predominantly leased ownership business model. There are three rolling stock operating companies who own the trains and 25 train operating companies that provide rail services. As the result, OEMs design and build trains to meet broader market requirements. The management of design change and maintenance of design integrity require the

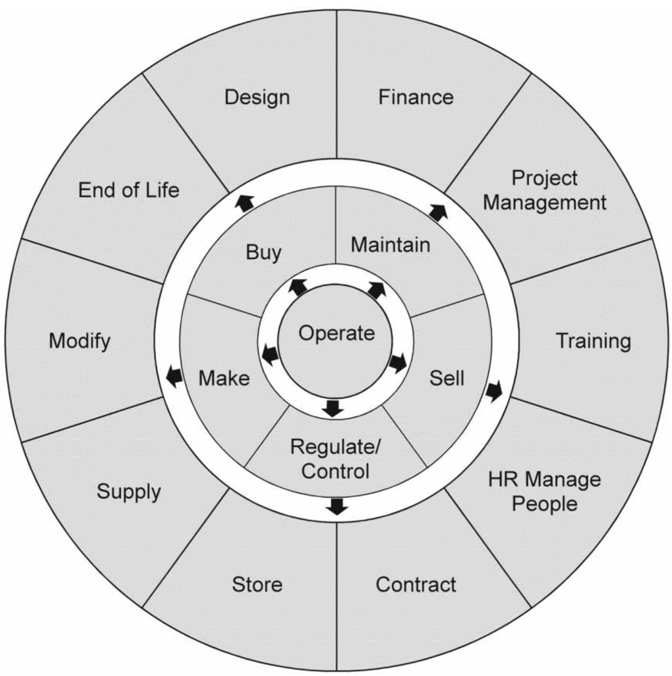

Figure 1. Prominent product-related enterprise processes.

collaboration of the leasing company, the operator and the rolling-stock OEM. Due to this, the need for a design authority function has been recognised.

3.1.1. *Rail: required design knowledge*

To illustrate the complex design issues in this sector, the Rail Research Association have summarised the factors that need to be considered when designing a new train (Wennberg 2007). They identified 13 requirement areas that encompass safety, reliability, transport needs, regulation, economic constraints, product lifecycle and technology lifecycle. Other factors embrace the complexities of integrating new trains and passenger services with the existing transportation infrastructure and environmental factors. In a similar way, the Strategic Rail Research Agenda 2020 of the European Rail Research Advisory Council has identified interoperability as a priority to embrace such issues as supply chain management, third party logistics, real-time management of customer information along the supply chain and the emergence of new technologies (Wennberg 2007). Managing design change in the context of all of this knowledge, divided as it is amongst OEMs, owners and operators, represents a massive challenge.

3.1.2. *Rail industry: design control*

The UK's Rail Safety and Standards Board (RSSB) have identified four competences necessary for managing design integrity (UK Rail Safety and Standards Board (RSSB) 2004):

Competence one identifies the need for a body of knowledge that supports the development and specification of technical and operational requirements. How these influenced the original and current design of the system together with subsequent changes made must be recorded. This knowledge is different from that required by regulators, maintenance organisations or others who have the know-how to build or maintain a component or system. They are unlikely to have the detailed design knowledge which is so important in terms of retaining control over design integrity.

Competence two relates to the management of information that is required to retain and provide access to this design knowledge. There is a requirement to retain the design information so that when there is a need to make changes or understand a product's behaviour, the original design rational can be recalled.

Competence three supports the ability to validate design change. There is a need for a body of knowledge within people who are able to make informed judgements on whether an intended design change is compatible, from a technical, operational or safety perspective. This enables the ability to assess the implications of such changes.

Competence four enables the management of configuration levels. There is a need to keep records of the design changes and configuration of any particular product as it evolves throughout its life. This is necessary to enable the body responsible to certify that any particular modification is compatible not only with the original design, but also with the current design as achieved by subsequent modifications.

In the context of this paper, competences two and four refer to the need to maintain through-life design records which enable design decisions to be made under competences one and three. The efficient control of design change requires the collaboration of OEM suppliers, operators and, importantly in this safety critical sector, regulators. Within the UK these all operate under the control of a design authority. Given the increasing recognition of the importance of product information to support the change control process, there is an opportunity, by working collaboratively, to achieve improved control for less cost.

3.2. *Civil aerospace*

Commercial leasing represents a proportion approaching 40% of the total civil aircraft fleet. It utilises a similar industry structure (with lessors, lessees, OEMs and operators) to the UK rail industry. An aircraft can often move between operators as many as five times in its life and sometimes more frequently. However, the aviation industry's support model is mainly focussed on OEM to operator relationships and has yet to adapt to reflect the growth of leased ownership. There is a growing awareness that accurate engineering configuration information is key to reducing costs. However, the operating model linking manufacturers, operators and leasing companies is not well supported in terms of provision of through-life information management. The whole area of through-life information management is important because many airlines operate on very tight operating margins (typically 1–2%) and while fuel is a major cost, asset maintenance overheads are also significant.

3.2.1. *Civil aerospace: design knowledge*

The structure of the design methodology used by the civil aerospace sector is largely consistent among the prime aerospace contractors. Airbus's approach, for example, has five stages: feasibility, concept, definition, development and series (EASA). This approach has not been formally extended to cover disposal, but during development end-of-life and environmental factors are considered. Airbus has formed a company called Tarmac Aerosave to manage aircraft dismantling and recycling.

In order to operate, civil aircraft must be subject to the process required to obtain a certificate of airworthiness. This confirms that the plane conforms to the requirements defined within its type certificate. Doing so requires the enactment of all maintenance and design changes in accordance with requirements set down by the relevant aviation authority. This process also ensures that all subsequent changes are agreed by the aviation authority and that all changes required have been made. In order to obtain a type certificate, the aircraft will have been manufactured according to an approved design in compliance with airworthiness requirements. This is becoming more challenging as more advanced products are developed. These increasingly rely upon outsourcing of the design of significant items to application-specific partners. This problem has been recognised as increasing the number of interfaces between design functions, so adding to the potential risks (Pardessus 2004). This clearly demonstrates the need for the information management improvements targeted in this paper.

There is a clear recognition that during their operating life, aircrafts are generating significant product information that can be used to provide the knowledge required to reduce maintenance costs. At present this information cannot be exploited to full effect because the systems are not integrated and the terminology used is different. Ultimately there is a need to fuse data from multiple systems. Managing the increasing volumes of information that will be produced will require the development of innovative information systems. These are needed to support the closer collaboration of all partners which is required to improve aircraft lifecycle management, including design, manufacture, maintenance, parts distribution and recycling.

3.2.2. *Civil aerospace: design control*

Many aircraft operators have their own maintenance organisations that have gained regulatory authority. This allows them to make limited changes to the modified state of an aircraft, without input from the manufacturer. Operators are typically able to undertake modifications to areas such as internal trim (e.g. seat configuration, overhead storage bins and entertainment systems). These will have an impact on airframe loading and stress, but not on the extent that OEM design analysis is required.

Once an aircraft has been delivered, the OEMs develop modifications that are published as service bulletins. Between 15% and 20% of these modifications are mandatory. The remaining service bulletin modifications are optional. The impact that these modifications have on the ability of an OEM to provide after-sales technical support rests largely on its knowledge of the configuration of an individual aircraft. Without feedback from operators, OEMs must largely rely on information from the original configuration. Clearly the differential between the maintained and original configuration increases as aircraft age. The main challenge OEMs face is, therefore, retrieving information from operators on which modifications have been fitted. There is an opportunity by working collaboratively to achieve improved control for less cost.

3.3. *Managing design integrity through-life: current position*

These brief overviews of two important engineering sectors were presented to illustrate that managing the design change of complex products during their life is a challenging process. Both sectors are subject to significant regulatory and legislative control and so maintaining design integrity through-life is important.

The challenges of ensuring design integrity can be understood by considering that within a fleet of complex products, individual products will have configuration differences even when manufactured together at the same time. These small variations that exist at the time of purchase increase as the result of through-life modification and maintenance. Consequently, their configurations diverge to the point where the design differences at the end-of-life are much greater.

Current approaches to providing maintenance documentation and illustrated parts catalogues are not well suited to provide accurate information in a product-centric way that is able to respond to this level of design complexity. As a consequence, a great amount of maintenance documentation often does not closely match the maintained product configuration. This can mean that engineers spend a significant amount of time searching for information and problem-solving. For progress to be made, adjustments are needed to the way product information is currently managed. There are also opportunities for increasing industrial efficiency by changing the way that technology supports organisations.

Information systems currently provide some commonality of terminology between software applications, but many fields are different. Examples of the different systems deployed and required to support each area are as follows:

- Design systems: There are many PLM/design systems including Siemens PLM, PTC Windchill, Dassault Catia, Bentley Systems (Projectwise and Assetwise) and Autodesk/Autocad;
- Inventory and procurement systems: These functions are typically covered by enterprise resource planning (ERP) systems such as SAP and Oracle;
- Maintenance recording systems: Examples of maintenance recording systems include IBM's Maximo, SAP's Asset Management, Ramesys and TACT XV;
- Maintenance manuals are supported in a variety of ways from paper documentation, electronic document formats (such as Adobe Acrobat) and increasingly content management systems.

Most of these applications set out to support activities related to the management of products and product information. The current lack of standardised terminology complicates the challenge of achieving the closer integration required to enable the smooth flow of information. There are currently many industry product information standards and while some have achieved broader adoption, the overall picture is patchy. If standards adoption by applications vendors were more comprehensive, the cost and time of implementing systems could be reduced.

4. The challenges of managing design integrity through-life

Following this review, it was apparent that the need for better management of product information through-life represents a huge challenge. It requires the alignment of three topics: design management processes, information technology and the management models used to guide decision-making. To further define this process, an industry survey was designed and undertaken by the authors in late 2012 and early 2013 across nine industry sectors. The four largest sectors represented by responders, as shown in Figure 2, were rail, automotive, aerospace defence and industrial equipment.

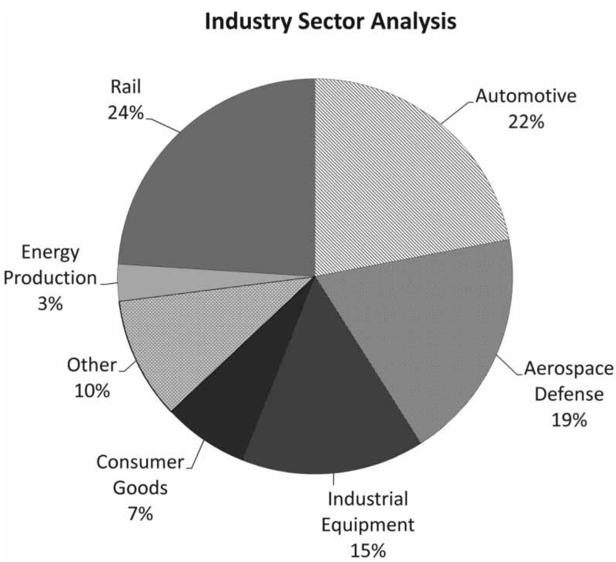

Figure 2. Survey responses segmented by the industry sector.

4.1. *Industry survey*

The aim was to investigate how well the requirements identified by the reviewed literature matched the experiences of different organisations. Ten survey questions were designed to establish the current practice, problems and perceptions of future requirements in industry.

Current research requirements in configuration management, PLM and related technology identified in the literature review were considered. In each case the questions were aligned with specific requirements identified by previous research.

Thus, the current ability of organisations to track design change information through-life previously cited as being a requirement (Burgess, McKee, and Kidd 2005; Gerritsen et al. 2011; Jun, Kiritsis, and Xirouchakis 2007) was rated in Question 1. Questions 2 and 3 were written to invite responses on the current difficulties in accessing accurate product information (Eckert et al. 2009; Jarratt et al. 2011; Ouertani et al. 2011; Millson and Wilemon 2002) and penalties of not having this (Jun, Kiritsis, and Xirouchakis 2007; Millson and Wilemon 2002; Ouertani et al. 2011). The literature review had highlighted that the flow (Barki and Pinsonneault 2005; Burgess, McKee, and Kidd 2005; Wasmer, Staub, and Vroom 2011) and the duplication (Burgess, McKee, and Kidd 2005; Jun, Kiritsis, and Xirouchakis 2007; Ouertani et al. 2011) of product information between systems within an organisation were a concern. The frequency and impact of these were explored in Questions 4 and 5.

The discrepancies arising in product information between organisations and their customers (Burgess, McKee, and Kidd 2005; Chandrasegaran et al. 2013; Corella, Rosalen, and Simarro 2013; Jun, Kiritsis, and Xirouchakis 2007; Wasmer, Staub, and Vroom 2011) and suppliers (Burgess, McKee, and Kidd 2005; Chandrasegaran et al. 2013; Corella, Rosalen, and Simarro 2013; Jun, Kiritsis, and Xirouchakis 2007; Rachuri et al. 2008; Wasmer, Staub, and Vroom 2011) were also seen as a concern. The frequency and impact of each were assessed in Questions 6 and 7. Question 8 tested the potential for ambiguity arising in the allocation of configuration information when following current rules (Burgess, McKee, and Kidd 2005; Corella, Rosalen, and Simarro 2013; Jun, Kiritsis, and Xirouchakis 2007). The limitations to the skills of the workforce in regard to operating within this sector (Barki and Pinsonneault 2005; Burgess, McKee, and Kidd 2005) were the subject of Question 9. The frequency and impact of inconsistent terminology (Corella, Rosalen, and Simarro 2013; Gerritsen et al. 2011; Ouertani et al. 2011; Wasmer, Staub, and Vroom 2011) were rated in Question 10.

The survey covered both complex product manufacturing and maintenance organisations. The questions were used to identify individuals' roles and direct experiences of the IT systems used to manage product information in organisations where product information was important. Fifty-nine responses were received from people who represented 39 organisations, including 15 Fortune 500 or equivalent-sized organisations. No organisation-specific information is included herein due to commercial and related considerations.

The results are indicated in Table 1. While this was largely subjective, participants were requested to consider how often issues arise and the impact they had on cost, time and the quality of the organisation's product or service. The survey also required the ranking of five issues, identified after consideration of the research accessed in producing this questionnaire.

Table 1. Survey questions and summarised results.

Question			Response (%)				
1	How do you rate the ability of your organisation to track product changes throughout the product life cycle? Rated from good (1) to significant difficulty (5)	Options	11	21	31	41	51
		Results	181	251	221	321	31
2	How easy is it to search for product information? Rated from easy (1) to difficult (5)	Options	11	21	31	41	51
		Results	31	241	361	251	121
3	How does inaccurate product information impact your business? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	311	471	221		
		Impact	641	361	01		
4	The flow of product information from one information system to others causes problems? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	341	491	171		
		Impact	341	561	101		
5	Instances of duplicate product information exist in our systems? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	221	391	391		
		Impact	241	541	221		
6	Discrepancies in product information exist between our records and those of our customers? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	111	381	511		
		Impact	231	451	321		
7	Discrepancies in product information exist between our records and those of our suppliers? Response considered problem frequency and impact: Rated high-medium-low		High	Medium	Low		
		Frequency	141	441	421		
		Impact	271	541	191		
8	Rules for managing the allocation of important configuration information to new or modified products are sometimes ambiguous? Rated from agree (1) to disagree (3)	Options	11	21	31		
		Results	411	371	221		
9	Deficiencies in workforce skills contribute to discrepancies in product information? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	281	361	361		
		Impact	411	471	121		
10	Inconsistent product terminology causes problems for our organisation? Response considered problem frequency and impact: rated high-medium-low		High	Medium	Low		
		Frequency	241	321	441		
		Impact	191	471	341		
11	Top five issues: Rated greatest (1) to least concern (5)	Options	1	21	31	41	51
	Inaccurate product information		321	241	291	121	31
	Product change process		241	371	221	121	51
	Product information flow between systems		271	251	201	171	101
	Product information search		141	241	271	241	121
	Product duplication		71	171	141	121	511

In order of priority, responders considered that the greatest challenges were the following:

(1) Inaccurate product information;
(2) The difficulty of managing the product change process;
(3) The flow of product information between systems;
(4) The time spent searching for product information;
(5) Duplicate product information.

Further knowledge was sought by segmenting respondents into their own principle activities, thus investigating the needs of product maintainers versus product manufacturers and also systems users versus non-systems users. The summary of sector-specific responses made in this survey is given in Table 2.

Table 2. Sector-specific responses made in response to industry survey.

Industry	Product life (Years)	Design variation between different production batches of the same products (%)	Overall through-life design change (%)	Variation at end of life between initially common products (%)	Comments
Rail	30–40	70–80	Not known	Not known	High levels of technological change mean that electronics products are often manufactured for five years. During this time, changes will be made to the design mostly triggered by changes to supplier parts
Civil aerospace	30–40	Not known	30–40	20–25	These design changes arise due to the need to upgrade the avionics, engines and 'refresh' the internal trim and seats
Defence aerospace	30–40	20	Not known	20–25	The design difference between aircrafts of the same specification produced as separate batches arises mainly due to changes in software and electronics components
Gas turbines	30–40	Can be as high as 100%	40–50	Not known	As much as 100% difference can be experienced between different versions of the same product – similar to the design variation between different versions of mobile phones (version 1, 2, 3, etc.).
Nuclear power plant	40–60	Not known	25%	Not known	The main component areas that require 'refreshing' are the reactor vessel heads, pumps and steam turbines. Electronic/ electrical elements also require replacement due to obsolescence

4.2. *Discussions with industry specialists*

Understanding of the situation relating to design change management information systems was further enabled by a series of in-depth discussions with industry specialists, starting in 2012 and continuing throughout 2013. These discussions were initially framed around the five rated issues identified within the survey.

This process identified the following common major concerns that organisations currently experience:

- Both manufacturing and service organisations are experiencing difficulties improving the product change process because it is highly information intensive.
- Change occurs throughout product lifecycles and obsolescence is one of the key drivers.
- Applications architectures are not optimised to support the effective flow of product information across the enterprise.
- Existing information management standards are overly complicated but not sufficiently detailed to provide guidance on the activities required to achieve accurate information. To illustrate this, it should be noted that the Institute of Configuration Management's CMII for Business Process Infrastructure (Guess 2014) proposes over 80 requirements,

whilst both the ANSI/EIA-649 National Consensus Standard for Configuration Management (ANSI/EIA 649-B: Configuration Management Standard 2011) and ISO 10007 (ISO/TR 9007: Information processing systems - Concepts and terminology for the conceptual schema and the information base 1987) identify over 40 principles.

- The level of understanding of the allocation rules for various categories of product information and/or part numbers is too low.
- Allocation rules for some categories of product identification including unique product numbers are open to interpretation or not always followed.
- Standardised approaches to estimating the cost of inaccurate product information have yet to emerge.
- Master information management best practice appears to be poorly understood.

The industry specialists were consulted over the findings of the survey and the issues were raised. They were also used to provide feedback with regard to the generation of the requirements specifications associated with the deficiencies of the current approaches.

4.3. *Analysis of survey and discussions with specialists*

Based on the findings of the survey, discussions with industry specialists and the sector-specific responses shown in Table 2, it was seen that the amount of design change experienced through-life can vary. For complex products, the evidence gathered indicated that 40% (±10%) over 30–40 years represents a reasonable guide.

The problem of inaccurate product information was identified as being the number one issue by the survey, with responses to question 1 indicating the medium to high level of the current difficulties. This formed an important part of the discussions with the industry specialists. The issue of the difficulties associated with managing the product change process was ranked second in the survey and again was at the centre of the discussions with specialists. This should be set in the context of the fact that manufacturers of complex products, including those within which a number of the industry specialists were placed, have often outsourced much of their manufacturing activity. This means that much of the design change is undertaken by suppliers. The nature of these changes clearly needs to be managed into the design of the final product by the manufacturers. Supplier product information plays a critical role in the provision of services because it must be communicated from the supply base into manufacturers' information systems. The current frequency and impact of not achieving this were assessed as medium by responses to the survey question 7.

The acquired information is used to manage procurement, inventory, production and maintenance and also update parts lists and process manuals. A high rating was given to the concerns related to the overall impact of inaccurate information in response to question 3 in the survey. Improving the management of product information has the potential to achieve significant savings, but the survey also indicated in responses to question 8 that a high level of ambiguity currently exists in the way in which configuration information is managed. Again this point was confirmed within the discussions, indicating that better support is currently needed in this regard.

It was established that improved information management does not also resolve the problem of information growth. That will always arise and cause increasing divergence within the bill of materials associated with a product family. As products age, some parts will become obsolete and modifications will be required. Some suppliers may no longer be available to supply the original parts and the original design may need to be modified to maintain or enhance the performance. One might argue that this process of part removal and addition could have a neutral impact on the overall number of line items required for the support bill of materials. However, modifications take time to implement, meaning there will always be a requirement to have more than one version of a part in the supply chain. The occurrence of such differences between customers and supplier partners in such a supply chain was identified as being medium to low in questions 6 and 7, with the impact on the organisations being rated as medium.

A further contributing factor is that, in a fleet scenario, the configuration of each of the delivered products can be slightly different. Comments recorded in Table 2 reflect the challenges this can cause. While the difference between the initial delivered products might be slight, it increases as the products age as their designs diverge. Over life these changes occur at different rates and so the number of parts required to support a fleet of products increases. An example of design change for the commercial aviation sector provided in response to the survey and associated discussions with sector specialists identified that all commercial aircrafts have slightly different designs, but the differences between the designs of a group of commercial aircrafts at the end of their life are much greater than at the start of their life. This also reflects user- and usage-specific requirements, which means that the OEM needs to carefully track each aeroplane as they are modified by different owners. This divergence in design is an additional complication to the product change process.

One of the implications of the fact that the designs of products are slightly different is that there is a need for an approach to providing access to accurate parts and maintenance information. This needs to be readily available to product support engineers throughout the entire product life cycle. The range of between two and four out of five for difficulty in responses to question 2 of the survey indicated that this was a real challenge to some organisations. It has been previously suggested that maintenance engineers can spend as much as 30% of their time searching for the information they need to diagnose and rectify failures (Robinson 2010). Discussion with the industry specialists confirmed that engineers can spend a significant time searching for product and part information. It was also suggested that, as they are not trained to do so, discrepancies can and do occur. This was confirmed by the high to medium impact registered in responses to question 9 in the survey.

The costs in labour and time spent searching for information were identified as the fourth most important issue in the survey and were considered in discussions with the industry specialists, This does not, however, represent the broader impact of the full costs of resolving problems that arise from inaccurate, duplicate or even missing information. Figure 3 seeks to outline the problem-solving behaviour demonstrated by engineers taking part in this collaboration. These were located in train maintenance depots. The lines show how a query by a maintenance engineer is passed along the supply chain in a way that leads to the creation of temporary problem-solving 'spaghetti teams'. The concept of the spaghetti team describes the way people collaborate temporarily in an informal way to resolve technical problems that arise from discrepancies in product information, such as maintenance documentation. These are usually discovered by one individual. This can lead to the temporary creation of substantial informal problem-solving teams

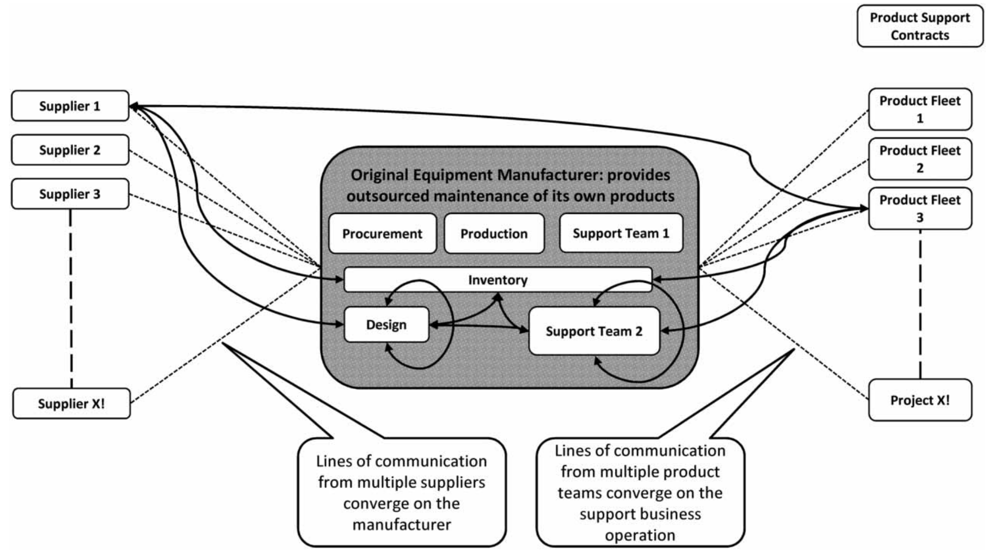

Figure 3. Problem-solving behaviour demonstrated by maintenance engineers.

that can extend across the supply chain when difficulties are experienced. These are in addition to the formal lines of communication established between organisations, which are shown in Figure 3.

The spaghetti team effect explains how the initial labour cost of the first person is amplified as the collaboration of colleagues is required to achieve a resolution. In this case the originating engineer is located within the end-user organisation operating Product Fleet 3. He/she makes contact with known persons within the inventory and support team functions of the OEM. They in turn liaise with each other, and with other colleagues within their departments and within the design department. Persons now involved with this problem within the OEM and the end user also contact people within the part supplier, using formal and informal links. While it is relatively easy to find people who recognise this effect, the impact does not appear to be well understood and more work is required to understand the broader implications.

The industry survey identified a number of clearly related issues which support the need for more closely integrated information systems. The need for better flow between information systems was rated the third most important issue raised and seen as being of medium impact and frequency in the responses to question 4 in the survey. If achieved, this would mean that the product change process could be better supported and product information flow would be improved and accuracy increased.

The integration allowing the development of a system of systems would also enable easier searching. Implicit in this is the need for more consistent product terminology, confirmed as being of medium impact in question 10 of the survey. The need for enhancement of information flow between systems was assessed in question 4, which recorded a significant number of organisations having problems in this regard. This was seen as a key issue by the industry specialists and is considered as an important future development in Section 5 of this paper.

The result of such an approach should be a reduction in information duplication, which was the final issue identified in the survey. The impact of this was judged to be of medium concern in responses to question 5 in the survey. To achieve a closer alignment between through-life design management processes, information technology and the management models used to guide decision-making will require an architectural approach that enables closer process integration across complex organisations.

5. Future needs of design change information systems

The main impetus for the work contained in this paper arose from the need to improve the configuration management of trains. Working closely with a major company in this sector, it was possible to surmise that configuration management could be viewed as an activity that was supported by five processes: planning and management, configuration identification, configuration changes, configuration status accounting and finally, verification and audits. Inaccurate product information was the number one issue identified by industry specialists and the difficulty of managing the product change process was the second issue identified. The aim must be to support an enterprise to ensure that its data are managed with the same level of integrity as its finances, people or physical assets. This can be met by having a function responsible for it and the information which could impact upon safety, security, quality, schedule, cost, profit, the environment and the company's reputation.

Despite significant technological developments, the closer integration of enterprise processes and wider attainment of industrial interoperability remains elusive. The flow of product information between systems was seen as an issue by the industry specialists. The aim of this paper was to identify what needs to be put into place to enable the achievement of enhanced interoperability. Figure 4 provides a simple illustration of the information model required to support the management of product information to

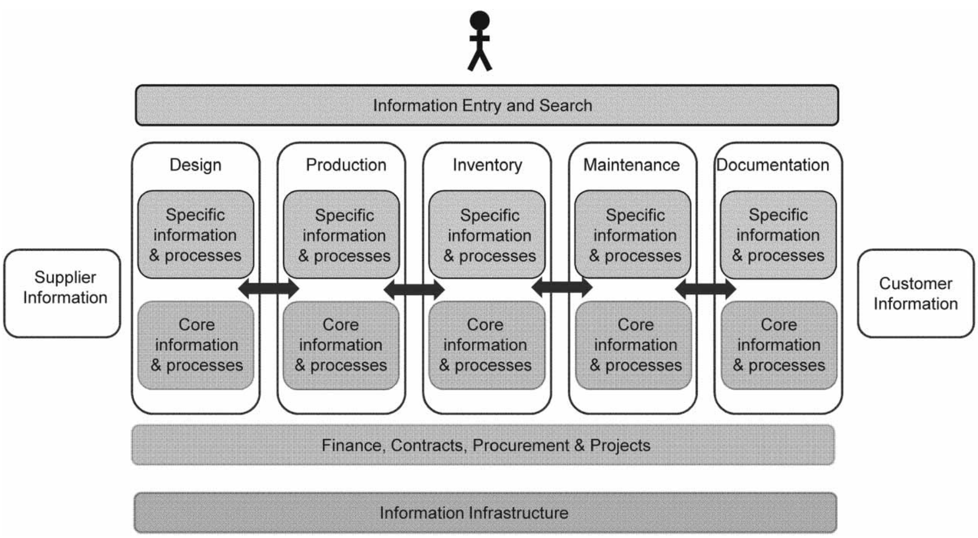

Figure 4. Potential future applications architecture.

provide through-life support. Figure 4 illustrates the need for significant design information reuse across an organisation that manufactures and maintains products. This is represented by the need for core product information and processes under each distinct activity. At the same time, each activity has its own specific information and processes.

Current technology represents a point solution approach of loosely coupled information systems. These support early life design, manufacture, inventory, documentation and through-life maintenance records. The architecture supporting this approach is unlikely to scale-up to support the anticipated increase in information that is likely to arise. Information entered by users into one system is not replicated readily into other systems. This prevents a common standard from being adopted. This restricts the accurate and efficient monitoring of the quality of new information entered into systems and does not lend itself to enterprise-wide, pan-system searches.

Users invariably are most skilled to search on the system they use most frequently. They also typically have fewer access rights on the systems they use less. These issues restrict user search ability and result in time wasting and errors, seen as the fourth issue by industry specialists. Many systems currently use a tabular approach to the presentation of product information that is based on one version of a product's design. It is obvious that a graphical user interface that presented a dynamic perspective of a product's change history would help users to more easily identify the correct configuration of parts they required. This would be more helpful if some form of generic or neutral format were to be adopted, forming the information entry and search element in Figure 4.

The maintained status of products is usually recorded in asset or product maintenance systems. Unfortunately, while asset management systems are becoming increasingly complex, they are not set up to provide the level of detailed product documentation that fully reflects the actual maintained product status. Whilst part manufacturers and OEMs usually provide maintenance documentation and illustrated parts catalogues, these must be limited to the knowledge of the manufactured configuration of the product as it leaves them.

To manage design integrity and enable organisations to continue to operate as effective design authorities requires improved accessibility to all product stakeholders, particularly at a time when the pace of change and complexity is increasing. The challenge of retaining the functions needed for the application of design authority rests on two capabilities. The first is the technical expertise in the appropriate field of a design and the second is the ability to exert influence over the design activity itself. Both areas require skill, knowledge and access to accurate information. Thus, there is a need for skilled individuals who are able to participate in collaborative discussions using design information that is accurate and not impaired by updates that are triggered by design changes.

Bringing together these concerns, it is apparent that the ability of organisations to operate effectively is increasingly defined by their ability to manage information. This situation presents enormous information management challenges. Through-life support of these products usually requires collaboration between several organisations. To ensure that accurate and up-to-date product information can be made available to those who need, it is vital that IT systems become more closely integrated. The implementation of the new systems required to allow this must be achieved economically and more quickly than is currently possible. This is seen as being made more possible by the specification and observation of new standards, based upon a common taxonomy.

5.1. *Ten requirements for the future*

It is difficult to summarise a topic as complex as the challenges facing organisations needing to better manage design change. Previously cited standards (ANSI/EIA 649-B: Configuration Management Standard 2011; Guess 2014; ISO/TR 9007: Information processing systems - Concepts and terminology for the conceptual schema and the information base 1987) have been considered as being difficult to utilise. It was, therefore, decided to attempt to represent the requirements identified by the industry survey, consultation with industry specialists and the review of the current situation in a usable yet comprehensive form as 10 points. Table 3 summarises the inputs made by these different activities in evolving these requirements.

The reason for this approach is to capture the essence of what is required to make improvements. The aim is one of encouraging further engagement with the complex issues that need to be addressed. These 10 requirements seek to provide different perspectives of the overall nature of the product change management challenge. By offering alternative aspects, the intention is to provide a world-view appreciation of the prominent issues to be considered.

- *Requirement 1*: The business impact of inaccurate product information should be better understood and monitored by business stakeholders and shareholders.
- *Requirement 2*: Product lifecycles should be managed proactively with a system of system perspective to ensure that opportunities for implementing changes are optimised regardless of the level in the product hierarchy at which they appear.
- *Requirement 3*: Product characteristics should be designed and monitored to ensure they comply with legislation, standards and customer requirements. Where appropriate, this will more closely integrate the design process with the role of any relevant design authority.
- *Requirement 4*: A single product change control process should be established that supports effective control of product changes and enables information about each change to be found easily. This will improve access to information needed to maintain design integrity and, where necessary, help meet the assurance requirements of any related design authority.
- *Requirement 5*: A single point of entry for new product information should be established across the business that enables consistent standards to be applied and duplication to be reduced.
- *Requirement 6*: All product records should include parent and child relationships, birth and death information, revision/modification history and the details of any constraints on product use (guidance on use or applicability).
- *Requirement 7*: A common system of terminology (taxonomy) for product information and processes should be established and incorporated into information systems, documentation, parts and product labels.
- *Requirement 8*: All staff should be familiar with the product information model used by their organisation or industry and with the purpose of the main systems of unique product identification in use and the allocation rules used for each. The importance

Table 3. Inputs made by the different sources utilised by the authors in this work.

Requirement	Identified with responses to these questions in the industry survey	Developed in response to these issues from industry specialists	Informed by this referenced literature
1	1,3	1: Inaccurate product information	Jun, Kiritsis, and Xirouchakis (2007), Millson and Wilemon (2002), Eckert et al. (2009), Jarratt et al. (2011), Ouertani et al. (2011), Burgess, McKee, and Kidd (2005)
2	4,6,7	2: The difficulty of managing the product change process	Jun, Kiritsis, and Xirouchakis (2007), Rachuri et al. (2008), Chandrasegaran et al. (2013), Barki and Pinsonneault (2005), Burgess, McKee, and Kidd (2005), Wasmer, Staub, and Vroom (2011), Corella, Rosalen, and Simarro (2013)
3	8	1: Inaccurate product information	Jun, Kiritsis, and Xirouchakis (2007); Srinivasan 2011), Corella, Rosalen, and Simarro (2013)
4	1,2,3,9	2: The difficulty of managing the product change process 4: The time spent searching for product information	Jun, Kiritsis, and Xirouchakis (2007), Millson and Wilemon (2002), Barki and Pinsonneault (2005), Jarratt et al. (2011), Ouertani et al. (2011), Burgess, McKee, and Kidd (2005)
5	5,8,10	1: Inaccurate product information 5: Duplicate product information	Gerritsen et al. (2011), Jun, Kiritsis, and Xirouchakis (2007), Ouertani et al. (2011), Burgess, McKee, and Kidd (2005), Wasmer, Staub, and Vroom (2011), Corella, Rosalen, and Simarro (2013)
6	3,8	2: The difficulty of managing the product change process	Jun, Kiritsis, and Xirouchakis (2007), Millson and Wilemon (2002), Eckert et al. (2009), Jarratt et al. (2011), Ouertani et al. (2011), Burgess, McKee, and Kidd (2005)
7	4,10	3: The flow of product information between systems	Gerritsen et al. (2011), Barki and Pinsonneault (2005), Burgess, McKee, and Kidd (2005), Wasmer, Staub, and Vroom (2011), Corella, Rosalen, and Simarro (2013)
8	8,9	2: The difficulty of managing the product change process 5: Duplicate product information	Jun, Kiritsis, and Xirouchakis (2007), Barki and Pinsonneault (2005), Burgess, McKee, and Kidd (2005), Corella, Rosalen, and Simarro (2013)
9	6,7	3: The flow of product information between systems	Jun, Kiritsis, and Xirouchakis (2007), Rachuri et al. (2008), Chandrasegaran et al. (2013), Burgess, McKee, and Kidd (2005), Wasmer, Staub, and Vroom (2011), Corella, Rosalen, and Simarro (2013)
10	2,3	2: The difficulty of managing the product change process 4: The time spent searching for product information	Jun, Kiritsis, and Xirouchakis (2007), Millson and Wilemon (2002), Eckert et al. (2009), Jarratt et al. (2011), Ouertani et al. (2011)

of maintaining an accurate recording discipline, regardless of whether their activities relate to procurement, design, manufacture, sales, maintenance or support, should also be understood. Information allocation rules in the context of product change should be unambiguous.

- *Requirement 9*: Product information should be able to flow freely along the supply chain between and through organisations to match the physical flow of products and be available to users when required.
- *Requirement 10*: Product information should be presented in a dynamic way that enables users to see a product's change history from the past, present and future.

Taken individually these 10 requirements are not new. However, when viewed collectively. they represent an excellent basis upon which to assess the challenges involved. They are intended to provide a better clarity in the nature and magnitude of the challenges to be met. Their realisation will require standards to improve the management of structured product information. This will include steps such as the adoption of a common, market-focussed, product ontology. This should utilise standardised terminology together with defined relations. It will then be possible to engineer a new range of virtual enterprise software products. Such products would have the potential to reduce the time and costs of implementing new information management solutions, while at the same time enabling significant operational business benefits.

Today one might purchase a stand-alone product management-related software product. In the future, following the meeting of these requirements, it will be possible to purchase a similar product that has been developed to a shared common standard. This will be implemented faster and cheaper and provide superior information management characteristics. Factors that would need to be considered include how the innovation required launch such a range of software into an established market might be stimulated. To mitigate the risks of launching such a new product type would require significant market preparation, investment and accurate targeting towards industry situations where the need is greatest. This process may not be forthcoming until there is some direction and strong governance leading to the development and specification of standards. The intention in producing these 10 requirements is to stimulate discussions in this direction. It is envisaged that such discussions will require the collaboration of PLM/ERP and other IT system developers, OEMs and researchers in this field.

6. Conclusions

The proposed 10 requirements provide a means of promoting a closer alignment of through-life design management processes. They can aid the specification of the information technology and the management models used to guide decision-making. These requirements have been considered in relation to the actions required by stakeholders if such an alignment is to be achieved.

Innovation- and evolution-based changes will occur in complex products during their often extended life times. The efficient utilisation, and safe and effective operation and maintenance of such products will involve several stakeholders. These will include OEMs, their suppliers, customers and service providers. Each of these may be operating different information management systems. Requirements 1, 2 and 3 can be the basis for the work which is needed to integrate change management systems within and across organisations. This will require more proactive collaboration and partnership between users and providers of such information management systems.Product-related information must be shared and better communicated within and between stakeholder organisations. Included within the requirements 4, 5 and 6, this demands that all stakeholders and their partners should collaborate and cooperate. The challenges faced are not confined to data alone, but also to format and semantics. This will require the investment of time and effort to support the development of applicable and transparent product data exchange standards. Elements to be produced will include the use of common terminology, as identified in requirement 7. This produces the need to engineer a structure and ontology using software and systems which can better support business information process flow.

Furthering the understanding of this topic must consider how the provision of product configuration information might be improved. It must more accurately reflect the actual status of the products being used. The aim, identified with requirement 8, is to enable the operators and owners of high-value, long life products to close the gap between the maintained status of the product and the maintenance manual. There is much to be gained by improving the flow of and access to information within a fully integrated supply chain. This aim can be identified with requirements 9 and 10. Meeting it will mean that all stakeholder organisations will be better able to quickly respond to customers, while minimising energy and material usage and maximising economic competitiveness.

To offset the considerable costs in terms of time and effort this engenders, an improved understanding is required of the current situation. This includes the assessment of the impact made by the effect of inaccurate information and the benefits of improvement. This requires research into how the product change process needs to be improved. This will include the management of embedded software. To facilitate such developments, the IT industry must be encouraged to embed the information standards within its products. Most critically, an improved understanding is required of rates of product change and their real effect on design divergence.

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