Product Change Management:

to improve the through-life management of
high-value, long-life products

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Declaration

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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Abstract

The designs of complex products such as aircraft, trains and industrial plant continually evolve, during design, manufacture and also during their operating lives. Such products are invariably managed in complex multi-stakeholder environments. The product change process generates significant volumes of information and this continues through-life as designs are modified in the light of technological innovation, supplier changes and operating experience. The volume of information generated is enabled by increased network connectivity together with the competitive advantages that can be derived from greater product knowledge derived from monitoring product performance.

As the service economy has grown, manufacturing and maintenance activities have increasingly been outsourced to enable a greater focus on higher, value-added, aftermarket, support services. Consequently, while the responsibility for managing the design of the end product rests with “Tier 1” manufacturers, operators and maintainers, there has been a significant increase in the responsibility for suppliers to manage design changes. To improve the management of the product change process is difficult because it spans many organizations in the supply chain and to make progress requires collaborative action.

Managing products during their life, particularly in the context of design changes, is a complex process that requires the coordination of many activities spanning design, procurement, production, marketing, sales, support and disposal. These activities constitute a complex process model that is highly dependent on accurate information and can have a significant impact on an organization’s cost base. In addition "products" sold by a Manufacturer are often described as "assets" by a product operator. Regardless of whether something is considered a "product" or an "asset", the change process is supported by a value chain that spans both the domains of manufacturing and support services.

Working practices and skills must constantly adapt in response to innovation and this includes the mental perspectives with which people view the world and solve problems. A significant challenge that organizations face when seeking to remain competitive relates to the need to respond to the challenges of innovation. This drives a perpetual cycle of problem solving whereby existing operations are assessed and opportunities for improvement identified.

This research assesses the challenges to maintaining design integrity throughout the product lifecycle, explores the impact of inaccurate product information and sets-out an approach to achieving improvements to the management of product information specifically for complex products.

Publications

Journals

- Assessing the challenges of managing product design change through-life, Journal of Engineering Design, Volume 27, Issue 1-3, 2016.

Conferences

- SDM'2016 the Third International Conference on Sustainable Design and Manufacturing (5 & 6 April 2016 Chania, Crete, Greece);
- SDM'2015 the Second International Conference on Sustainable Design and Manufacturing (12 to 14 April 2015 Seville, Spain);
- SDM'2014 the International Conference on Sustainable Design and Manufacturing (28 to 30 April 2014 Cardiff, Wales, UK);

Journal Papers - submitted but not published

- Problem Solving in Design: from the Industrial Revolution to 21st Century, International Journal of Information Management;
- Modelling paper, Computers in Engineering.

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Nomenclature

Abbreviation	Definition
Big Data	A term used to describe the phenomenon associated with the growth in information volumes
BOM	Bill of Materials – in simple terms a list of parts required to build a product.
CAD	Computer aided design
CAM	Computer aided manufacturing
Digital Twin	The concept of the digital twin describes how a digital record of a product held in IT systems should exactly (or very closely) match the actual physical status of that product.
DOD	Department of Defense (usually used to refer to the US DOD)
EBOM	Engineering Bill of Materials – the list of parts usually generated by a product's designers
ERP	Enterprise resource planning – a term used to describe a category of software that supports enterprise processes. ERP is usually associated with applications that have a financial focus.
GS1	GS1 is a not-for-profit organisation that develops and maintains global standards for business communication. It predominates in the Retail, Healthcare and related Logistics Sectors.
HVLL	High-value long-life - a term used to describe complex products
ICT	Information and communication technologies
Industrie 4.0	The "fourth industrial revolution", is a collective term embracing a number of contemporary automation, data exchange and manufacturing technologies. Closely related to IOT.
IOT	Internet of Things closely related to Industrie.4.0
ISO	International Organization for Standardization
ISTAT	International Society of Transport Aircraft Trading
Management Science	A branch of academic research that is concerned with improving action orientated managerial thought
MBOM	Manufacturing Bill of Materials - the list of parts usually generated to support production
MOD	Ministry of Defence
PDM	Product data management – a term used to describe a category of software used to manage product design information.
PLM	Product lifecycle management - a term used to describe: A category of software that supports enterprise processes. PLM is usually associated with applications that have a design focus; A management model that describes a product centric approach to managing product information.
SCM	Supply chain management - a management model that describes approaches to improving the performance of groups of

	organizations working together in customer/ supplier relationships, logistics and procurement
SSM	Soft Systems Methodology. A method developed to aid the complex problem solving required support information systems design and implementation.
Strategic Thinking	A way of thinking that is associated with developing the solutions to resolve complex problems.
Systems Engineering	An engineering management discipline created to support complex problem solving
Systems Thinking	A management discipline created to support complex problem solving
TSI	Total Systems Intervention – a structured approach to systems problem solving

Chapter One: Introduction

1.1 Context

The designs of high-value, long-life (HVLL) products such as aircraft, trains and industrial plant continually evolve through-life. Such products are invariably managed in complex multi-stakeholder environments. To fulfil their respective roles these stakeholders (manufacturers, operators, owners, regulators and users) require access to accurate information about a product's configuration. Technological evolution and changes in industry practices, such as outsourcing and leased purchase are creating pressure to improve design management.

This research 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 versus the perceived needs of industry. The design management and change control methods used in the past are unsuited to a new generation of increasingly connected products. The growth of outsourcing, power of networked enabled technology and need for greater efficiency has led to increased complexity and so product change management practices therefore need to evolve. To improve the management of product change, there is a need to improve the alignment between through-life design management processes, information technology and the management models used to guide decision making. For example, the need to maintain design integrity over long periods of time (30 to 40 years and sometimes longer), the management of design information and the change control process is often managed by an organization or function called a design authority.

The complexity of this field means that there is a role for multi-disciplinary researchers to identify cross domain problems that might benefit from a systematic approach. This may help to support the creation of a unifying process model. These points support the intention and methodology proposed in this research analysis.

1.1.1 Design Management

The product change process generates significant volumes of information and this continues through-life. Product modifications are required to maintain performance in the light of operating experience; because suppliers are no longer able to provide replacement parts to the original design specification and also when there is a requirement to adapt the operating performance from the original specification. The volume of information generated is increasing as computing power grows and organisations derive competitive advantage from the knowledge that is embedded in product designs. This area of product innovation is generating demand for greater levels of information management enabled by increased network connectivity.

With the growth in the service economy, manufacturers have sought to shift the focus of their operations to include increasing levels of aftermarket through-life services. At the same time, they have increasingly outsourced between 70% and 80% of their own manufacturing capability. Consequently, while the responsibility for managing the design of the end product rests with “Tier 1” original equipment manufacturers (OEM), operators and maintainers, increasingly important amounts of design change are undertaken by suppliers. The challenge of making improvements to the product change process is complicated by the fact that it spans many organizations in the supply chain and resolution therefore requires collaborative action.

1.1.2 Through-Life Design Change

In a period of rapid technological development, the rate of design change has increased significantly. Outsourcing, the growth of networked technology, need to respond more efficiently and rapidly to changing business needs. Legislative changes to improve product disposal and material recycling, have additionally created a need to develop a more integrated approach to provide whole life support. Therefore, to maintain competitive operations in the areas of manufacture, operation and maintenance, original equipment manufacturers (OEMs), owners and end users of complex products must collaborate more closely.

Managing products during their life, particularly in the context of change, is a complex process that requires the coordination of many activities spanning design, procurement, production, marketing, sales, support and disposal. These activities constitute a set of logical processes that are highly dependent on accurate information and can have a significant impact on an organization’s operating costs.

1.1.3 Growth of Outsourcing and the Service Economy

As outsourcing has grown, responsibility for managing the design change process has required the support of multiple supply chain participants. Furthermore, stakeholder arrangements become more complex when there is a need for industry regulation and leasing is used as a method of product purchase. The outsourcing of design activities has been identified by the European Aviation Safety Agency (EASA) in its safety plan 2012 to 2015 (EASA 2012). EASA comments: “All major aircraft programmes are encountering delays due to their complexity and the way industry is organised. Designers tend to outsource design of significant items to risk sharing partners; thus increasing the number of interfaces.”

1.1.4 Communication Challenges

Significant volumes of information are generated during product development which are then used to create catalogues, bills of materials and support a variety of processes that include, production, test, operation, inventory management and maintenance. The modification process also leads to the creation of multiple product variants in the supply chain. This makes it harder to determine the relevant information about a design modification that needs to be communicated to customers and suppliers. While OEMs typically have a structured approach to managing the internal product design change process, many experience real challenges when coordinating and communicating change information to support their businesses and customers.

Cumulative design changes over a period of time have been observed to cause a divergence of the designs of groups of the same product that are managed as a fleet. Furthermore, when ownership or maintenance responsibility changes the records of the maintained status and historical design changes need to accompany the product to its new owner. Transferring this information can be complicated but is necessary to ensure continued safe operation as well as compliance with regulatory arrangements. A better understanding of the impact of engineering design change within complex systems is crucial to making improvements and research is needed. This should include analysis of how information related to design changes can be best understood and represented.

1.2 Motivation for the Research

The seeds of this research were sown in 1995, in an aircraft hangar at a military airbase in Germany. The hangar was used to store and maintain a surface to air missile system and difficulties arose when trying to identify spare parts required for maintenance. This led to pictures of the required items being sent to the supplier to confirm the identity of the parts required. Later, when the Author was working in a fleet management role for the same weapon system back in the UK, queries from operating units identified that orders for spares were not being satisfied because design information was missing from inventory systems. Searches for parts showed there was no inventory when alternative spares were actually available, even though their design was slightly different. This problem was caused by missing alternatives or succession links that are used in ICT systems to enable systems users to identify alternative compatible spare parts that are related by modification or design change.

The information that linked spares related by design change, was important for not just efficient resource management but also for confirming that spares are safe and compatible to use in maintenance. This experience isolated the information challenges that underpin the through-life management of products.

Later, with several years' experience of working in the ICT industry it became clear that many other organisations were experiencing similar problems to that witnessed by the military. Furthermore, the enterprise software sold by major vendors, was not as integrated as was often claimed. This initial motivation for taking a deeper look at the information management challenges being experienced by industries that used HVLL products such as the Transport, Defence and Energy Sectors, was consolidated through discussions with a number of product manufacturers and maintainers.

These discussions established that while most organizations had a structured approach to managing design changes, many experienced difficulties communicating the various categories of design information coherently in support of their businesses. The following points were common themes that were identified:

- Both manufacturing and service organizations are experiencing difficulties improving and managing the product change process because it is highly information intensive;
- Change occurs continuously 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 and not sufficiently detailed to provide guidance on the activities required to achieve accurate information. To illustrate, 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 2011) and ISO 10007:2003 Quality management systems — Guidelines for configuration management both identify over 40 principles. None address specific shortfalls in the underlying information and communication technologies (ICT) required to manage design information;
- 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. For example, many organisations allocate new part/product numbers based upon an assessment as to whether a modification has changed the "fit, form or function" of a product. Other numbering systems for example GS1 simply require that a new product number to be allocated if there has been any design change. GS1 is a product identification system that is widely used but with a centre of gravity in the fast-moving consumer goods/ retail sectors;
- Standardised approaches to estimating the cost of inaccurate product information have yet to emerge;
- Master information management best practice appears to be poorly understood.

While there is a substantial body of information available that describes the discrete activities required to improve through-life product management (business objectives, standards, information strategy, technology and so on), it is difficult to make improvements. The increasing complexity of ICT and industrial practices means that enhanced techniques are required to improve the management of products and product related information.

In the context of the emergence of concepts such as "Big Data", the Internet of Things and Digital Twin, research to devise ways to improve the management of the design information through-life is a real priority (Parhizkar and Comuzzi 2017; Mattos and Laurindo 2017; Ehret and Wirtz 2017).

What currently appears to be lacking is an evidenced based management approach that provides a consolidated list of activities that offers specific and detailed guidance on what is required to achieve success. While operations research made good progress helping to support the resolution of well-structured problems the view in the 1950s was that ill-structured problems had been left largely untouched (Simon and Newell 1958). Executives continue to point to the lack of formal techniques to support the resolution of most of the top-level management issues (Checkland 1988, Smith 1988, Senge 1992, Lawrence 1999, Cook et al 2003, Amitabh and Sahay 2008, Kasser and Zhao 2014).

This research assesses the challenges to maintaining design integrity across the three phases of beginning, middle and end of the product lifecycle. It explores the impact of inaccurate product information and sets-out an approach to achieving improvements to the management of product information specifically for HVLL products.

1.3 Research Aims and Objectives

To aim of this research is to address the challenges of maintaining design integrity throughout the product lifecycle where there is a need to more closely align, through-life design management processes, information technology and the management models used to guide decision making.

The objective of the research is to develop a coherent set of guiding principles, underpinned by evidence of the behavior of the designs of HVLL products as they change through-life. The principles should offer a range of benefits:

- Enable the development of "business models" that inherently support more accurate product information;
- Support improved flow of products and product based services through the supply chain;
- Reduce the cost of managing product change;
- Increase returns on investment in information technology.

1.4 Research Approach

The use of the product change process was chosen as an investigative path following the author's experience of the problems caused by errors in design information that arose following product modifications in the aerospace defense sector. Missing relationship information (alternative or succession links) between the part numbers of similar products related by a design change or revision was observed to prevent maintenance engineers from identifying the spare parts required to support product rectification. The inability to identify spare parts that were physically in a warehouse but could not be accessed created a situation where inventory was, in effect hidden from those that needed it. Figure 1.1 illustrates a simple product design and the relationships between constituent parts. Component P is a product that is used to create a higher order assembly P_{parent}. P is also a sub assembly with components denoted as $P_{child.}$

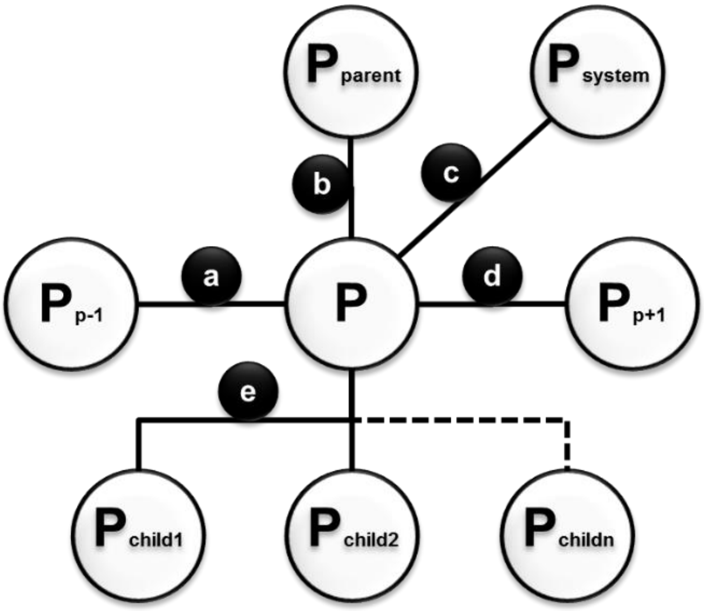


Figure 1.1: A simple product design with relationships between components identified

Comprehensive product design records should show a product's current configured status current status P, previous modification state P_{p-1}, and post design change status P_{p+1}. These relationships are illustrated in Figure 1.1 and described as follows:

- The relationships a and d support decision making regarding choices of alternative parts such as might be available from inventory. These can be safety critical and solving engineering problems when this information is missing can be extremely difficult;

- Relationships b, c and e relate to the hierarchical position that a product takes in a design as well as its system membership. These relationships also support decision making relating to end use compatibility. For example whether a subassembly or spare part is compatible with a higher order assembly or end product.

Further investigations identified that missing alternatives links (relationships a and d) represent a small aspect of far greater inefficiencies that are caused by other types of inaccuracies in product information. Rates of product design change have a significant role in driving the volume of information that flows through supply chains.

To conduct an investigation, a research approach was derived that considered the issue of managing product change from the four separate perspectives of: product design information; information technology; industry lifecycle and finally, thought systems. The research environment is illustrated in Figure 1.2:

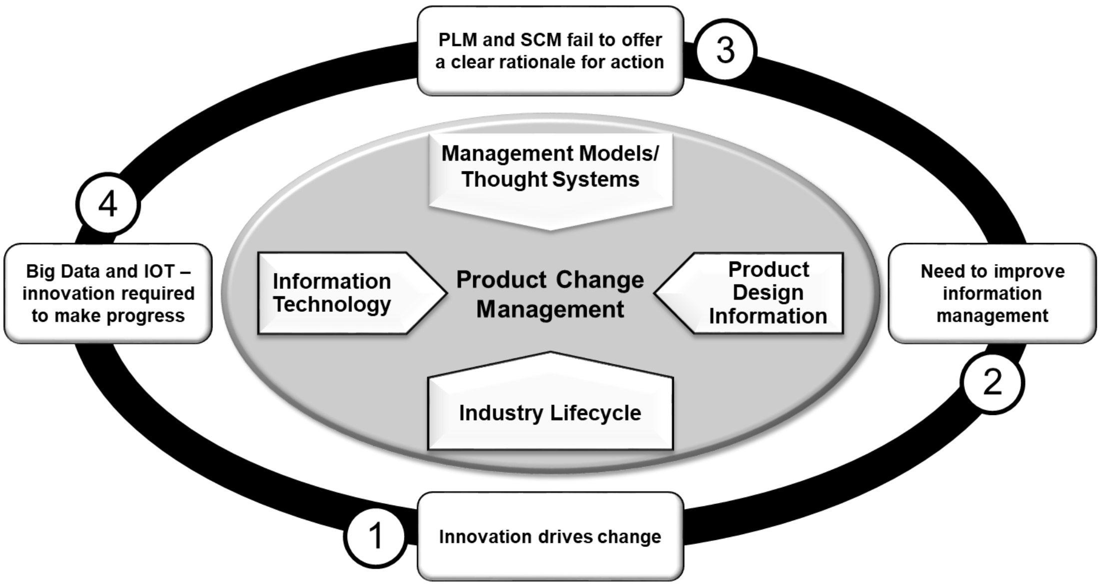


Figure 1.2: Research approach

Figure 1.2 places the product change process at the heart of the research surrounded by four prominent issues: first industry lifecycle; second product design information; third management models/ thought systems and finally, information technology. These issues are being impacted by a number of issues that are presented in the diagram. The first is the innovation that drives industry lifecycles; second, to improve competitiveness there is a need to improve the management of product information and knowledge. This requires adaptations to the management paradigms of product lifecycle management (PLM) and supply chain management (SCM) which are relevant to this field and which are discussed in the literature review. Both appear problematic. Finally, the phenomena of Big Data and the

“Internet of Things” (IOT) illustrate significant trends that are emerging from the growing importance of information and require significant changes to ICT.

The investigation followed a conventional problem solving approach as follows: identify the goal state concept; investigate the problem space concept; develop knowledge concepts; and, finally, create process concepts (Smith 1988).

The research approach sought to focus on the challenges of managing the "product change" or modification process which requires accurate and up to date product information to be communicated and shared between supply chain participants. This enabled an improved understanding of the rates of through-life design change that will help to develop improved information flows and so reduce support costs. The following stages were followed:

- Initial investigation to frame the research and to develop and define the proposal. This focussed on the information challenges associated with managing the design change process and the allocation of part numbers;
- This was followed-up with an industry survey;
- A subsequent investigation sought to quantify potential annual rates of design change and related issues;
- The findings of the investigation were explored using software models;
- Proposals for improvement are made and validated with additional modelling.

1.5 Research questions

1.5.1 Initial Position

The initial thoughts on the aims of the research inevitably needed to be adjusted in the light of early experiences. It was perceived by the author that the actual levels of design change were not understood and that the details of the changes being made may well be lost within the change process. In this context, it quickly became apparent that it would be extremely difficult to identify the true costs (financial and non-financial) of inaccurate information.

1.5.2 Through-Life Design Change

The main research question became how much through-life design change takes place? This enabled further questions to be derived:

- How are industry practices changing?
- How is technology supporting the new practices?
- How does the nature and use of this technology need to change?

- What are the prominent features of the main standards and what are their strengths and/or weaknesses?
- How might these standards be improved?
- What approaches to product management might support the greatest level of information accuracy?
- What approaches to product management might maximise the accuracy of product information across the whole lifecycle?

1.6 Research Constraints

The research constraints identified at the start of this process related to:

- The difficulty of obtaining research data due to commercial sensitivities, complexities of corporate enterprise architectures and a lack of research funding;
- The difficulty of replicating research findings due to the complex nature and volume of the information involved in the product change process.
- Presentation of research assessments. The final requirement was to present the generic information generated in a form that could be understood and applied back into specific contexts.

1.7 Thesis Chapter Structure

Chapter One provides an introduction to the research topic, describes the motivation for the investigation and states the research approach.

Chapter Two presents a literature review of the key topic areas. These include: trends in product information; developments with information technology; the relationship between innovation and industry lifecycles; mental models, thought systems and complex problem solving; and, finally, product change and information management.

Chapter Three describes the industry investigation used to gather information to support the analysis. It presents the background to the research conducted to formulate the survey and the approach taken to gathering and analysing the data.

Chapter Four explains the initial, Phase One analytical process. A spreadsheet based model was developed to validate the observations of product change obtained from discussions with industry specialists. This demonstrate the scientific process. Further analysis to illustrate the complex nature of product information was undertaken with a second Phase Two model that is presented in Chapter 6. Chapter Five discusses the findings of the analysis, offers a vision of the future and proposes Ten Principles for making improvements to product change. Chapter Six describes the second modelling undertaken to assess the validity of the Ten Principles. Chapter Seven describes the rationale and benefits of the Ten Principles. Chapter Eight provides a summary and concluding remarks.

Chapter Two: Literature Review

2.1 Introduction

The safe and effective operation of HVLL products is invariably safety critical and so it is important that design integrity is maintained and accurate records of modifications kept. There is a further significance to the field of product management because the processes that people use to manage products in terms of design, manufacture and use, shapes the structure of the World's economies. Some theorists believe there is even a direct "mirror" relationship between the structure of economies and the products produced (Colfer and Baldwin, 2010).

2.1.1 Growth of the Service Economy

The main areas of economic activity are broadly categorized into agriculture, manufacturing and services. Wealthy countries (the G12 countries for example) derive the greatest economic value (over 70%) from services activities (Soubbotina 2004 and Wölfl 2005). As economies develop, competitiveness drives organisations to focus on the activities where the greatest value can be derived. Consequently, many organizations now outsource non-core activities to focus on those from which they are able to derive greatest value. These may be expected to include research, new product development and services. This reflects a structural shift in consumer, collective, and business demand towards higher value-added, knowledge intensive goods and services (Brinkley 2008).

2.1.2 Industry Lifecycle

Innovation drives the creation of new products, the need for new markets in which to trade them and also industry lifecycles. The concept of an industry lifecycle describes the evolutionary process by which markets emerge and develop in response to both innovation and economic conditions. The four stages in a market's life are birth, growth, maturity and eventually decline (Audretsch and Feldman 1996).

In his book The Wealth of Nations, the economist Adam Smith described his thoughts on market behavior and the role of a guiding "invisible hand". This concept describes how market forces, generated by the supply and demand of goods, enable the effective allocation of resources within economies. While Smith clearly recognized the fallibility of markets his fundamental belief was that economic efficiency would be maximized through the self-motivation of market participants (Smith 1776). Such a free market scenario would ultimately enable the needs of all parties to be met.

Complex products require the integration of many technologies. Sometimes improvements in one market are dependent on changes in other related markets. For example, autonomous cars and air vehicles require new regulations, standards and procedures to enable economic benefits to be derived from current investments in product research and innovation. Developments in mobile devices and electric cars are dependent in part on technologies that store electric charge – batteries.

There are however, many impediments to the successful operation of free markets: production economies and sunk costs; transaction costs; and imperfect information (Yao 1988). These impediments to economic activity often prevent free markets from responding automatically to changes that are made to products and product related services. When markets are unable to respond to changes that arise from innovation, external intervention may be required to prevent market failure (Datta-Chaudhuri 1990).

There are many factors that differentiate markets, products (goods, services) resources (labour and capital); customers and suppliers; number of market participants; regulations and standards; location and trading process; taxation and legislation; levels of investment as well as research and appetite for innovation. This complexity means that while the concept of the free market is useful, it is clear there is a role for the state. To protect the environment, secure the enduring availability of natural resources, provide national security and implement legislation that protects rights to property ownership. These activities illustrate the issues where government action is required to ensure that markets are organized into a disciplined environment that minimises the wasteful use of resources and meets the needs of stakeholders and society. Thus the role of government intervention is to ensure that markets continue to operate effectively in a way that is economically sustainable. The notion of government intervention in markets is to ensure that equitable economic activity continues by providing political solutions that resolve social problems – conflict (Lerner 1972).

2.1.3 Management Thinking

The way people think is important. To operate effectively, organizations need an integrated set of ideas and practices that enable problems to be solved and decisions made. To make decisions about their daily lives, people develop mental models about the world around them. These models are fuzzy, imprecise and change over time, yet they are the basis of human reasoning (Forrester 1971 and Johnson-Laird, 1983).

When a group of people adopt a common mental model it might appear as an organizational culture or management paradigm. Invariably the ideas and problem solving practices used, are based on the knowledge and cultural values that that are available at the time. An ongoing challenge that organizations face relates to the need to ensure that the business thinking that is in use remains current and adapts to meet the changing operational needs (Senge, 1994). People who are trained to think about products from a functional basis demonstrate a greater ability to think systemically (Tomko 2017).

The Mirror Hypothesis sets out ideas about the role that products play in structuring the World's economies (Colfer and Baldwin, 2010). It sets out to illustrate that a systemic relationship exists between the way that products are designed, manufactured and used. In this context, it is clear that products and the way they are managed, are a function of a larger system that can be viewed from the perspective of an organization, industry or wider economic perspective.

Significant progress has been made over the last 50 years towards developing a better understanding of how people think about and solve complex problems and the interrelationships that exists both within and between systems. Management science, systems engineering and systems thinking are fields of research that have evolved to support the development of complex problem solving (Newell et al 1958, Hitchins 1998 and Checkland 1988). Checkland for example identified four fundamental system properties that must be understood to make progress and these are: emergence (system properties); hierarchy; communication; and, control.

As innovation drives change, ideas and thinking processes need to adapt too and this includes the mental models people use to view and interact with the world and solve problems. To remain competitive, organizations need to continually identify ways to improve their efficiency. This drives a perpetual cycle of problem solving whereby existing operations are assessed and opportunities for improvement identified.

The process for implementing design changes to HVLL products is a complex, information intensive process that requires the collaboration of multi-disciplinary teams drawn from many organisations. In this context it is important that a coherent problem solving approach exists at all levels in an organization (Amitabh and Sahay 2008).

2.1.4 Context: the Era of Increasing Precision

As the understanding of the World advances and technological capabilities increase, many aspects of people's lives are being influenced by a trend towards "greater precision". For example increasingly precise knowledge of the time is necessary to support satellite navigation and real-time safety critical systems. However the current position has evolved from the period of the late 1600s and mid 1700s when chronographs or time pieces were developed to provide increasingly accurate time for long distance marine navigation. In the 1800s the introduction of the railways initiated the first steps towards standardizing time. The development of the Global Positioning System requires very accurate timing signals that are globally synchronized and supports increasingly precise navigation. High definition television is increasing the resolution of pictures transmitted into our homes; and a greater understanding of genetics is improving the accuracy of criminal evidence. These developments represent the growing importance of accurate information, knowledge and our ability to manage it. However, the attainment of more accurate product information will require people and organizations to make substantial changes to the way products, parts and information are managed.

The benefit to be derived by improving the availability of design information to market participants is well recognised yet making improvements continues to be a challenge. The attainment of more accurate product information, will require fundamental and substantial changes to the way products, parts and information are managed (Chandrasegaran 2013, Canaday 2011 and Vianello 2012). These factors are explored and demonstrated in the modelling and analysis research reported in this thesis.

2.1.5 Smart Manufacturing

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

International research priorities recognise that there must be a change from the largely static network of embedded systems to the adoption of integrated systems-of-systems which are highly dynamic, evolving and that are never down (Grimm 2011). An approach for sharing product knowledge was developed as part of the Thermal Overall Integrated Conception of Aircraft (TOICA) project, carried out in the Seventh Framework Programme funded by the European Union. This considered the need for closer integration of information dispersed throughout ERP and PLM ICT systems that are in use today. These include SAP, Oracle, IBM Maximo, ABB Passport, Siemens Teamcentre – there are many more. However, to enable this information to be utilised more effectively, further research and standardization is needed – a step change is required (Baalbergen et al 2017; Quentin and Szodruch 2010; Jun et al 2007).

2.1.6 Information Technology Challenges

The product development process generates significant volumes of information and this continues through-life as designs are modified in the light of operating experience. The volume of data generated is growing and exacerbated by software updates, product support monitoring and “self-reporting” all enabled by increased network connectivity. A term used to describe the phenomenon associated with the growth in information volumes is “Big Data”. This trend is set to accentuate the need for accurate information as inconsistencies (such as in the areas of catalogues, bills of materials, inventory, manufacturing assembly and maintenance instructions) can have a disproportionate impact on both performance and cost (labour, material and operating capital) (Redman, 2004, 2005 and 2008). The single largest challenge associated with product development remains a lack of detailed design information and relatively limited design changes at a component level can have a wider systemic impact (Sandberg et al 2017).

Despite significant technological developments, the closer integration of enterprise processes and, more broadly, the wider attainment of industrial interoperability remains elusive (Agaram 2017; Ferreira et al 2017). Current technology provides an architectural system of “point solutions” approach of loosely coupled information systems that separately support early life design, manufacture, inventory, documentation and through-life maintenance records (Boehme et al, 2012; Xu and Liu, 2011). Software vendors use different terminology and database relationships to support their product management applications and this increases the difficulties of improving interoperability. A new type of technology and associated information management protocol is therefore required to enable information to flow more easily both within and between organisations (Tao et al 2017). Such technology is required to enable the combination of information from different actors and sources (Herterich 2017). Both aspects are considered in the research reported in this thesis.

2.1.7 Sustainability

This work examines the issues that need to be addressed to improve the through-life management of complex, HVLL products. The primary driver is to investigate the topic of product change from the need to improve economic competitiveness. However, as recognition of the environmental vulnerability of our planet increases, the need for greater competitiveness must be considered from a more circumspect perspective that places a pure focus on industrial performance in the context of environmental and social needs. According to the World Bank (1987), sustainable economic development can be defined as: "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The concept of sustainability thus seeks to balance economic goals with social and environmental objectives and goes far beyond the primary economic objective of increasing average income, to include improvements to freedom, equity, health, education, safe environment and much more (Soubbotina 2004). This investigation will not address the issue of economic and environmental sustainability but should be considered from a position that looks beyond the narrow perspective of “what is required to be more competitive” to include consideration of how it might support sustainability improvements.

2.2 Industry Trends Impacting Design Management

2.2.1 Engineering Change

One of the issues that is important to organisations in the context of industrial competitiveness relates to the need to reduce the time that is required to design and develop new products after a market opportunity has been identified – this is also referred to as the “go-to-market” process.

Methods that have been developed to reduce product development times include the use of modularised designs and product families that enable increased commonality through “design component” reuse. At the same time, these methods enable greater variations of a similar product for less cost (Alizon 2007, Fabrice 2007 and Thevenot & Simpson 2007). These product design innovations have also enabled processes to become increasingly structured and activities more easily outsourced.

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 identified that business process improvements were required to enable a company to maximize the advantages available from better managed change processes in complex product design.

Although progress has been reported in this area the complex multi-disciplinary nature of this field means that there has been less focus on engineering and design change while related issues have been pursued under alternative research topics. This is 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).

The need for iteration (repeated changes) in the design process to achieve an end product is rcognised however, despite substantial research, a consensus model or terminology for describing iterative situations has remained elusive (Wynn and Eckert 2017).

The design, manufacture and through-life support of complex products is often only achieved as the result of the mutual collaboration of many organizations acting as a coherent supply chain (Baalbergen et al 2017). It is important that regardless of the number of modifications made to a product that its design integrity is preserved. The integrity of engineering design includes consideration of reliability, availability, maintainability and safety of systems and equipment (Stapelberg 2009). Information is distributed throughout the supply chain and the overhead of monitoring design changes to ensure that design integrity is maintained could be reduced by improving the access that product stakeholders have to accurate design information.

There is no consensus on what constitutes best practice for the management of engineering change in this context but 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 as inconsistencies in product information 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 2011). However, the effects of change propagation were not included. A further comprehensive review of design research themes placed an emphasis on how through-life engineering data was managed over long timescales. 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 (McMahon and Ball 2013).

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 2013; Sandberg et al 2017). 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. A jet engine is only part of the complex product that constitutes an aircraft. It is possible to see that PLM technology can assist in synchronising design change information within and between organizations; however, interoperability between PLM 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. Research reports difficulties associated with the capability of tracking changes automatically.

In 1998 the UK National Audit Office published a report on the management of modifications to defence equipment including ships and aircraft (NAO 1998). The paper documented the volumes of modifications and identified when they were conceived, authorized for implementation and finally when the implementation of the modification was complete. Figure 2.1 from that report illustrates the modification volumes and timescales involved for the Hunt Class Minesweeper and Figure 2.2 provides the same for the Tornado combat aircraft.

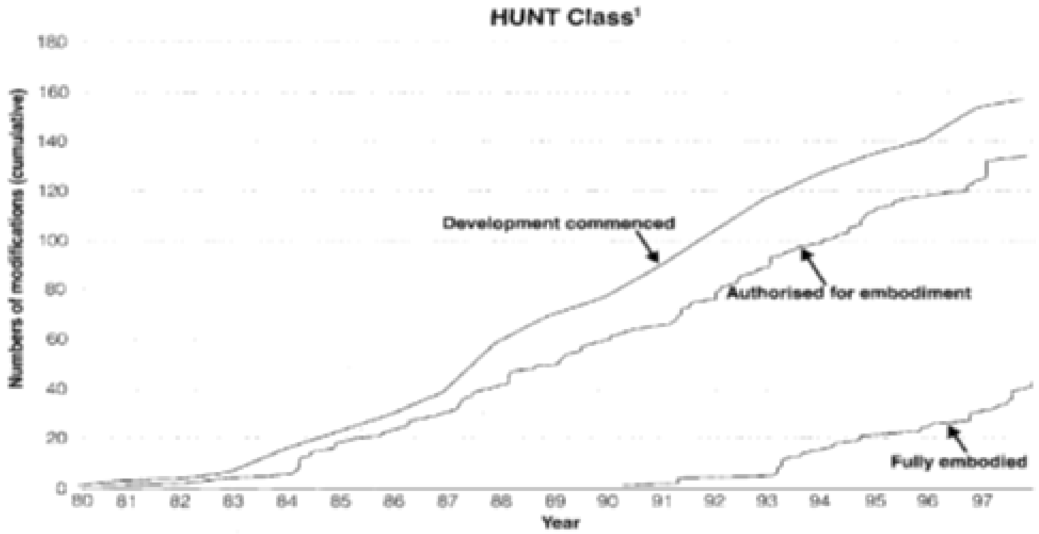


Figure 2.1: Modification volumes to the Hunt Class Minesweeper (NAO 1998)

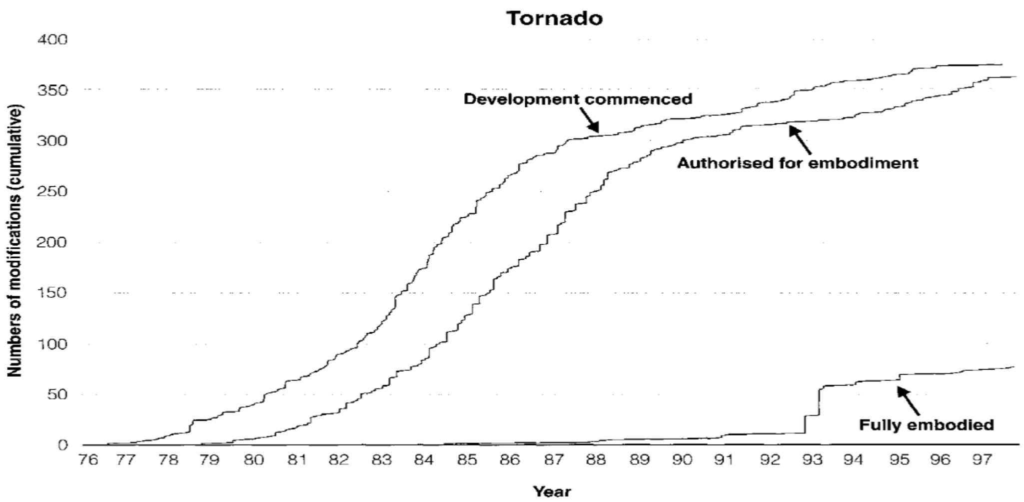


Figure 2.2: Modification volumes to the Tornado combat aircraft (NAO 1998)

The NAO report identifies that in many cases modifications are not fully implemented and that full implementation can take many years, over 10 years in some cases. In the figures illustrated here the timescales are of the order of 20 years. The report also identifies that responsibility for modifications falls to a number of stakeholders in the supply chain, not just the MOD which owns and operates the products.

Complex products, such as aircraft and trains often have systems upgraded 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 et al 2009)].

Managing changes during life is a challenging process (Vianello and Ahmed-Kristensen 2012). Management of this 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.

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; Ehret and Wirtz 2017).

2.2.2 Design Process – Structure

The defence sector is a significant operator of HVLL products. Since the 1960s, a trend can be observed in the pattern of reforms to the UK Ministry of Defence (MOD) procurement process that indicates an increase in the structure of the through-life design management process. In the 1950s the process was essentially one largely unstructured process that comprised of three phases. The first involved a "feasibility" analysis, the second conducted "technical and financial investigations", while the third phase embarked on "full development". In 1961 Sir Solly Zuckerman (Chief Scientific Officer UK MOD) sought to break this process into three clearer and separate phases (Gibbs and Zuckerman 1961).

In 1969, the need to improve the effectiveness of the MOD's through-life product management process led to a review which culminated in the "Downey Report". The Downey Report recommended that the MOD's product management process adopt a more structured approach and entailed splitting the previous three phases into 7 (Downey et al 1969). The aim was to introduce more decision points between the stages to reduce cost over-runs and improve the management of risk. The Downey stages were: staff target (requirement); development; feasibility studies; project definition; full development; production; and, finally, operational service.

The 1998 the UK Strategic Defence Review replaced the Downey process with the "CADMID" process: concept, assessment, development, manufacture, in-service and finally disposal. CADMID offers a relatively simple structure for the through-life management of major equipment programmes that covers the beginning, middle and end stages. The following points are evident from developments in the evolution of the UK's defence process:

- In the 1950's there was little or no structure to the product development process but over the years the process has been defined with greater clarity (Chin 2004);
- With each revision, the design process has been extended from initial product design to include the whole of the product's life;
- As defence products have become more complex the design, manufacture and procurement process has become increasingly difficult to manage;
- The challenge of managing the product development process has led the world of defence to consider the purchase of an initial product with modest capability and then to gradually modify it to add extra functionality. This is a concept called 'incremental acquisition' (Kirkpatrick 2010).

2.2.3 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. Organizations 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 (Atasu and Subramanian 2012).

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 across enterprise ICT systems but to derive efficiency improvements requires techniques to be developed that enable this knowledge to be fused (Ouertani et al 2011).

2.2.4 Alignment of Business and Product Strategy

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 (Parhizkar and Comuzzi 2017; Burgess et al 2005). The efforts to integrate change management systems within and across organizations are considered to be fragmented despite the apparent capability of PLM systems to tackle this. There is a suggestion that companies seem to view the engineering change process as a compliance issue rather than a potential source of competitive advantage (Burgess et al 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 organizational domain (Hamraz et al 2012). This will need the type and level of inter-organizational collaboration proposed later in this thesis.

Despite significant investment in the development of product data exchange standards such as ISO 10303 (STEP) and ISO 14306 (JT), 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-standardized implementations that bring with them high organizational 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). This is an issue that will be further explored by the research reported in this thesis. It is recognised that changes can propagate with associated impacts on product configuration (Cardin et al 2017). Mapping these changes and monitoring the effect that they have within an organization is recognised as being a challenging but nevertheless a valuable and important research topic (Parhizkar and Comuzzi 2017; Mattos and Laurindo 2017).

2.2.5 The Growth of Embedded Software and Sensors

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 two million lines of code, distributed over eighty nodes and using five different networks (Patil, and Kapaleshwari 2010). Producing and maintaining this facility in new and existing vehicles is 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.

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 computing devices that already report problems direct to software vendors. It is a challenge just to keep track of these developments.

2.2.6 Change Propagation

Design and manufacturing organisations must process many changes that require information to be transferred between multiple engineering change management systems with multiple formats and multiple definitions. The information discrepancies contribute to significant lost man hours and delays with factors such as the use of alternatives for replacement parts (Wasmer et al 2011). There is a need for knowledge level communication within distributed computational resources to enable designers access information in a simple and meaningful way. The requirement of providing design knowledge in a usable form with 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 standardized data model to provide a common understanding of the underlying business process between various stakeholders (Wasmer et al 2011 and Corella et al 2013).

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). The level of such changes was used as a guide to the efficacy of the simulation procedures deployed in the research reported in this thesis. 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 standardized information systems will be necessary.

2.2.7 The Emergence of the Design Authority

All organizations with responsibility for managing products (and assets) have a need to maintain design integrity to ensure that the purpose of the product is realised. Not just during production and manufacture but also maintained through-life to disposal or recycling. Design integrity for many organizations can be the foundations of their business reputation (brand) and often underpins product safety. However managing and maintaining the necessary control to sustain design integrity becomes increasingly difficult as the complexity and length of product life increases.

HVLL products such as aircraft, ships and trains are invariably managed in complex multi-stakeholder environments. For example, some product users such as airlines have their own maintenance organizations that are regulated to make limited changes to their aircraft, without input from the OEM. Operators are therefore able to undertake modifications to products such as internal trim and entertainment systems. These will have an impact to airframe loading and stress but not to the extent that OEM design analysis is required. There are also third-party maintenance organizations, regulators and asset leasing companies together with other financial institutions that offer secured loan finance. Each of these stakeholders has an interest in the design integrity of each product.

In some industries, where the longevity of a product exceeds the life of the organizations that support that life, there has been perceived to be a requirement to create an organization that specifically provides a through-life "design authority" for that product. The nuclear industry is one example but other industries such as the UK rail and defence sectors have also felt the need to adopt this concept (Kemp 2005, RSSB 2004 and Andrews, 2006)

A design authority is defined as 'An organization with the professional competence and authority to specify technical design requirements, undertake design tasks, apply configuration management to design and continuously monitor the effectiveness of design/material and its maintenance - through-life'. To restate this issue in an alternative way, the complexity of managing product change in multi-stakeholder environments, has led to the requirement in some industries for a "design authority" to execute the necessary control to maintain product design integrity through-life. Consequently, the role of a design authority is ultimately to maintain compliance and reduce risk.

2.2.8 Design Integrity

The definitions of integrity include: of unified or sound construction; or, of being whole and undivided. The UK's Rail Safety Standards Board (RSSB) states that an asset (product) is fit for purpose when it meets the requirements for technical integrity and delivers the required performance (Porter 2004). Many organizations, particularly in safety critical industries, are required to maintain extremely high levels of design integrity. The execution of the control necessary to maintain design integrity may be undertaken by an organization acting as a design authority or by a group of organizations that are collaborating to ensure a design is effectively controlled (RSSB 2004). The role and responsibility that a design authority (organization) plays in maintaining design integrity varies according to specific product circumstances. The scope of responsibility of design authorities is changing in response to industry practices and market forces (Webb and Cees 2009). The ability of a design authority to exert control depends on the existence of a wider management or regulatory system (RSSB 2004 and EASA 2012). Some industries such as the UK rail sector have established systems to maintain design integrity that do not require a single organization to operate as a design authority.

The design authority concept seeks to provide greater coherence and control of a product's design. This requires two qualities: the technical knowledge to manage the design combined with the organizational power or governance to provide authority. 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. In the face of rising economic and competitive pressures the resources allocated to maintaining design integrity are constrained and so achieving greater efficiency is therefore of great relevance. By improving the management of product modification, more effective assessments of design integrity should be possible.

2.3 Problem Solving in Design

2.3.1 Historical Perspective

There are times when significant technological innovation combines with social and economic forces to create tremendous pressure for change. Established industry leaders underestimate the disruptive ability of new innovations (Kang and Song 2017). Such periods of turbulence require significantly greater problem solving skills to enable people respond to and overcome the fresh challenges presented. Today, the pervasive use of ICT in product design is creating a closely integrated and complex web of systems that is increasingly difficult to manage. The emergence of newly industrialised countries combined with the growing dominance of ICT is creating significant social and economic upheaval. A better understanding of the current product management challenges can be gained, if the difficulties associated with managing through-life design change today are put into a historical context.

2.3.2 19th Century Warship Design

The Mary Rose, HMS Victory and HMS Warrior are British warships that can be seen at the Historic Naval Dockyard in Portsmouth, UK. Collectively they offer a perspective of ship designs between the early 1500s to the late 1800s (Portsmouth Historic Dockyard, 2017).

The Mary Rose had been in service for 34 years when in 1545, shortly after the completion of a major refit, she capsized and sank. HMS Victory was Admiral Horatio Nelson’s flagship at the Battle of Trafalgar (1805) and was built in 1765. After Trafalgar, Victory remained in service until she was decommissioned in 1812 and therefore had formal operating life of 47 years. HMS Warrior was the first armor plated, iron-hulled warship and was built in response to France's development of the Gloire (launched 1859). The Gloire was the first ocean-going wooden hulled, ironclad warship. Warrior was commissioned in 1861 and decommissioned in 1883 - an operating life of 23 years. After the construction of HMS Warrior, all ships built for the Royal Navy were made from iron. This illustrates that throughout naval history, warships have had operating lives of around 30 to 40 years, similar to that of modern complex products.

2.3.3 The Gun Deck

The gun deck was a significant feature of warships for several hundred years from the late 1400s until they disappeared suddenly in the 1870s. The Mary Rose, Victory and Warrior all have gun decks that were equipped with cannons that were positioned along ships’ sides to fire through gun ports. However, in the decade following the launch of HMS Warrior, a series of innovations led to changes in warship design that required guns to be mounted in turrets. The first ship to be fitted with turrets was HMS Monarch (launched in 1868) and it was just three years later that HMS Devastation (launched 1871) was only fitted with gun turrets. Consequently, a consistent feature of ship design for around 400 years was replaced with a new technology.

2.3.4 Disruptive Impact of Rapid Technological Change

Rapid technological developments such as the ability to improve the manufactured quality of iron and steel, exacerbated by the need to compete with the military capabilities of other nations, led to significant increases in the power of naval artillery. Smooth bored, muzzle loading cannons were replaced with guns that had breach loading rifled barrels. For a few years, gun calibers increased so fast (around 2cm per annum) that there was a real risk that a ship would be outclassed during the three years often required for construction. Furthermore, as calibers increased, gun weight increased too, to the point that cannons became too difficult to maneuver by hand using the traditional rope, block and tackle equipment. It thus became necessary to find alternative means to mount naval artillery on ships and the gun turret emerged as the solution. The gun turret thus represents a disruptive innovation because it was a radically new technological approach that made the design concept of the gun deck obsolete.

This also helps to illustrate that a product's design, in this case a warship, can be sustained and improved even though a subsystem is rendered obsolete by the emergence of a new technology. The design difficulties experienced during the transition from gun deck to gun turret were exacerbated, because wood was replaced as a construction material by iron and steam engines with propellers replaced sails. To put the changes in warship construction into perspective, the SS Great Britain (launched in 1843) was the first ship to combine iron construction with a steam powered screw propeller.

The implications of these changes on engineering problem solving and decision making can be understood by considering the interaction between the three prominent systems involved in warship design: the weapon system (gun deck/turret), structure and flotation system (hull), and the propulsion system (sails/ steam engine). Before the transition under examination, the design configuration of a warship's gun deck was relatively flexible. The number of cannons installed could be varied reasonably easily during a ship's operating life. In contrast, the design of steam powered warships fitted with gun turrets, required closer integration of the activity to design the hull with that required to design the weapon and propulsion systems. A further consideration during the design phase was the method of manufacture and whether this presented any design constraints. Thus, technological innovation led to a significant adjustment of existing working practices and created a need for a greater level of knowledge and problem solving skills.

2.3.5 Product Modularisation and Families

As the complexity of products has increased, engineers have developed problem solving strategies to improve product development. The concepts of modular design, product families and control engineering are examples of these methodologies. The use of modularization and product families helps new products to be designed in a way that enables specific customer requirements to be addressed more easily. It also helps to reduce the costs incurred during design, manufacture, service and disposal and thus can be seen to directly support economic sustainability. In its simplest form, the use of bricks or building blocks (modules) helps to make construction easier. While stone blocks and bricks have been used for thousands of years, modularization came to prominence during the 18^{th} and early 19^{th} Centuries as steam engines and rail transport emerged.

During this period, the wider adoption of steam powered locomotives was supported by creating the concept of a product family. Basing products on a common design reduced the challenges of problem solving because it enabled engineers to reuse the design knowledge embedded in existing products (Kong et al, 2010). The efficiencies gained from modifying the designs of existing parts (by reusing existing design knowledge) reduced the time to develop new products. However, this approach breaks down when, as a consequence of innovation, a radically new technological approach is identified that makes existing products obsolete. In this case, an innovation that dislocates the existing process of product adaptation through incremental design change can be viewed as disruptive.

Control engineering emerged in the early 19^{th} Century as the result of difficulties that arose with regulating water turbines and steam engines. Engineers struggled to understand why for example, a set of spinning governing balls helped to regulate the speed of one engine but didn’t work as intended on an engine with a different design. It wasn’t until the second half of the 19^{th} Century that the theoretical concepts were sufficiently understood to develop the underpinning mathematics required to design more complex control systems (Oppelt, 1984).

2.3.6 Twentieth Century Developments

The difficulty of design problem solving has increased with the prominence of complex interdependent systems combined with the growth of outsourcing. In the 1950s, GE experienced difficulties at its Kentucky based household appliance factories, that helps to illustrate the problems associated with coordinating the activities of a number of organizations working collaboratively in the supply chain. GE’s manufacturing plants experienced noticeable cycles of high production during which extra staff were recruited, followed by periods of low activity when staff were laid-off. This pattern appeared independent of the business cycle.

Analysis by Jay Forrester (a professor at Massachusetts Institute of Technology), identified that the peaks and troughs of production activity at GE's factories were caused by minor variations in the frequency and volume of customer orders in retail stores, that were amplified as the orders were passed along the supply chain (Forrester, 1958). Forrester's analysis led to a growing awareness of the benefits of closer supply chain integration and the disruptive problems that arose from information disconnections between supply chain participants.

Separately, in the field of telecommunications, the challenges of designing complex systems was recognized in the 1940s at the Bell Laboratories. The concept of systems engineering, emerged as a problem solving methodology to help address the challenges of designing complex telecommunications systems (Hitchins, 1998; Kasser & Zhao, 2014; Schlager, 1956). The significance of the need for new design problem solving strategies is illustrated by the emergence of new approaches in the 20th Century to support the management of complex, technologically orientated problems, which include:

- Total Systems Intervention (TSI): TSI can be described as a branch of systems engineering that seeks to differentiate between the engineering of actual complex systems, and the problem solving undertaken by the engineering organisations that create complex systems (Cook, Kasser & Ferris, 2003);
- Systems Thinking: Systems Thinking describes a less structured approach to problem solving that places a greater emphasis on the social context in which problems exist. It emerged in the 1980s following observations of the limitations of the "hard and systematic" approaches of the 1950s and 60s (Checkland, 1988; Kumar, Ressler & Ahrens, 2005);
- Strategic Thinking: Strategic Thinking is an approach that appears to focus on solving the complex unstructured problems typically faced by organizational leaders (Lawrence, 1999; Amitabh & Sahay, 2008);
- Systems Dynamics: Systems Dynamics is a problem solving approach that seeks to identify the interacting relationships between different social systems in a way that helps to resolve underlying problems (Forrester, 1971);
- Concurrent Engineering is an approach that emerged in the 1980s to support the cross functional (organizational) problem solving necessary to design and manufacture complex products to meet customer requirements (Smith, 1997; Pardessus, 2004);
- Management Science: Management Science is concerned with improving action orientated managerial thought and has made more progress solving well-structured problems that can be defined mathematically (Simon & Newell, 1958; Smith 1998);

- Others methods that have been identified include: Action Theoretical Problem Space Model (ATPSM) (Grieff, 2012).

To adapt to new innovations, societies must continue to adapt existing problem solving strategies or even develop new approaches.

2.3.7 General Problem Solving Characteristics

A generic problem solving method can be summarized as follows: firstly recognize a need; second, define the problem, the objectives and the constraints; third, collect information and data; fourth, generate alternative solutions; fifth, evaluate alternative solutions; and finally, select the favoured course of action (Sharp, 1991). This represents a conventional linear or sequential process that can be easily understood, however, it does not necessarily reflect the underlying problem solving activity. The method for solving complex problems is rarely linear or sequential and often involves iteration. For example, it may be necessary to cease one investigative activity when progress becomes difficult, in favour of another that appears to offer opportunities for greater progress. Deeper analysis of the approaches that people adopt when problem solving, requires consideration of the workings of the mind (MacLellan, Langley, & Walker, 2012). A more circumspect perspective to problem solving also sets-out a staged approach: identify a problem or field of interest where these problems occur; generate a theory about the nature of these problems; confirm the theory works; and finally, use the theory to progress resolution (Cook et al, 2003; MacLellan et al, 2012).

There are naturally complicating factors. The definition of a problem can be subjective and depends on a sense of perspective. One of the most important problems that organisations face relates to defining their target market, customers and what products and product related services should be offered and how. Such problems are typically complex and difficult to structure but ultimately shape the overall product design process (Amitabh & Sahay, 2008). Some problems cannot be solved because multiple stakeholders are unable to agree on the nature or scope of the problem to be addressed (Rith & Dubberly, 2007). The approaches described above indicate some important problem solving characteristics. For example, the resolution of complex problems involves some recognition of the existence of a system.

In this context, a system is a set of related concepts or objects that interact with each other. Checkland identified four fundamental characteristics of systems: the existence of emergent properties, evidence of a hierarchy of subsystems and a need for communication and control (Checkland, 1988). The concept of emergent properties describes the characteristics of a system that are only evident when one considers the behavior of a whole system versus the properties of individual components. Emergent properties are not evident from an analysis of individual system components. For example an aircraft’s flight properties are derived from all subsystems operating in an integrated way as one product. A further important property relates to the concept of systems hierarchy where the operation of a functioning product is derived from the support of sub systems. The systems hierarchy concept can be applied to any system including and perhaps more importantly social systems (Cook et al, 2003; Checkland, 1988).

2.4 Design Information Management

2.4.1 Design Information

Managing products during their life, particularly in the context of change, is a complex process that requires the coordination of many activities spanning design, procurement, production, marketing, sales, support and disposal. These activities constitute a set of logical processes that reflect the nature of the product management operation. Furthermore, they are highly dependent on accurate information and can have a significant impact on an organization's cost base.

To support maintenance, engineers typically need to identify spares, order them from an inventory system and record maintenance activity in an asset management or maintenance system. This activity is supported by a variety of software applications that are implemented to support the prominent process areas, or focus points. This is illustrated in Figure 2.3 which provides a simplified perspective of the information enterprise architecture required to support the through-life support management of complex products. At the centre of the diagram, is an engineer who works for an organisation that operates and maintains a product fleet. The engineer is responsible for a maintenance activity that must be completed in accordance with product specific maintenance manuals. When a need for spares is identified the engineer must firstly identify any required items from a parts catalogue. The parts catalogue, provides a representation of the design of the product. Once the required items have been identified, an inventory system is then used to place an order. The engineer must record any maintenance in an ICT system to ensure there is an auditable trail of work that has been undertaken. In this way, the design configuration of the product can be viewed. The design information in the parts catalogue and maintenance instructions invariably originates from the product manufacturer. Information about spares, inventory holdings and product configuration (fixed assets) is used to maintain the company's accounting records.

It is important to note that the change process spans the whole enterprise and extends out to other organizations. To improve through-life product management, there is a need to improve the way information systems support the product change process. Improved software application interoperability is an important priority (Corella, 2013). This will require a departure from the current point-to-point approach to application integration where users are able to enter product information directly into individual systems with little control as to the quality of that information (Boehme et al, 2012; Xu and Liu 2011).

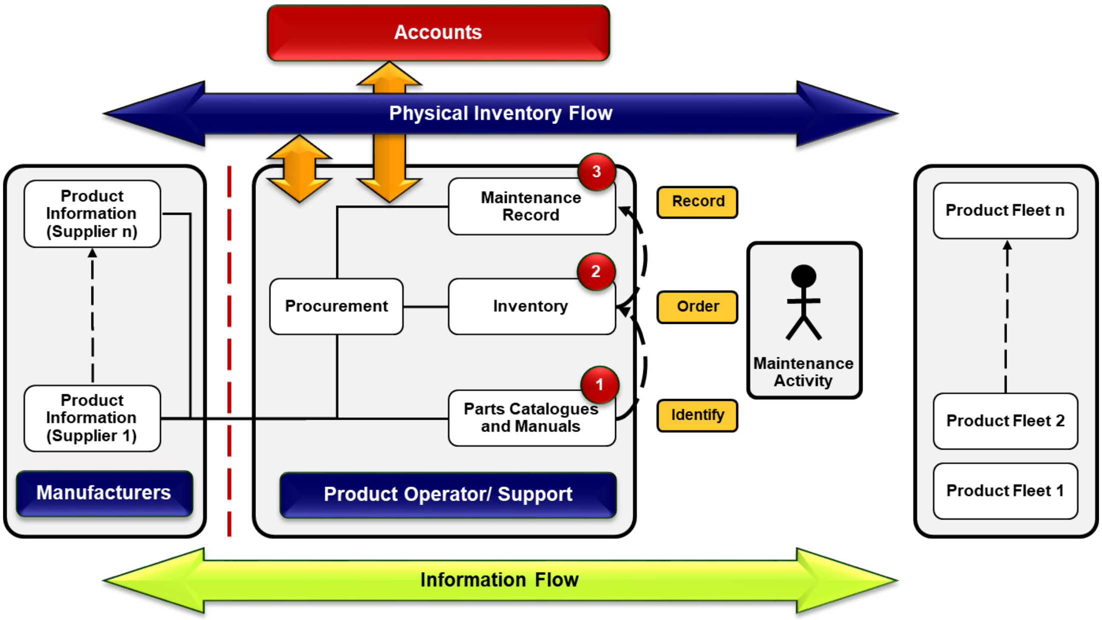


Figure 2.3: Information model required to support product maintenance

One of the current obstacles to progress relates to the fact that many software applications use different terminology for the same item - this is also true of the labels of the physical product that are being managed (Namchul 2015 and Bernus et al 2016). This doesn't help maintenance engineers and it makes integrating the software more complicated too (Wan et al, 2017). For example a product might have a label that uses one set of descriptions while the software applications (inventory, procurement, maintenance etc) use different descriptions again.

2.4.2 Enterprise Architectures

Despite significant technological developments, the closer integration of enterprise processes and wider attainment of industrial interoperability remains elusive. The MAYA EU project is seeking to create a technical solution that is able to integrate physical and information systems to begin to realise the concept of the “Digital Twin” throughout the manufacturing lifecycle (Ciavotta et al 2017). This topic can be described in the context of cyber physical systems. The current generation of software used to support product design information is implemented as a range of “point solutions” to support specific process areas. As a consequence, current architectures represent a collection of loosely coupled information systems that separately support early life design, manufacture, inventory, documentation and through-life maintenance records (Boehme et al, 2012; Xu and Liu, 2011). Furthermore, current technology does not enable the close collaboration of multidisciplinary teams and multiple supply chain participants.

Despite efforts by software vendors to improve the integration of their product portfolios, organizations still experience difficulty optimising their enterprise application ICT architectures to support the effective flow of the information that is generated by the design change process. These difficulties are likely to be further exacerbated by the phenomenon of “Big Data” (Boyd and Crawford, 2012). It is also currently difficult to prioritise investment because standard approaches to establishing the costs that arise from inaccurate information (labour, material and operating capital) have yet to emerge and finally, it seems master information management best practice is poorly understood.

A further issue that is increasingly expressed regarding current ICT systems, relates to the time and cost of implementing complex application landscapes across large multinational enterprises. These concerns have been highlighted by a number of organizations including the US Department of Defense DOD).

The US DOD has identified that limited interoperability reduces information sharing and mission collaboration. Complex ICT programs can take many years to implement and consequently it is difficult to rapidly and efficiently field technology to meet new requirements (Smith and Cecil, 2012). In the UK, the Ministry of Defence also acknowledged the affordability challenges of implementing information superiority systems (Tucker, 2011). The oil and gas industry also makes extensive use of HVLL products such as drilling rigs, production platforms, sub-sea equipment and refinery plant. There is evidence to suggest that organizations in the oil and gas sector that chose to implement a standard ERP solution were able to complete projects more quickly and so derive greater strategic and operational benefit, than those organizations that chose to implement tailored ERP solutions (Anderson, 2011). It is important that regulatory systems are able to easily monitor that the original integrity of a design that is established when a product is first created, can be maintained through-life. However, today this can be a challenge even in highly regulated safety critical industries, because technology is currently unable to offer a coherent integrated approach that supports through-life design management. To enable faster and cheaper IT systems integration, the development of new data standards will be critical (Friess, 2012).

2.4.3 Experience of Other Sectors

Developments in other industry sectors indicate the potential for improving the support ICT provides to business processes. Examples from the retail/ consumer goods and financial services sectors have been examined because they illustrate the information sharing and industry process sharing that have evolved from a real need to address market challenges and competitive pressures.

In the retail/ fast moving consumer goods sectors, the Global Data Synchronisation Network (GDSN) was launched in 2004 by GS1 (formerly EAN and UCC). The GDSN supports the transmission of largely consumer/ retail product information between manufacturers/ distributors and retailers. The aim is to streamline supply chain transactions and reduce costs. It has seen exponential growth and has improved the accuracy of product information. GS1 is an international not-for-profit association and in the UK at least GS1 is an organization that is owned by its members.

In the banking sector, the Society for Worldwide Interbank Financial Telecommunications (SWIFT) is a member-owned cooperative that comprises 9,700 banking organizations, securities institutions and corporate customers in 209 countries. SWIFT was formed when seven major International Banks met in 1974 to discuss the limitations of Telex as a means of secure delivery of payment and confirmation information, primarily in the treasury and correspondent banking areas. SWIFT enables its customers to automate and standardize financial transactions, thereby lowering costs, reducing operational risk and eliminating inefficiencies from their operations.

2.5 The World of Tomorrow

In the future, networked technology will enable the seamless flow of information in real time. This world will have an "Internet of Things" or create, as HP Research Laboratories has described, a central nervous system for the earth (Banerjee, 2012). The potential benefits in terms of industrial competitiveness that might be achieved are considered to be significant. For example, a report prepared by the US Smart Manufacturing Leadership Coalition (SMLC) a US Department of Energy initiative, set-out to establish a roadmap to identify the priorities for modernizing 20th Century factories, with 21st Century technology and working practices. Their concept of 21st Century smart manufacturing is heavily focussed on the efficiencies to be gained by improving the integration of information and manufacturing intelligence (knowledge) within a seamlessly integrated supply chain. Ultimately this seeks to improve the management of product information, by enabling organisations that are highly responsive and able to quickly respond to customers while, minimising energy and material usage and maximising economic competitiveness (SLMC, 2011).

To make progress there is a need to address the challenges of maintaining design integrity throughout the product lifecycle. This will require adjustments to business models, product design practices, information technology and, the way people think about how product information is managed (Parhizkar and Comuzzi 2017; Mattos and Laurindo 2017). Any changes will inevitably be in response to market forces. For example, the US Department for Trade has recently recognised that as tariff barriers to trade have fallen, the need to remove standards-related obstacles to the flow of products and product related information has emerged as a key concern. Particularly for complex and increasingly global supply chains (Marantis, 2013).

To navigate a path towards the vision requires the resolution of a number of complex issues including a better understanding of the business models, standards and required governance (Friess 2012). Progress in these areas will require a need for greater conceptual clarity that abstracts fundamental level issues (Checkland 1988).

As economies shift further away from agriculture to manufacturing and on to services, the importance of information and knowledge becomes increasingly important. Charles Handy summarized the challenge as follows: "Fewer people, thinking better, helped by clever machines and computers, [will] add more value than gangs or lines of unthinking "human resources" (Handy, 1989).

Peter Drucker went on to state: "The most important, and indeed the truly unique, contribution of management in the 20th Century was the fifty-fold increase in the productivity of the manual worker in manufacturing. The most important contribution management needs to make in the 21st Century is similarly to increase the productivity of knowledge work and knowledge workers." (Drucker, 1999).

Finally from an EU research paper generated as part of the iCargo programme has identified that: "Adaptive decision making requires a 'plug & play' exchange of information within the logistic network. Full visibility is required between all interacting stakeholders." (Dalmolen 2012). This provides further evidence of the need for increasing information connectivity in the supply chain, together with the need to reduce the barriers to making the necessary connections.

2.6 Chapter 2 Summary

The literature review considered published papers on the fields of engineering change, problem solving in design, the increasing structure that has developed in the design change process, through-life product support services, alignment of business model and product strategy alignment. It also considers related topics such as, the growth of embedded software, change propogation and emergence of the concept of a design authority. The review uses a case study to consider the evolution of problem solving in design and how innovation leads to the development of new problem solving techniques. The review of published literature confirms that the interface between product management and the underpinning IT systems remains poorly defined and there is a need for an evidence based approach to support the improvement of through-life product management.

Chapter Three: Industry Investigation

3.1 Through-life Design Management: Rail and Aerospace

The knowledge and organizational capabilities required to design and manufacture complex products cannot be replicated easily, product operators and maintainers often rely on the original equipment manufacturer (OEM) for through-life product support. To ensure that design integrity is sustained there is thus an enduring need for manufacturers, operators and maintainers to collaborate. As a result there is widespread recognition of the benefits to be achieved from the closer integration of supply chain processes. However, little progress has been made over the last two to three decades (Childerhouse et al, 2011; Baalbergen et al 2017).

The safety and performance of HVLL products is often a priority design consideration and requires regulatory involvement in the design process. Design integrity can be the foundation of a business’s reputation or brand and often underpins product safety. Product designs may need to be changed for a number of reasons: to maintain product performance in the light of operating experience; because suppliers are no longer able to provide replacement parts to the original design specification; or, when there is a requirement to adapt the operating performance from the original specification. Regardless of the motivation for a modification, product manufacturers and operators must ensure that a product design continues to be fit for purpose and that the design integrity established at the start of a product’s life is maintained. This process can be challenging as complex products are invariably produced and maintained through the collaborative endeavour of many organizations. The nature of the processes involved for two industry sectors that operate HVLL products, aerospace and rail, will now be considered. At the time of this initial investigation the author was working with Bombardier Transportation a large multi-national rail manufacturer. This work involved examining how to improve the management of design information through-life, particularly as rail vehicles moved from manufacture and into support. Bombardier Transportation often secured outsourced rail vehicle maintenance contracts in support of the trains it had manufactured. As a consequence, the rail sector was selected for investigation. The aerospace sector was selected because the leased purchase approach to procurement that is prominently used, is similar in concept to that used by the UK rail industry. The aim of the analysis is to inform the modelling and simulation processes conducted later in this thesis.

3.1.1 Rail

The Rail Research Association (RRA) summarised the factors that need to be considered when designing a new train (Giffin et al 2009). They identified thirteen 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, and real-time management of customer information along the supply chain (Wennberg 2007).

The management of design information in the UK rail industry provides a useful case study for understanding some of the important trends underway in managing design information for complex products. In the early 1990s the state-owned rail operator (British Rail) was privatised and the management of UK rail vehicles moved from British Rail to a predominantly leased ownership business model with separate leasing companies, train operating companies, design consultancies and Railtrack (now Network Rail). Prior to the privatisation, British Rail was able to take a holistic perspective of the systemic design issues that needed to be monitored to maintain design integrity. After the privatisation, responsibility for maintaining design integrity required the collaborative endeavour of the various industry participants that included the train manufacturers. Under the new arrangements, passenger and rail workforce accident rates have consistently fallen even though no single legal entity has the obligation to control the design integrity of groups or classes of assets owned and operated by several parties. No organization can be said to be acting as a design authority.

To provide guidance to industry participants, the RSSB outlined four competences that are required to ensure the control of design information. The first of these competences is a need to understand the technical and operational requirements and to retain records that show how these influenced the design of the system. The second proposed that design information should be retained so that, should there be a desire to make a modification or change a product's (asset's) use, the original design information can be recalled. The third identified that, in an evolving railway there is a need to be able to decide whether an asset (such as a vehicle or its systems) can be used for a new route or application and assess the implications of any proposed modifications to an existing asset or its use. Finally the fourth identified that there is a need to ensure that records are kept of different configuration levels of any design, as it evolves throughout its life so that compatibility and interchangeability issues can be assessed.

In the context of this research, 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. These competencies illustrate the information challenges faced by complex industries where multiple supply chain participants need to collaborate to support the management of HVLL products. Furthermore, consideration must be given to the fact that ownership and responsibility for operation and maintenance of rail vehicles can change several times through-life. A major rail company in this sector recognized that configuration management was critical to the management of design integrity and employed standard industry processes such as defined in the US Department of Defense Military Handbook: Configuration Management Guidance (MIL-HDBK-61A (SE)). The five key configuration management processes are identified as: management and planning; configuration identification; configuration control; configuration status accounting; and, finally verification and audits.

3.1.2 Civil aerospace

In the commercial aerospace sector, the system for maintaining design integrity through-life, requires the cooperation of many organizations that are individually responsible for the design, manufacture, regulation, operation, and maintenance of an aircraft type. The difference between the rail and commercial aerospace sector is that the role of design authority is formally undertaken by the aircraft manufacturer in accordance with the regulation of an airworthiness authority.

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 services (Pardessus 2004). This approach has not been formally extended to cover disposal but during development end-of-life and environmental factors are considered.

Many aircraft operators have their own maintenance organizations 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 (for example seat configuration, overhead storage bins and entertainment systems etc). These are likely to have a minimal impact on airframe loading and stress and so OEM design analysis is unlikely to be 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 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. The differential between the maintained and original configuration increases as aircraft age. One of the challenges OEMs face when providing through-life support services is retrieving configuration information from operators on which modifications have been fitted.

There are additional factors that need to be considered. Firstly modern aircraft are generating increasing volumes of information that can be used to reduce maintenance costs, downtime and improve repair efficiency. In future, to derive maximum benefit from this information will require an information ecosystem (system of systems) for aircraft maintenance and support (Pardessus 2004). Secondly as manufacturers expand their service business the aerospace business is changing from a traditionally product driven environment to a more capability driven environment. As a consequence, the product supplier must take responsibility of the serviceability of the product from design, manufacture, to operations and disposal (Webb and Cees 2009). Thirdly, the aviation industry's support model is mainly focussed on OEM to operator relationships and has yet to adapt to reflect the development of leased ownership. The implications for this are discussed in section 3.3.

While there is a growing awareness that accurate engineering configuration information is key to reducing costs, the operating model that links manufacturers, operators and leasing companies is not well supported in terms of provision of through-life information management. What is more, the growing value of information is creating pressure for change. 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 the 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 the parties required to improve aircraft lifecycle management including design, manufacture, maintenance, parts distribution and recycling.

There is a regulatory discrepancy between maintenance, repair and overhaul (MROs) and airlines. MROs are required to maintain records for 3 years while airlines are required to keep records for two years longer than the whole life of the airframe. To ensure that accurate records are maintained, operators pay close attention to MRO relationships.

All aircraft parts must be labelled with a Form 1 which provides the minimum level of part information required; a snapshot of the part at the time of the last overhaul. For example, consumed life such as flying hours, take-offs and landings.

However, substantially more information is required to satisfy airlines' safety and quality procedures and lessor parts information requirements. For example, an undercarriage could be assembled with a 10 year old oleo (a pneumatic-hydraulic air-oil shock absorber) and a 30 year old truck beam where the overall life of the undercarriage is guided by the oldest component. In the event that complete information about the consumed-life of a subcomponent is not known or unavailable, then the life of the assembly is reduced to that of the OEM's fleet leader. This could have a significant impact on component life and value and consequently great care is taken to ensure that only parts with traceable histories are sourced, whether from spares pools or elsewhere.

3.2 Leased Product Management

The procurement of complex products especially in the rail and aerospace sector is increasingly achieved with financial capital provided by loans or lease finance. This is a market that has grown significantly over recent years and seems set to continue. Leased product ownership in the aerospace sector represents 42% of the total civil aircraft fleet (Morris et al 2016) and utilises a similar industry structure (with lessors, lessees, OEMs, maintainers and operators) to the UK rail industry. In addition to changes of ownership, an aircraft can often move between operators as many as five times in its life and sometimes more. Changes of ownership and or operator can trigger a need for minor design modifications.

Furthermore, the movement of products between organistions must be supported by the movement of maintenance records between organisations. Maintenance records are complex bodies of information that contain important historical information about a product’s configuration. While rail vehicles are moved between operators less frequently than aircraft, there is still a requirement to transfer this information and this adds to the demands of the lease transfer process.

The lease finance approach to product acquisition also increases the complexity of the stakeholders involved in through-life product management process. The stakeholders include the investors, product/asset owners (lessors), operators (lessees), product manufacturers, third party maintenance providers and also the organizations that police or enforce regulatory compliance. In accordance with the industry authority design and maintenance records are required to support compliance with commercial arrangements and must be transferred between market participants. The benefit to be derived by improving the availability of design information to market participants is well recognised (Canaday 2011 and Vianello, 2012). Figure 3.1 provides an overview of how the main participants of the asset/ product leasing industry (operator, lessor, OEM (manufacturer)) relate to each other.

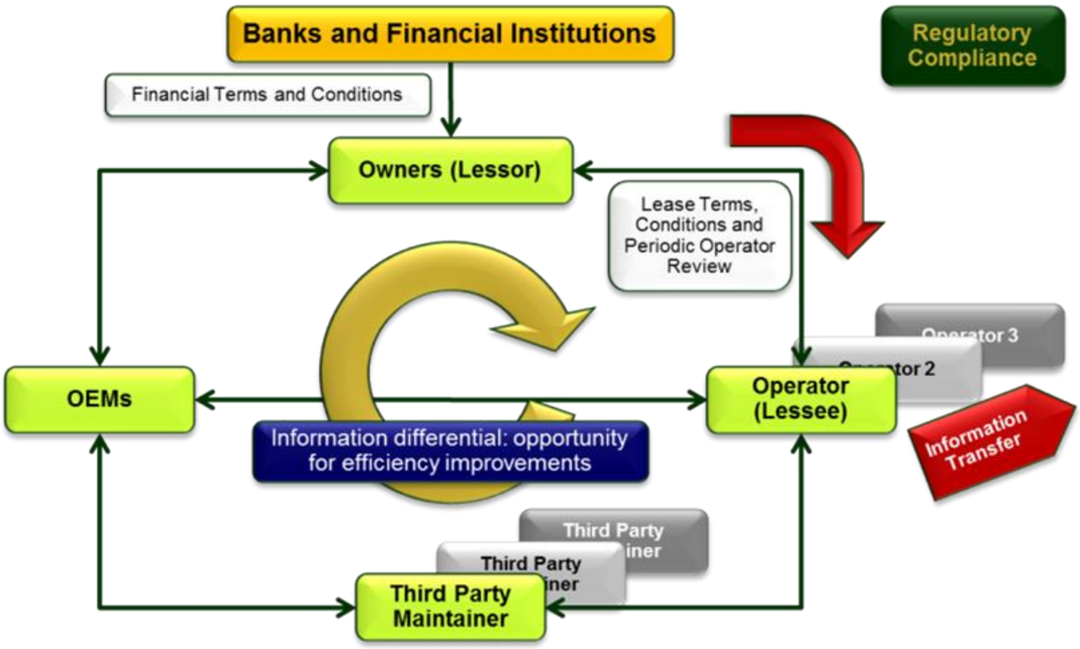


Figure 3.1: Industry Model: Product/ Asset Leasing

Where a product (aircraft or train for example) is leased, the number of organisations with an interest in its through-life product management increases. Banks are increasingly interested in product configuration to ensure that they understand the risks of investing. Product owners (lessors) also increasingly take a long-term view of through-life product management to ensure they can continue to make a profit on the leased payments they receive from product operators (lessees). Lessors are interested in the maintained configuration of products and wish to ensure that products retain sufficient value for releasing. Leasing enables product operators to smooth their cash flow by avoiding significant capital payments.

However, as the networked economy emerges each participant is able to derive increasing value from the knowledge contained in through-life configuration information.

3.2.1 Industry Engagement - Aerospace Leasing

The UK rail industry predominantly operates using the leased purchase ownership model that involves: banks (lenders/investors), lessors (owners), lessees (operators). The aerospace sector similarly uses the leased purchase approach to procurement, that is prominently used by the UK rail industry. To support an improved understanding of the management of product information in the rail industry, an analysis was undertaken of information management practices within the aerospace leasing industry. Both sectors require the management of HVLL products and The investigation was achieved through a series of unstructured interviews with people of a variety of seniority levels up and including group vice president and group senior vice president. Organizations that supported this activity included banks, lessors (product owners), lessees (product operators) and manufacturers in both the rail and aerospace sector. The organizations are listed in Table 3.1.

Organization	Industry Role
GECAS	**Aviation Lessor**
BBAM	**Aviation Lessor**
CIT Aviation	**Aviation Lessor**
BOC Aviation	**Aviation Lessor**
Embraer	**Aerospace Manufacturer**
Boeing	**Aerospace Manufacturer**
Airbus	**Aerospace Manufacturer**
Bombardier Aerospace	**Aerospace Manufacturer**
BMI	**Aircraft Operator**
DHL Aviation	**Aircraft Operator**
British Airways	**Aircraft Operator**
Easyjet	**Aircraft Operator**
JP Morgan	**Investment Bank**
Santander	**Investment Bank**
HSBC	**Investment Bank**
Goldman Sachs.	**Investment Bank**

Table 3.1: Organizations consulted during aircraft leasing analysis

3.2.2 General Design Change Process

The design change process is complex and has a hierarchical structure. Table 3.2 seeks to present a simplified view of the hierarchy that exists for HVLL products.

Level	Description
5	**Through-life ownership: Top level**
4	**Production change: Design changes that arise to satisfy the needs of different customers - triggers are a new order with customer specific requirements**
3	**Bill-of materials change: The process required to specify the materials needed to manufacture and support each aircraft produced – relates to airline aircraft maintenance programme (AMP)**
2	**Part or assembly change: The process required to manage individual design changes (modifications) – allocation of unique identification commonly guided by "fit, form, function" test.**
1	**Additional change controls exist to manage finer levels of product instances such as batch numbering and serial number identification (lifed components etc).**

Table 3.2: Hierarchical levels of change in the design change process

The Table lists a hierarchy of processes whereby activities that have greater influence, sit in a higher level of hierarchy than processes that typically require more detailed information that individually has less influence.

For example, at the lowest level (Level One), manufacturers use serial numbers to uniquely identify individual components that require specific attention. Serial numbering is used to individually identify components that have properties that must be managed for safety or maintenance reasons such as fatigue life. Batch numbering is used to provide product traceability relating to manufacturing processes. Each numbering system is used to differentiate between parts that might change as the result of a manufacturing process. Part numbers are used to identify generic parts that have a common design.

In the next level (Level Two) Collections of parts are managed as assemblies. Such items may have their own serial numbers, batch numbers and part numbers that may reflect changes made to any of their component parts.

Level Three describes how lists of assemblies are created to support the design, manufacture and support of the higher order, end product. The bills of materials of the end product are adapted to respond to the needs of specific customers.

While a product (aircraft or train) might be attractive to a number of customers, invariably there is a need to make modifications to the core product to meet the needs of specific operators. This process is explained by Level Four. Finally, Level Five describes the through- life management process that encompasses the design, manufacture and support process of each product or fleet of products.

3.2.3 Design Change Management

The manufacturing process for a large fleet of aircraft and trains can run for several years and over this period designs may need to change. Design changes during the manufacturing process may be required to address performance problems identified in products made earlier in the production run or, because the designs of parts from suppliers change. To respond to finer information details in the manufacturing records can present a significant challenge and some changes are not always reflected in the delivered maintenance documentation. Consequently, documentation provided with new aircraft is not always accurate (a point some manufacturers have recognised).

The maintenance planning document (MPP) developed by OEMs is used (for example by British Airways) to create its own aircraft maintenance plan (AMP). Maintenance regimes are adapted to suit aircraft operations and consequently, other airlines and lessors often devise their own maintenance approaches.

It can take up to 6 months to collate repair files to support an aircraft transfer because the information is held in a variety of systems/locations. BA recognise the benefits of reducing the cost and time of managing aircraft change – making the process “lean”.

According to the Airbus structured finance team some banks have been exploring the topic of a centralised coordinating ICT system to improve recovery of technical records in support of aviation finance. The Aviation Working Group has also been discussing this topic with ISTAT (International Society of Transport Aircraft Trading) in the context of improving acceptance of e-records to reduce the cost of aircraft transfers.

3.3 Survey

3.3.1 Overview

The author's experience identified a growing body of people who recognise the significant improvements to productivity that might be achieved by enhancing the accuracy of product information. It has been estimated that over the next decade improved information management practices (for example standard industry information models) could lead to increases in productivity of as much as 100% (SMLC 2011). Productivity improvements are expected to be derived from a number of areas such as reductions in labour costs associated with searching and manipulating information. These might be derived by improving the transparency of design decisions, product specifications, and cost estimations required to ensure product safety, reliability and business profitability. The pressing need to achieve improvements from better information management arises because of the significant increase in the volume of information many products are now able to generate (Baalbergen et al 2017). Many products have been able to "self-report" for some time (for example desktop computers and mobile phones) and now trains and aircraft are being developed with sophisticated reporting capabilities too. To quantify the challenges identified through industry discussions a survey was undertaken in 2012.

3.3.2 Survey Aim

The results of a survey were needed to provide a body of evidence to justify further investigation and help to target lines of enquiry. In each case the questions were aligned with specific issues identified by previous research. The aim was to investigate how well the requirements identified by the reviewed literature matched the experiences of different organizations. Ten survey questions were designed to establish the current practice, problems and perceptions of future requirements in industry. Current requirements in configuration management, PLM and related ICT technology identified in the literature review such as the need for improved information flow in the supply chain and closer process integration between supply chain participants were considered.

3.3.3 Survey Participation

Fifty nine responses were received from people who represented 39 organizations that spanned 7 industry sectors including 15 Fortune 500 or equivalent sized organizations. This represented a response rate of approximately 5%. A summary of the organizations represented by survey respondents is provided in Table 3.3. A summary of the nature of participation by organization, function, sector and individual role is as follows:

- **Industry sector:** responses spanned 9 industry sectors (Figure 3.2) the four largest sectors represented by responders were, rail (24%), automotive (22%), aerospace defence (18%) and industrial equipment (15%).
- **Organization:** 68% of responses were received from manufacturing organizations versus 32% from those involved in product maintenance (Figure 3.3);
- **Role:** 24% of responses were received from systems users, versus 76% non-systems users (Figure 3.4). In this context "system" referred to the IT applications used to manage product information including PLM/PDM, ERP, procurement, inventory, procurement and asset management.

Organisations from which survey respondents were drawn	
• Aero – US space research and advisory services • ATK – Aerospace defence manufacturing • Autolov – Automotive trading and parts • BAE Systems – Defence manufacturing • Baker Hughes- Oilfield Services • BDR Thermea – Heating and energy • BMW – Automotive manufacturer • Boeing – Aerospace manufacturing • Bombardier Transportation – Train manufacturer • BSH Group - Bosch and Siemens home appliances • Cummins – Engine manufacturer – automotive and power generation • Danieli Corus – Steel and aluminium manufacturing • Delphi – Automotive components • DHL - Logistics • DNV – Quality and risk management • Easyjet - Airline • Fiat – Automotive manufacturer • FL Smidth – Minerals processing plant and services • Ford – Automotive manufacturer • GE – Rail manufacturing	• Harley Davidson – Motorcycle manufacturing • Herman Miller – Office furniture • Indesit – Home appliances • Jaguar Land Rover • Osang Jaiel – PLM software integration • Kostal – Electrical, electronic and electro mechanica components • Meyn – Poultry processing technology • Parker – Aerospace motion and control technologies • Qantas – Airline • Renishaw – advanced manufacturing measurement products • Rolls-Royce – Aeroengines • Sony – Consumer electronics • Steelcase - Office furniture • Stryker – Medical devices • TE Connectivity - Electrical and electronic components • TI Auto – Automotive components • UK Ministry of Defence – Defence • Volvo – Automotive manufacturer

Table 3.3: Organizations from which survey respondents were drawn

The four largest sectors represented by responders were, rail (24%), automotive (22%), aerospace defence (18%) and industrial equipment (15%). While the industry sectors are diverse, common engineering principles and practices seemed to enable a consensus of opinions. Responses were also segmented by business activity and job function: 68% of responses were received from manufacturers versus 32% from those involved in product maintenance. "Systems" users represented 24% of responses, versus 76% "non-systems" users, where "system" refers to the ICT applications used to manage product information including PLM/PDM, ERP, procurement, inventory and asset management. A summary of sector specific responses made in this survey is given in Figures 3.2, 3.3 and 3.4.

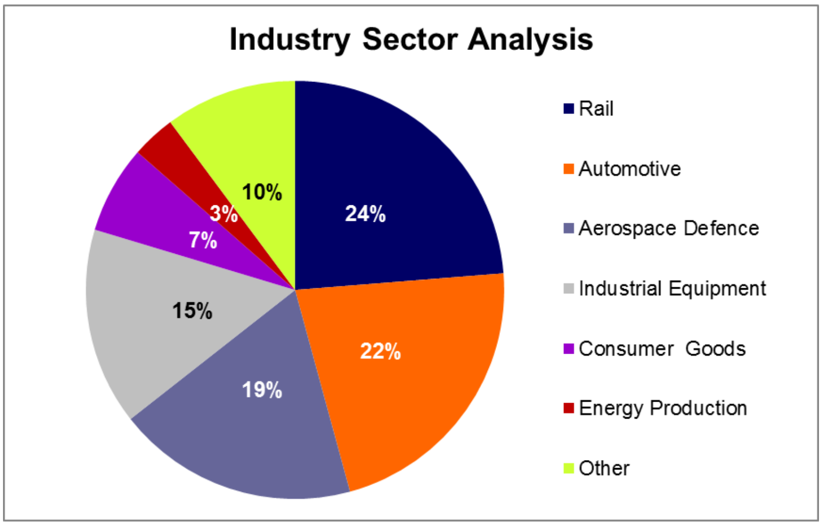


Figure 3.2: Survey Responses Segmented by Industry Sector

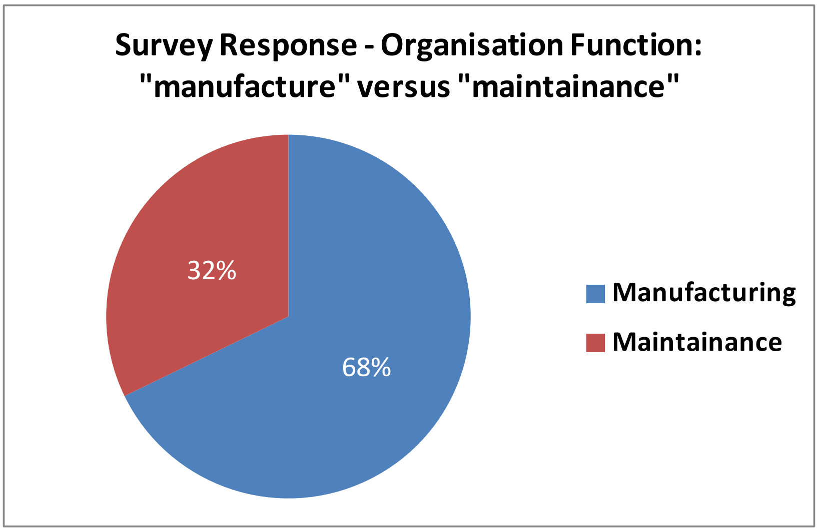


Figure 3.3: Survey Responders Segmented by Organization Function

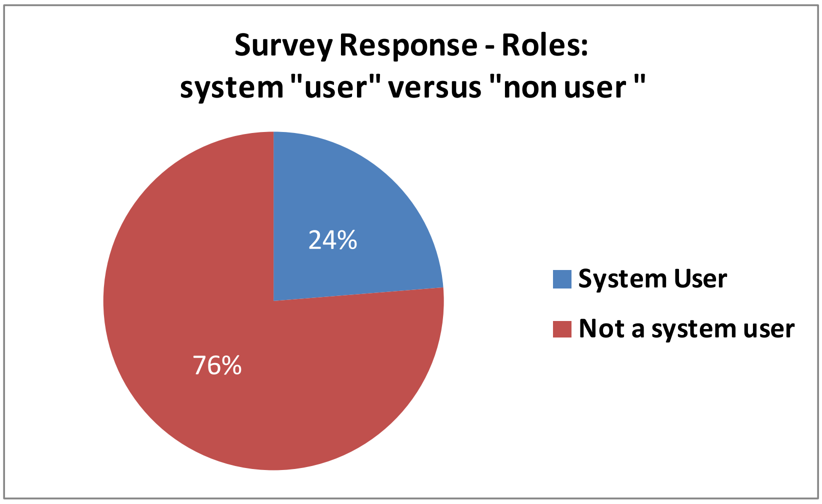


Figure 3.4: Survey Responders Segmented by role: IT system or non-IT system user

3.3.4 Question Design

A list of the questions used in the survey are provided in Table 3.4. Each question was designed to examine specific elements identified as being significant in the design change process. The ability of organizations to track design change information through-life has previously been cited as an important requirement (Gerritsen et al 2011, Jun et al 2007, Colfer and Baldwin 2010) and was investigated by Question 1. Questions 2 and 3 were written to invite responses on the current difficulties in accessing accurate product information (Millson and Wilemon 2002, Eckert et al 2009, Jarratt et al 2011, Ouertani 2011) and penalties of not having this (Jun et al 2007, Millson and Wilemon 2002, Ouertani 2011). The literature review had highlighted that the flow (Barki and Pinsonneault 2005, Burgess et al 2005, Wasmer et al 2011) and the duplication (Jun 2007, Ouertani et al 2011, Burgess et al 2005) of product information between systems within an organization were a concern. The frequency and impact of these were explored in Question 4 and 5.

The discrepancies arising in product information between organizations and their customers (Jun et al 2007, Chandrasegaran et al 2013, Burgess et al 2005, Wasmer et al 2011, Corella et al 2013) and suppliers (Jun et al 2007 Rachuri et al 2008, Chandrasegaran et al 2013, Burgess et al 2005, Wasmer et al 2011, Corella et al 2013) 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 (Jun et al 2007, Burgess et al 2005, Corella et al 2013). The limitations to the skills of the workforce in regard to operating within this sector (Barki and Pinsonneault 2005, Burgess et al 2005) were the subject of Question 9. The frequency and impact of inconsistent terminology (Gerritsen et al 2011, Ouertani et al 2011, Wasmer et al 2011, Corella et al 2013) were rated in Question 10.

The survey covered both complex product manufacturing and maintenance organizations. The questions were used to identify individual's roles and direct experiences of the IT systems used to manage product information in organizations where product information was important.

3.3.5 Summary Results

The results are provided in Table 3.4. 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 organization's product or service. The survey also required the ranking of five issues, identified after consideration of the research accessed in producing this questionnaire.

	Question	Response (%)					
1	How do you rate the ability of your organization to track product changes throughout the product life-cycle? Rated from Good (1) to Significant Difficulty (5)	Options	1	2	3	4	5
		Results	18	25	22	32	3
2	How easy is it to search for product information? Rated from Easy (1) to Difficult (5)	Options	1	2	3	4	5
		Results	3	24	36	25	12
3	How does inaccurate product information impact your business? Response considered problem Frequency and Impact: Rated High-Medium-Low.		High	Medium	Low		
		Frequency	31	47	22		
		Impact	64	36	0		
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	34	49	17		
		Impact	34	56	10		
5	Instances of duplicate product information exist in our systems? Response considered problem Frequency and Impact: Rated High-Medium-Low.		High	Medium	Low		
		Frequency	22	39	39		
		Impact	24	54	22		
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	11	38	51		
		Impact	23	45	32		
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	14	44	42		
		Impact	27	54	19		
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	1	2	3		
		Results	41	37	22		
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	28	36	36		
		Impact	41	47	12		

10	Inconsistent product terminology causes problems for our organization? Response considered problem Frequency and Impact: Rated High-Medium-Low.		High		Medium		Low
		Frequency	24		32		44
		Impact	19		47		34
11	Top Five Issues: Rated Greatest (1) to Least Concern (5)	Options	1	2	3	4	5
	Inaccurate product information		32	24	29	12	3
	Product change process		24	37	22	12	5
	Product information flow between systems		27	25	20	17	10
	Product information search		14	24	27	24	12
	Product duplication		7	17	14	12	51

Table 3.4: Survey questions and summarised results

3.3.6 Results

3.3.6.1 Presentation

A combination of bar and “bubble charts” is used to summarise the responses. The charts were created using an algorithm embedded within Excel. Where responders were requested to gauge the challenges associated with managing products and information in terms of frequency and impact “bubble charts” were found to provide an optimum presentation of the feedback received. Guidance on reading the charts is as follows:

- Horizontal positioning of the bubbles reflects feedback on the frequency;
- Frequency is greater for bubbles further to the right;
- Vertical positioning reflects impact - the higher the bubble, the greater the impact;
- The size of the bubble indicates the number of respondents reporting a defined impact - larger bubbles reflect a larger number of respondents.

3.3.6.2 Question 1: Tracking Product Change throughout the Life-Cycle

Question 1 asked respondents to consider the overall governance of the change or modification process between their organization and suppliers or customers. Despite the broad spectrum of organizations that participated there was a consistent profile to the responses across manufacturers, maintainers, system users and non-system users (Figures 3.5 to 3.7). The consistency of the overall industry average is achieved despite the fact that diverse responses were received from within the same sector such as automotive - even when multiple responses were received from the same organization.

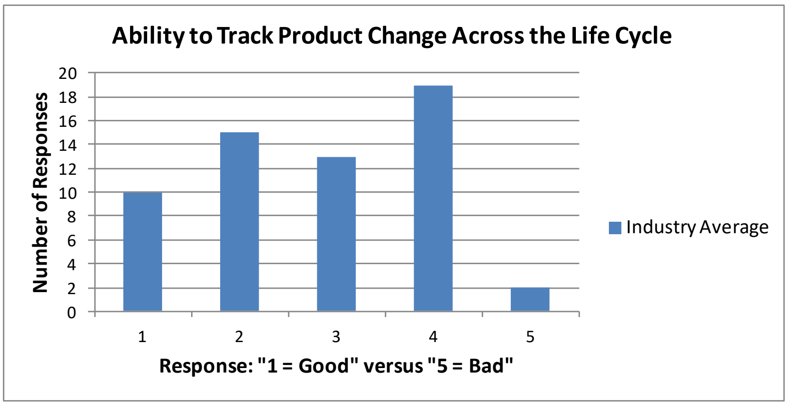


Figure 3.5: Industry average ability to track through-life product change

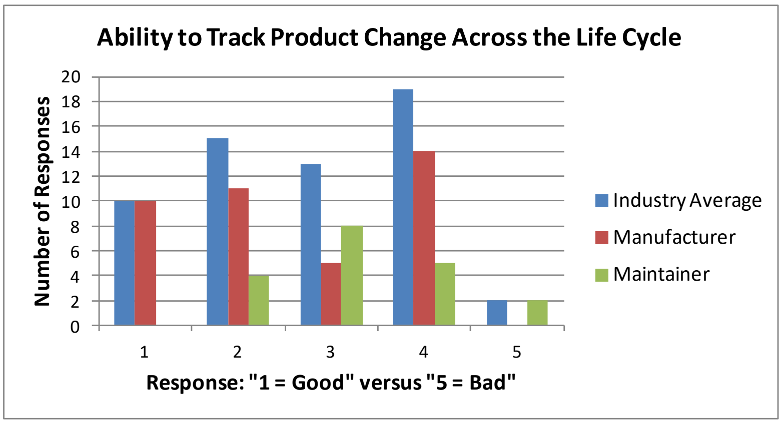


Figure 3.6: Manufacturer versus maintainer ability to track through-life product change

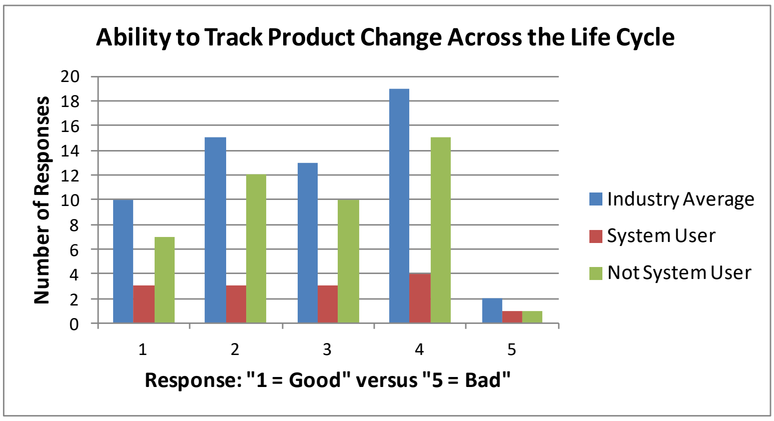


Figure 3.7: System user versus non system user average ability to track through-life product change

3.3.6.3 Question 2: Product Information Search

Question 2 investigated the difficulties of searching for product information (Figures 3.8 to 3.10). Very few respondents felt that finding the information they required was easy, yet information search was not viewed as challenging as tracking product changes. There is an observed bias towards "search is difficult" that was driven by responses from those involved in product/asset maintenance and systems users.

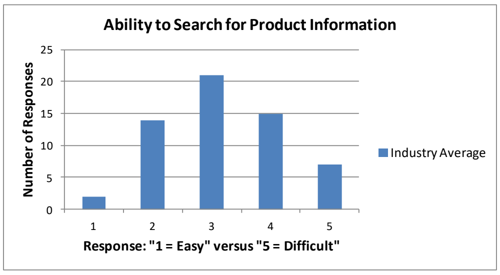


Figure 3.8: Industry average – product information search

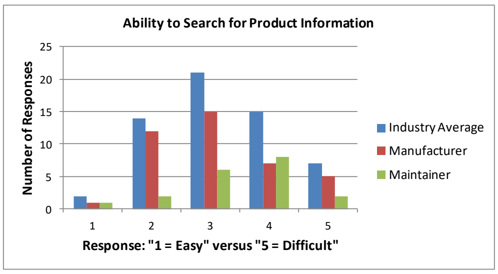


Figure 3.9: Manufacturer versus maintainer – product information search

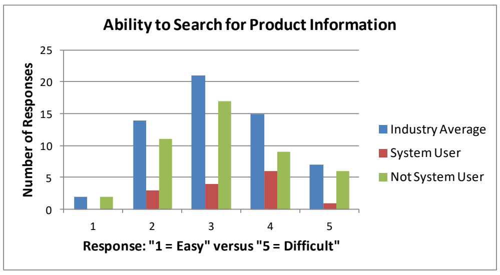


Figure 3.10: System user versus non system user – product information search

3.3.6.4 Question Three: Impact of Inaccurate Product Information

Question 3 asked respondents to consider the impact and frequency of inaccurate product information. A number of criteria were suggested that might provide evidence of the impact that inaccurate information might have, such as the volume of supplier or customer queries, inventory accuracy or cost of managing maintenance or engineering processes (Figures 3.11 to 3.15).

Overall responses varied from low to high frequency. All respondents ranked the issue of inaccurate information as having a medium to high impact – there were no "low impact" responses. Overall there is a clear centre of gravity favouring the top right "quadrant of greatest concern" - "medium to high" frequency and "medium to high" impact.

Maintainer organizations ranked the impact of inaccurate information more highly in the top right hand “quadrant of greatest concern”, whereas the manufacturing response was more balanced. There was no clear differentiation between system users and non-system users.

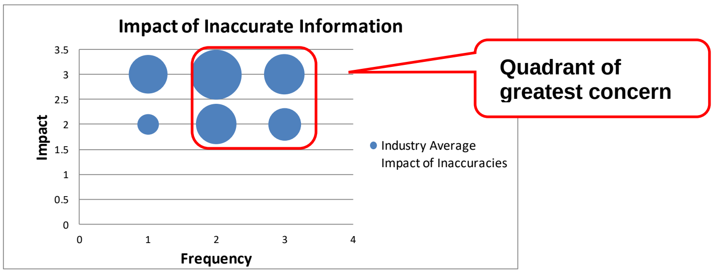


Figure 3.11: Industry average – impact of inaccurate information

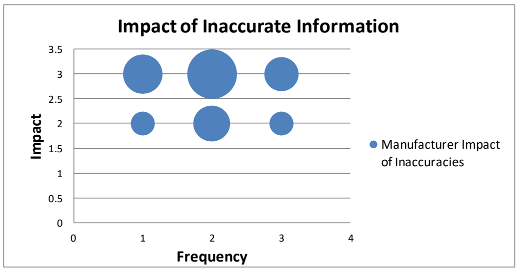


Figure 3.12: Manufacturer – impact of inaccurate information

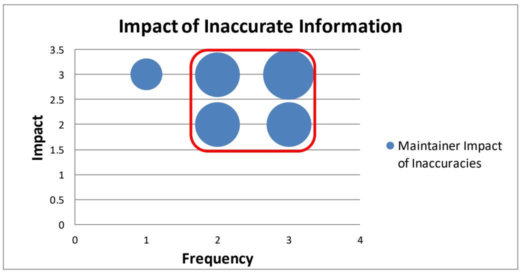


Figure 3.13: Maintainer – impact of inaccurate information

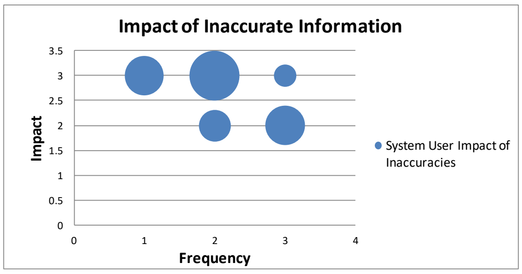


Figure 3.14: System User – impact of inaccurate information

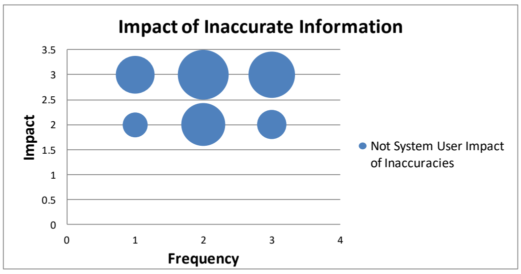


Figure 3.15: Non system user – impact of inaccurate information

3.3.6.5 Question Four: Product Information Flow

Question 4 investigated the impact associated with the flow of product information across organizations and from suppliers to customers. For example information might arrive from suppliers as a spreadsheet and then be entered into PLM/PDM or ERP systems and then be transferred on to asset or plant management systems incorrectly.

Responses indicated a clear centre of gravity favouring the top right "quadrant of greatest concern" – "medium to high" frequency and "medium to high" impact (Figure 3.16).

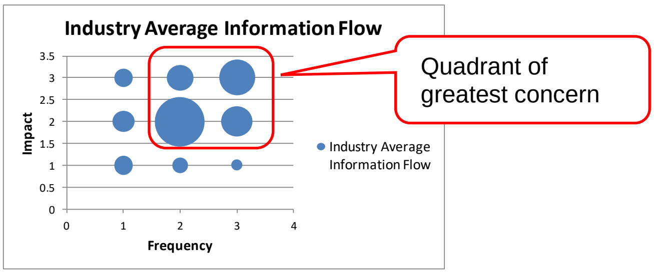


Figure 3.16: Industry average – information flow

Responses were consistent across manufacturer, maintainers, system users and non-system users (Figures 3.17 to 3.20). The lack of "shape" to the response from system users is probably a reflection that this constituency represented 24% of the overall sample.

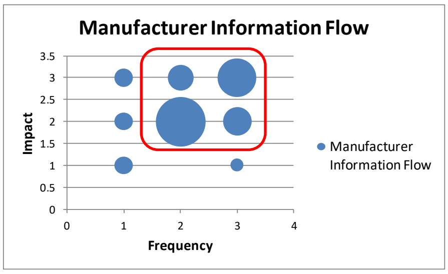


Figure 3.17: Manufacturer – information flow

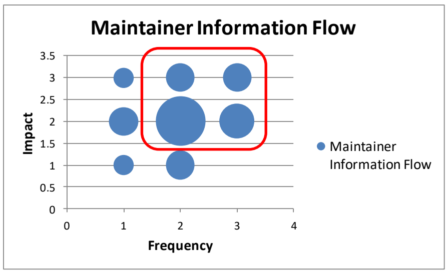


Figure 3.18: Maintainer – information flow

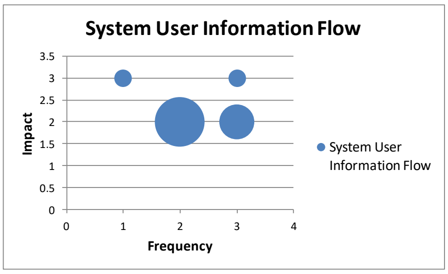


Figure 3.19: System User – information flow

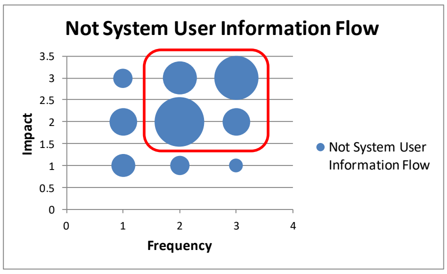


Figure 3.20: Non system user – information flow

3.3.6.6 Question Five: Duplicate Product Information

Question 5 investigated whether issues with the control of product revisions or modifications led to duplicate procurement or even the manufacture of items no longer required.

The overall response was mixed with a clear divergence of opinion. More responses ranked duplication towards the low frequency side of the chart (Figure 3.21). Greater clarity on the topic of duplication is provided by responses to Question 11 where respondents ranked duplication as the least important of five issues.

- Manufacturers followed the industry average (Figure 3.22);
- Maintainers (32% of respondents) provided a response that ranked duplication as having a medium impact with greater emphasis towards high frequency (Figure 3.23).
- No systems users felt duplication was a high impact issue and amongst the non-systems users, opinions again diverged (Figures 3.24 and 3.25).

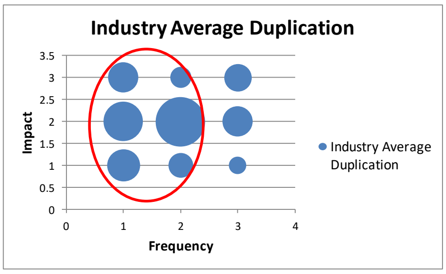


Figure 3.21: Industry average – duplicate information

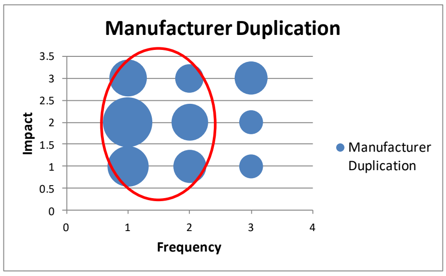


Figure 3.232 Manufacturer – duplicate information

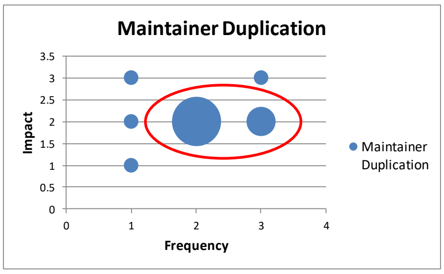


Figure 3.23: Maintainer – duplicate information

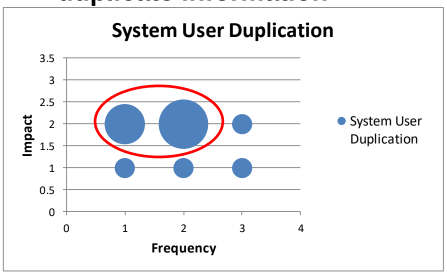


Figure 3.24: System User – duplicate information

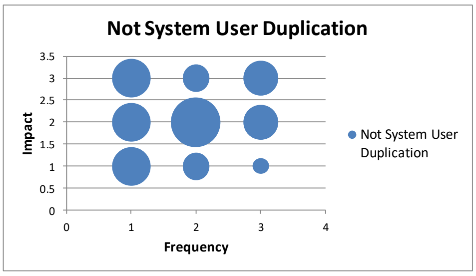


Figure 3.25: Non system user – duplicate information

3.3.6.7 Question Six: Customer Information Discrepancies

Question 6 investigated the impact of inaccurate product information on customer services. For example, manufacturers may experience difficulty receiving reliable information on customer requirements for complex configure-to-order products. Maintainers may also not receive adequate information regarding product configurations, history of product maintenance or upgrades that are important to perform their services.

The overall industry average response is clearly weighted towards the bottom left quadrant or “box of least concern” - “low to medium” frequency and “low to medium” impact (Figure 3.26. This is a surprise given the broader evidence base of trends in product life-cycle management. The broader evidence base is also acknowledged by some of the comments made by respondents - of which a selection is provided at the end of this report.

- Manufacturers reflected the industry average with an emphasis towards the bottom left “quadrant of least concern” (Figure 3.27).
- Maintainers responded with a clearer centre of gravity favouring the top right “quadrant of greatest concern” (Figure 3.28).
- Systems users offered mixed views (Figure 3.29).
- Non systems users reflected the industry average weighted towards the bottom left “quadrant of least concern” (Figure 3.30).

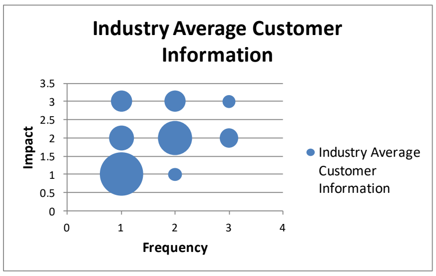


Figure 3.26: Industry average – customer information

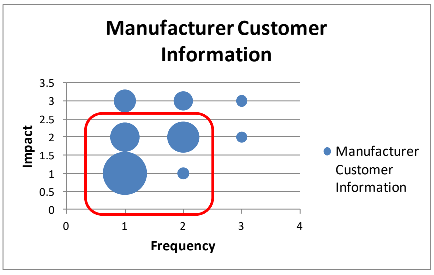


Figure 3.27: Manufacturer – customer information

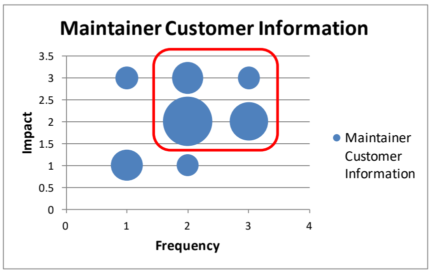


Figure 3.28: Maintainer – customer information

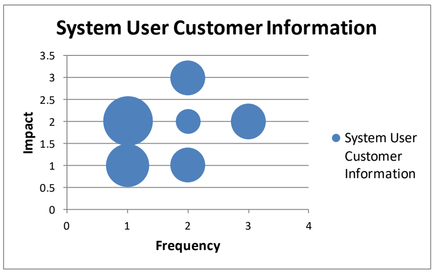


Figure 3.29 System User – customer information

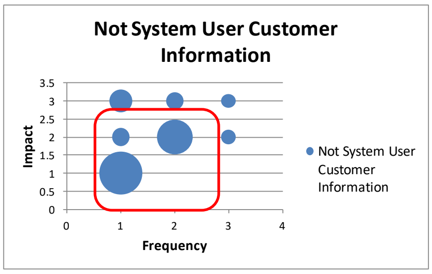


Figure 3.30: Non system user – customer information

3.3.6.8 Question Seven: Supplier Information Discrepancies

Question 7 investigated the impact of discrepancies in product information records between the responder's organization and those of suppliers. Responders were asked to consider the impact on operations, managing procurement activity, quality of goods supplied - including product documentation.

The overall industry average response offered mixed opinions although there is a marginal emphasis of responses towards "low to medium" frequency with a greater emphasis towards "medium to high" impact (Figure 3.31). Manufacturers reflected the industry average summary (Figure 3.32).

- Maintainers responded with a clearer centre of gravity favouring the top right "quadrant of greatest concern" (Figure 3.33).
- Both system and non-system users offered mixed views (Figures 3.34 and 3.35).

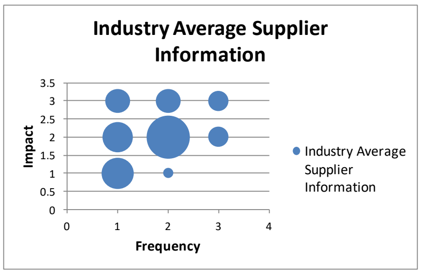


Figure 3.31: Industry average – information discrepancies

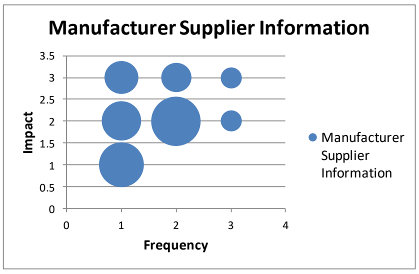


Figure 3.32: Manufacturer – information discrepancies

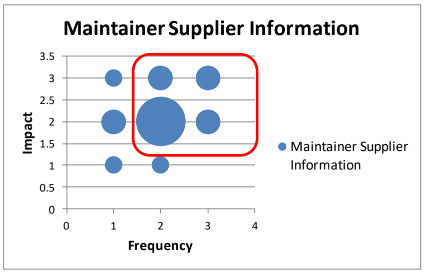


Figure 3.33: Maintainer – information discrepancies

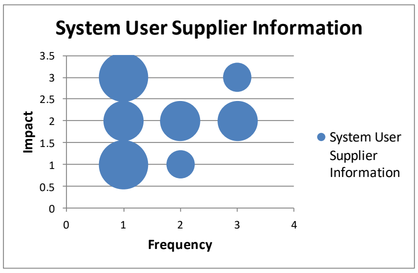


Figure 3.34 System User – information discrepancies

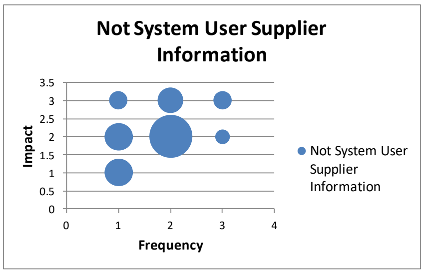


Figure 3.35: Non system user – information discrepancies

3.3.6.9 Question Eight: Configuration Rules

Question 8 investigated whether some rules for allocating product configuration information in the context of design change are clear or ambiguous. For example, a common test used across industry to assess whether a product has changed sufficiently to warrant the allocation of a new product or revision number is that of "fit, form or function".

The industry summary indicates that the number of responders who felt that some rules were ambiguous outnumbered those who felt they were clear. The number of respondents, who were undecided, was midway between the extremes (Figure 3.36).

- The number of manufacturing responders who felt that some rules were ambiguous outnumbered those who felt they were clear. Those who were undecided outnumbered the other two categories (Figure 3.37);
- Maintainers followed the industry average profile although with response numbers that reflected their lower representation in the sample (Figure 3.37);
- Non systems users and systems users followed the industry average were relatively evenly distributed (Figure 3.38).

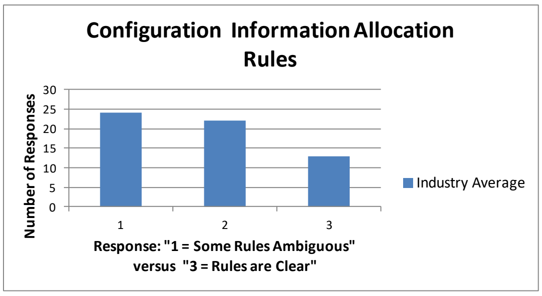


Figure 3.36: Industry average – configuration rules

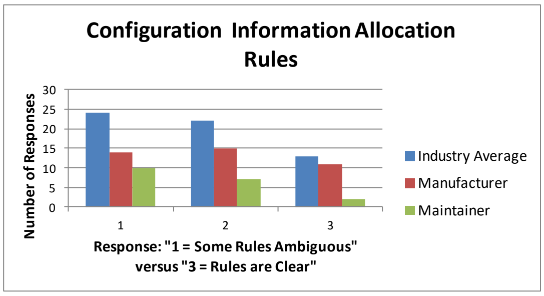


Figure 3.37: Manufacturer versus maintainer – configuration rules

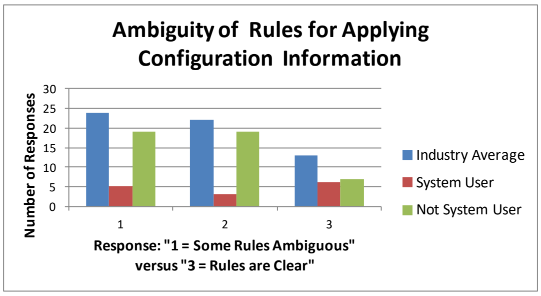


Figure 3.38: System user versus non system user – configuration rules

3.3.6.10 Question Nine: Skills Impact

Question 9 investigated the impact of skills considering the accuracy and completeness with which product information is recorded and communicated across the design, procurement, production, sales, change and maintenance processes.

Overall responses varied from low to high frequency. The majority of respondents ranked the issue of product information skills as having a medium to high impact. Overall there is a clear centre of gravity favouring the top half of the chart – medium to high impact (Figure 3.39).

With subtle variations the industry trend is continued in the manufacturing, maintenance and systems responses (Figures 3.40 to 3.43).

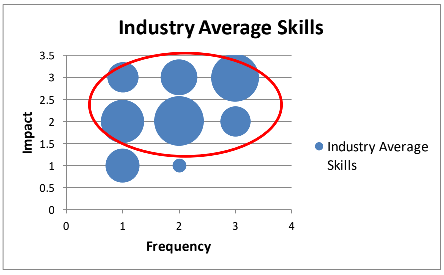


Figure 3.39: Industry average - impact of skills

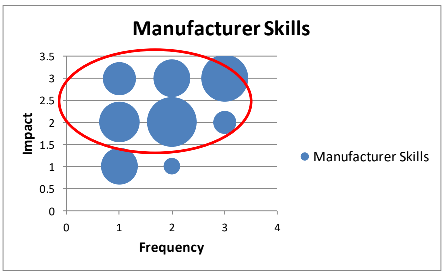


Figure 3.40: Manufacturer - impact of skills

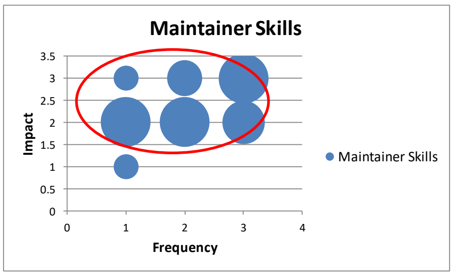


Figure 3.41: Maintainer - impact of skills

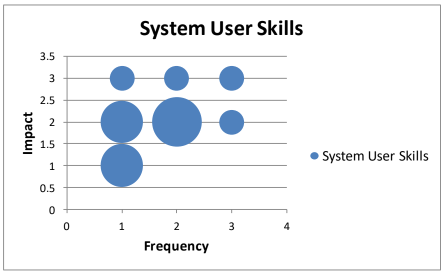


Figure 3.42: System User - impact of skills

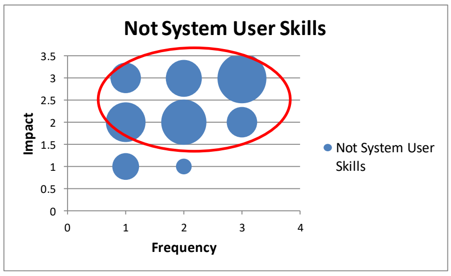


Figure 3.43: Non system user - impact of skills

3.3.6.11 Question Ten: Product terminology

Question 10 investigated the impact of differences in product terminology that exist for the same product perhaps between business units or between IT systems that use alternative terms for the same attribute.

The centre of gravity of responses is towards the bottom left "quadrant of least concern" - "low to medium" frequency and "low to medium" impact (Figure 3.44). This is a surprise as standardization of terminology (industry standard data models) has been identified in some research priorities as an area that has the potential to achieve significant efficiencies.

The industry average is broadly reflected in the responder specific analysis (Figures 3.45 to 3.48). The maintainer response reflects an even balance between the bottom left and the top right quadrants (Figure 3.46).

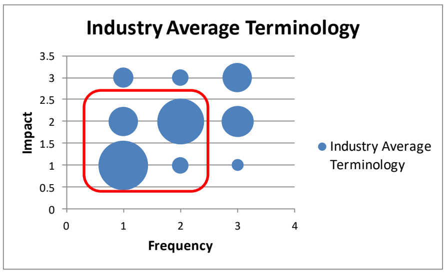


Figure 3.44: Industry average - product terminology

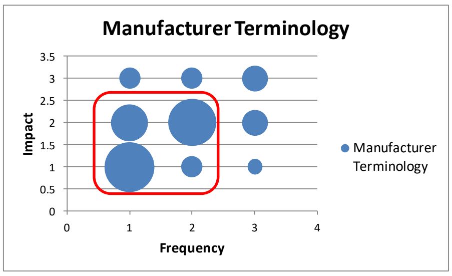


Figure 3.45: Manufacturer - product terminology

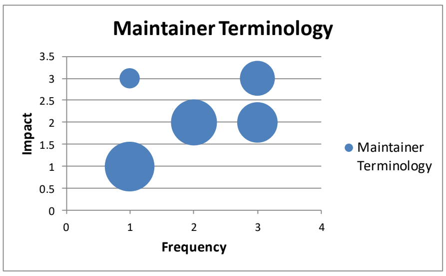


Figure 3.46: Maintainer - product terminology

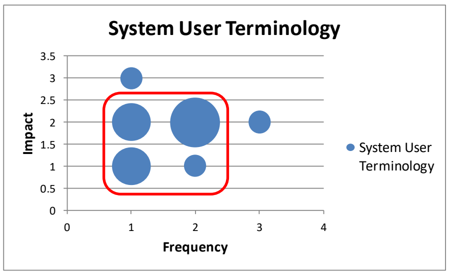


Figure 3.47: System User - product terminology

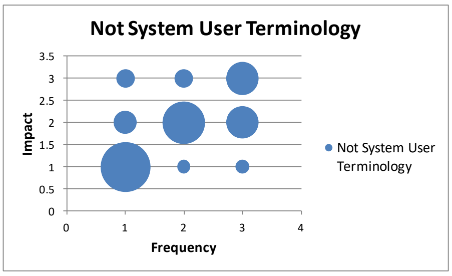


Figure 3.48: Non system user - product terminology

3.3.7 Top Five Issues

Question 11 selected five topics explored in the first 10 questions and sought to prioritise them according to the level of concern each represented.

The overall response is summarised below and in the Figures 3.49 to 3.53:

- Inaccurate product information (greatest concern);
- Managing product change process;
- Flow of product information;

- Product information search;
- Duplicate product information (least concern).

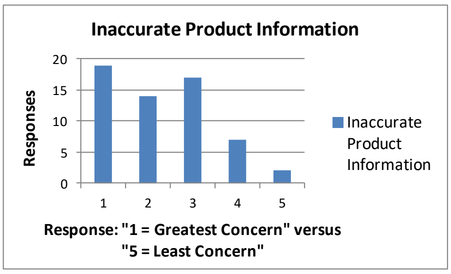


Figure 3.49: Greatest concern – top five priorities

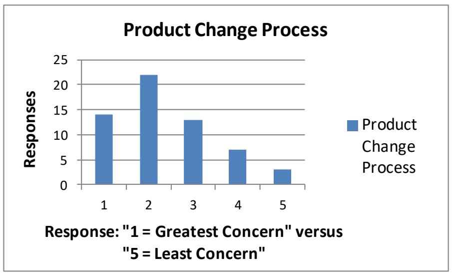


Figure 3.50: Second Greatest Concern

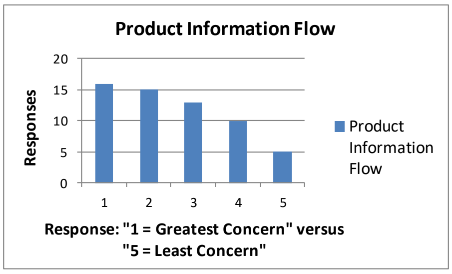


Figure 3.51: Third Greatest Concern

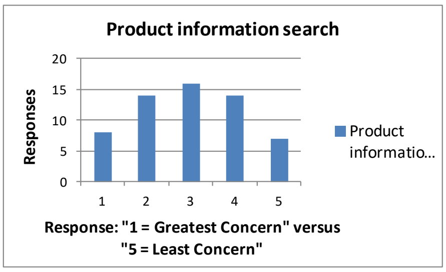


Figure 3.52: Fourth Greatest Concern

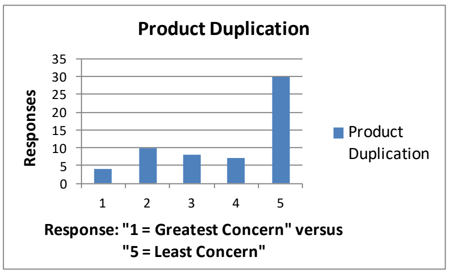


Figure 3.53: Least concern – top five priorities

3.3.8 Selected Remarks

Respondents were given the opportunity to offer comments on the topics and issues raised by the survey and the following remarks were received (Table 3.5). These remarks are consistent with the findings of the literature review and discussions with industry specialists:

- Information is becoming increasingly viewed as critical and difficulties are experienced making appropriate information available to support strategic milestones in the product lifecycle;
- Accurate information is a strategic asset and required to support continued safety and efficiency including regulatory compliance;
- Information systems need to provide better support to business processes and the flow of information between systems and organisations needs to be improved with better interoperability;
- Multinational information sharing which crosses national borders and associated legislative jurisdictions;
- Information systems are becoming increasingly complex in response to industry information trends
- Greater investment into ICT systems and the skills to design, implement and manage them is required.

Sector	Remarks
Automotive Manufacturing	Information flow between systems is a problem that leads to inaccurate product information since employees want to trust all of the systems they use. Most employees are not able to distinguish master data in one system from a copy in another system that they assume is known good data.
Automotive Manufacturing	There are significant difficulties surrounding availability of the right level of information to suit strategic milestones in product lifecycle. These problems arise from information consuming requirements not being well understood by those who generate / provide the information. Whilst individuals mitigate the risks associated with weaknesses in product information management, this leads to varied processes / duplicated effort / and over or under production of data.
Civil Aviation Maintenance	Product information management and change is a vital [issue] in our industry due to the highly complex systems that we are dealing with. Therefore a holistic solution needs to be in place from manufacture to product use that provides a good automated information platform ensuring safety and efficiency at the highest level.
Civil Aviation Maintenance	Often, attempting to replicate a paper-based system on an IT platform results in cumbersome, time-consuming and inflexible solutions forcing work arounds and compliance failures.

Consumer Products	• Data sharing/project collaboration is the greatest issue in our pan-European environment - in excess of twelve R&D Centres - solution underway - single data centre. • A whole group, single engineering change process is critical in our business vision. • Data duplication is inevitable where our business has grown through merger and acquisition rather than organically. This is not so critical, but there is great cost saving potential - data centre and classification projects will assist in reducing inventory.
Defence Maintenance	Inaccurate information would seem to most commonly arise because of a lack of investment in infrastructure or systems which ensure data quality is maintained at a high level. There is also a lack of incentive for people who generate transactional information to ensure high data quality for users of the information who are removed from them organizationally and geographically.
Defence Manufacturing	Our company deals with space-borne systems for civil and national security applications. We conduct detailed independent assessments of these systems and build and develop small, prototype, proof of concept systems. With our current baseline processes, information flow across company boundaries and across engineering discipline boundaries is slow, limited, and prone to errors and disconnects.
Industrial Equipment Manufacturing	Length of time taken to put design through to release a potential issue; Process slowed due to petty naming issues of parts; Parts rejected further down release chain due to minor errors on drawing (eg lack of full stops, incorrect colours).
Medical Device Manufacturing	Decentralized & disconnected systems with related data, impacts search, accuracy and cost (resources). Compliance drivers demand rapid records availability & accuracy.
Rail Manufacturing	Tracking product information / configuration after the product is handed over to the customer / operator is one of the biggest challenges.
Rail Maintenance	We are still trying to operate many old numbering and naming systems which have been introduced by successive parent companies, unfortunately no one company has ever closed the loop and completed a transformation to one system.

Table 3.5: Selected comments made by survey responders

3.4 Discussion of Industry Analysis

3.4.1 Inaccurate Information a Priority

Based on the findings of the survey and discussions with industry specialists it was evident that the amount of design change experienced through-life can vary. For complex products the evidence gathered indicated that 40% (+/-10%) over 30 to 40 years represents a reasonable guide. The problem of inaccurate product information was identified as the number one issue by the survey, with the response to Question 1 indicating the medium to high level of the current difficulties. 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 that manufacturers of complex products, including those within which a number of the industry specialists were placed, have outsourced much of their manufacturing activity. This means that a significant proportion 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 was assessed as medium by responses to the survey Question 7.

The acquired information is used to manage procurement, inventory, production, 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. This point was confirmed within the discussions and indicates better support is needed.

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 within fleets and so 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 customer 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 organizations being rated as medium.

A further contributing factor is that, in a fleet scenario, the design configuration of each delivered product will be slightly different. Comments recorded in Table 3.5 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 aircraft have slightly different designs but the differences between the designs of a group of commercial aircraft at the end of their life are much greater than at the start of their life. This affects user requirements and so operators and OEMs need to carefully track each aircraft as they are modified. This divergence in design is a complication of the product change process.

One of the implications of the differences between product designs is that there is a need for a way to provide 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 2 and 4 out of 5 for difficulty in responses to Question 2 of the survey indicates that this is a real challenge. 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). It has also been estimated that the acquisition of data to support production system planning represents 66% of the time required to develop options (Uhlemann et al 2017). Discussion with the industry specialists confirmed that engineers can spend a significant time searching for product and part information. This was confirmed by the high to medium impact registered in the response to Question 9 in the survey.

3.4.2 The Spaghetti Team

The costs in labour and time spent searching for information was identified as the fourth most important issue in the survey and was considered in the follow-up discussions. It would appear that there is the potential to achieve significant reductions in labour costs in the region of between one and two thirds (Robinson 2010 and Uhlemann 2017). 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 3.54 seeks to outline the problem solving behaviour demonstrated by engineers taking part in this collaboration who 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”.

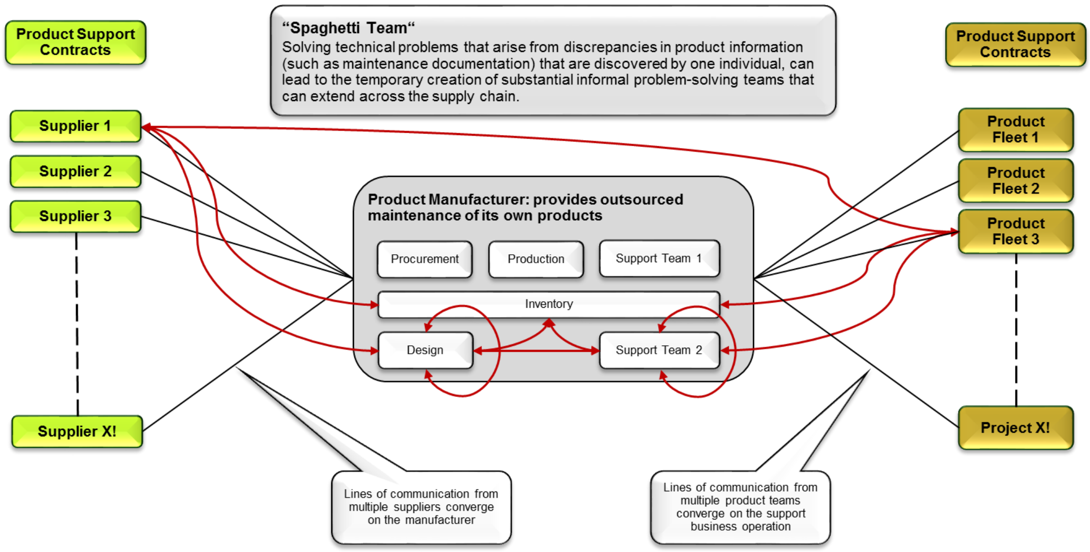


Figure 3.54: Problem solving behaviour demonstrated by maintenance engineers

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 that can extend across the supply chain when difficulties are experienced. These are in addition to the formal lines of communication established between organizations.

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 organization 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 and other departments. People who now support this problem solving within the OEM 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 ICT systems. The need for better information flow was rated the third most important issue raised and is 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 development of a closely integrated ICT 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 the enhancement of the information flow between systems was assessed in Question 4 which recorded a significant number of organization having problems in this regard. This was seen as a key issue by the industry specialists and is considered as an important future development.

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 the 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 the closer process integration across complex organizations.

3.4.3 Chapter 3 Summary

Chapter Three has described the investigative process used to establish in detail the nature of the challenges faced by industries when managing HVLL products through-life. A survey was designed to quantify the issues associated with managing design information. Engineering. Fifty nine responses were received from representatives of 39 organizations. Follow-up discussions were undertaken to capture further detailed information. The principle finding of this industry investigation is that the interface between product management methods and ICT is not fully defined and remains relatively unexplored. In addition, the nature of the inefficiencies arising from inaccurate product information are poorly understood and, consequently, the actions required to drive performance improvements have yet to be formulated.

Chapter Four: Change Modelling: Phase One

4.1 Design Divergence

The analysis discussed in this chapter was undertaken to validate the observations of industry specialists who had observed the effect of design divergence in product fleets. The analysis uses the rationale that the volume of information that flows through the supply chain (both within and between organisations) will relate in some way to the level and degree of product design change. To quantify the volumes of information that need to flow, a number of organisations were asked to estimate the level of design change that their products experience through-life. To establish a deeper understanding of the product change process and its impact, the findings of the survey were investigated further with a series of in-depth discussions with industry specialists, starting in 2012 and this activity continued throughout 2013.

For example, a series of conversations with representatives at Boeing Commercial Aircraft, Airbus, Bombardier Aerospace, British Airways, United Airlines and American Airlines was able to establish consensus on the following scenario.

The design variation between ten new civil aircraft can be estimated to be less than 5% (all aircraft are slightly different). Over the life of the aircraft however, changes that arise from "refreshes" of internal trim, seats and modifications to avionics and engines appears to have a cumulative impact on a design that can amount to between 30% and 40%. Other HVLL products (gas turbines and nuclear power generation plant) were observed to experience similar levels of design change. Across a product fleet the impact of this level of through-life change seemed to lead to a divergence in the designs that increases the initial 5% to a design variation of between 20% and 25%. When these issues are better understood, it is likely that conventional approaches to delivering maintenance documentation will need to be adjusted to support the provision of accurate through-life information that more closely matches the maintained configuration of the product;

These discussions were initially framed around the five rated issues identified within the survey. This process identified the responses provided in Table 4.1.

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 to 40	70 to 80	Not known	Not known	High levels of technological change mean that electronics products are often manufactured for 5 years. During this time changes will be made to the design mostly triggered by changes to supplier parts.
Civil Aerospace	30 to 40	Not known	30 to 40	20 to 25	These design changes arise due to the need to upgrade the avionics, engines and “refresh” the internal trim and seats.
Defence Aerospace	30 to 40	20	Not known	20 to 25	The design difference between aircraft of the same specification produced as separate batches arises mainly due to changes in software and electronics components.
Gas Turbines	30 to 40	Can be as high as 100%	40 to 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 to 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

Table 4.1: Sector specific responses made in response to industry survey

To support these comments, the analysis of the bill-of-materials needed to support the maintenance operations for a range of 5 fleets of a commuter train used in Europe was undertaken. The results of this analysis are illustrated in the data provided in Figure 4.1. This identified an average growth rate of 13% (across the fleets) in the number of line items required to support maintenance. The highest level of change was associated with Fleet 3, in which some 25% of the parts were observed to have changed over a period of eighteen months.

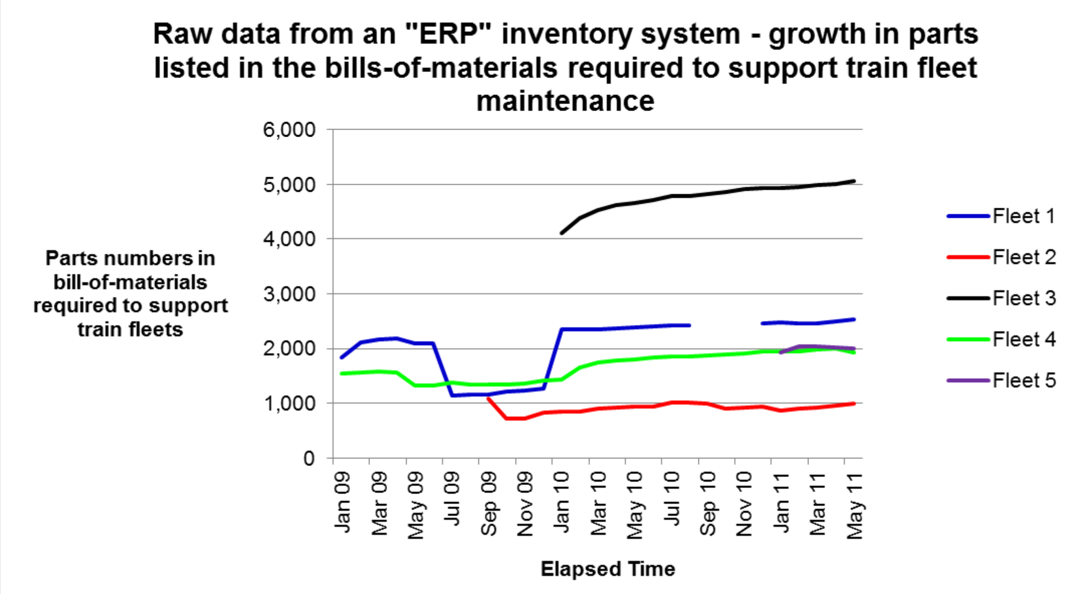


Figure 4.1: Bill-of-material parts growth - train maintenance support

The growth in the number of items included in the bill-of-materials is unlikely to be due purely to design changes or modifications. Some growth may be because additional parts are required for support that were not included in earlier analysis required to generate the trains' maintenance policies. Regardless of the detail, the data illustrates a growth in the volume of information needed to support maintenance activities as the fleets age. The missing data in 2010 for Fleet 1 cannot be explained.

To validate these observations a quantitative simulation modelling approach was developed. This aimed to support the development of a better understanding of how product support strategies need to respond to current challenges. While quantitative models are limited in that they cannot fully represent the real life situations that are created to investigate, they can nevertheless help to develop an improved understanding of problem structures and system behaviour. The ultimate goal is to develop a better understanding of the informational challenges faced by the respective industries. The modeling was undertaken in two phases. The first phase, described and discussed in this chapter, sought to replicate the design divergence in product fleets that was identified during the industry investigation. The second phase, considered in Chapter 6, sought to generate a better understanding of the information required to support complex products through-life. In both cases the intention was to better illustrate the magnitude of the challenges posed by design change and support the definition of the enhancements required to assure effective design change management systems.

4.2 Modelling Approach - Phase One

The operation of any organisation relies on a set of logical processes that reflect the nature of its operations – they also have a significant impact on its cost base. To minimise the risks of duplicate activity, many processes require unique indexation systems: invoices, purchase orders and account numbers to name a few. Where the core activity of a business is based on products and product-based services, an accurate system of unique product identification is also paramount. Figure 4.2 provides a simple illustration of how products are indexed against each change.

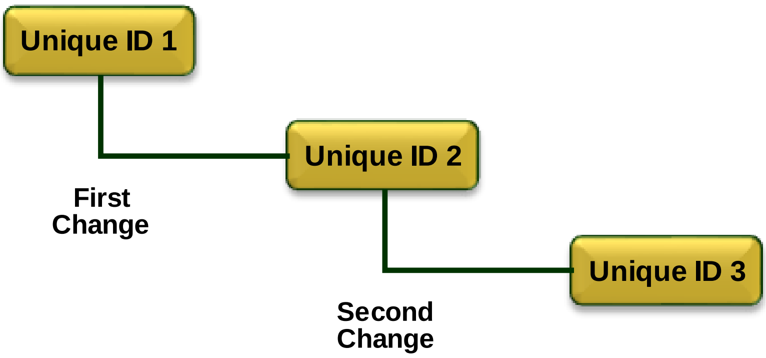
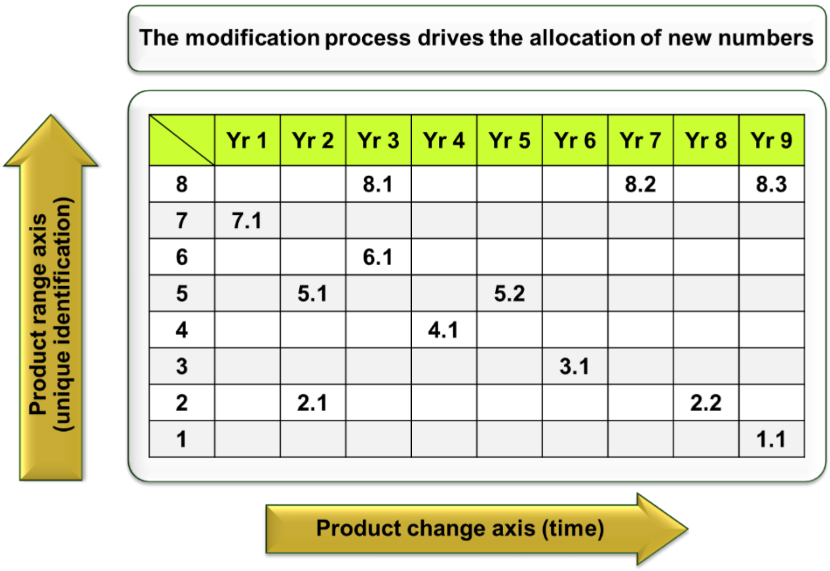


Figure 4.2: Indexing product changes

In the diagram, the connecting lines between the uniquely indexed parts illustrate the use of succession or alternative relationships that enable cross-referencing between products that are related by a design modification or change of supplier. The alternative links support searches for alternative parts and for HVLL products, can be safety critical items of information. For example and order for a product (Unique ID 3) may identify there is no inventory available; however, the presence of a succession link enables and alternative product or product variant (Unique ID 2) to be identified.

For efficient operation, businesses and customers (markets) require a degree of stability. Yet the process of product innovation requires considerable flexibility to change the designs of products. Between these extremes, designs must be managed so that products may be designed, manufactured, sold and accounted for. The challenge that remains with unique product identification systems is their ability to clearly differentiate between different products, across product lines, and also different variants of the same product, within a product line, as products are modified. This is illustrated in Figure 4.3.



	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9
8			8.1				8.2		8.3
7	7.1								
6			6.1						
5		5.1			5.2				
4				4.1					
3						3.1			
2		2.1						2.2	
1									1.1

Figure 4.3: Indexed product changes made through-life

The diagram illustrates a product range (vertical axis) that experiences modifications that are made over a period of time (horizontal axis). Modifications are implemented throughout the lifecycle. For example, product 8 is modified in years 3, 7 and 9, while product 2 is modified in years 2 and 8.

Accurate product or part information is important because it supports four important organizational processes: accessibility (inventory); utility (configuration); supportability (maintenance); and finally valuation.

4.3 Concept: Phase One Model

To support the aims of this research, the concept of a "100 part product" was developed. The model was set-up with 10 identical "100 part products" with each design comprised of 100 parts, with part numbers that ranged from 1 to 100. This created a model with a sample size of 1,000 parts that could be analysed over the product lifecycle. Design changes were applied to the fleet at varying modification rates from 1% to 10% per annum.

Every year a proportion of a product's parts are selected randomly for modification. Modifications are reflected in the product's design by increasing the value of each part number by 0.1 for each change. While significant design changes would eventually lead to the creation of duplicate part numbers, the model's algorithm is set-up to avoid this problem should it arise.

The rules of the simulation are that all 100 parts of the product are equally likely to be modified. The calculation of the degree of divergence between product designs is undertaken as follows:

- Each year all products in the fleet have a set percentage of their parts randomly selected for modification. In accordance with the discoveries made during the literature review, survey and engagement with industry specialists, the percentages were established to examine the effects of annual rate of design change;
- This process is repeated for each year of the product's life – for this thesis the model was set to simulate 40 years.

4.3.1 Phase One Model Structure

The model is structured into three parts: the core function calculates on an annual basis the changes to the design of each part of the 100 parts fitted to each product in the fleet. A second function calculates whether any design changes have been made to the original parts across the product fleet. The third function investigates design differences between each of the products in the fleet by comparing the designs of 9 products with a tenth. Finally, additional analysis is undertaken separately and presents the results graphically. The structure of the model is provided in Figure 4.4.

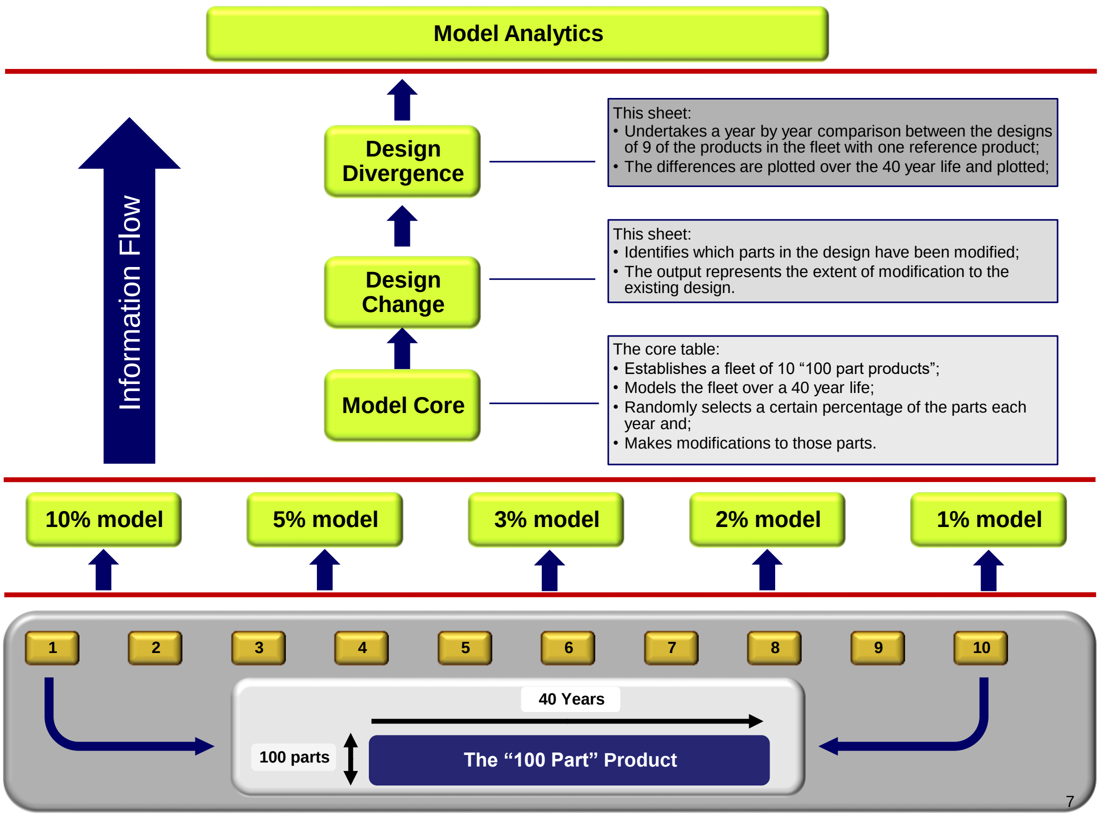


Figure 4.4: Structure of the – Design Divergence Model

The core table establishes a fleet of 10 “100 part products”. Based on the rate of design change per annum selected (1%, 2%, 3%, 5% or 10%), the model randomly selects a number of parts from each product’s design that are to be modified. The number of parts is determined by the percentage selected for the simulation. Parts selected for modification are changed by adding “0.1” to the part number. The consequence of this is that after nine modifications a part number (X.0) would become a different version denoted by part number X.9. Thus by only using one decimal place the maximum number of modifications each part could receive is limited to 9. This is a limitation of the model. This arrangement was acceptable for the product life and rates of change being modelled.

The core table in the model is thus able to simulate a fleet of products over a 40 year life based on varying levels of design change. The total design change table, identifies for each of the 10 products, how many modifications have been made to the product's original design – through-life. The table achieves this by:

- Firstly, for a particular year, it identifies for each part in a product whether a modification has been implemented in the previous year;
- For each product the model then establishes how many design changes have been implemented in a particular year (for example year 10);
- The changes for each product are added together to provide a total number of modifications for that year;
- The annual totals are then cumulatively added together to determine the total number of modifications implemented on the fleet since the start of the simulation. This is recorded as a yearly running total.

The design divergence sheet, undertakes a year by year comparison between the designs of 9 of the products in the fleet with the remaining product in the fleet which is used as a reference design:

- By year, the model compares individual part numbers from a product (x) with a reference product in the fleet, for example Product One:
- If the part number has the same value as the reference product in the fleet then the divergence value is set to "0";
- If the part number has a different value as the reference product in the fleet then the divergence value is set to "1";
- The total number of differences for the year indicates the divergence of product x from the reference product, for example Product One.
- The differences are plotted over the 40 year life.

4.4 Phase One Modelling Results

4.4.1 Rates of design change modelled

Figure 4.5 illustrates the linear relationship of cumulative design change versus time that the fleet experienced over 40 years for different modification rates. With a 1% annual change rate the total number of design changes will be 400 by the end of life. For an annual rate of design change of 10% the fleet of 10 "100 part products" might experience around 4,000 modifications.

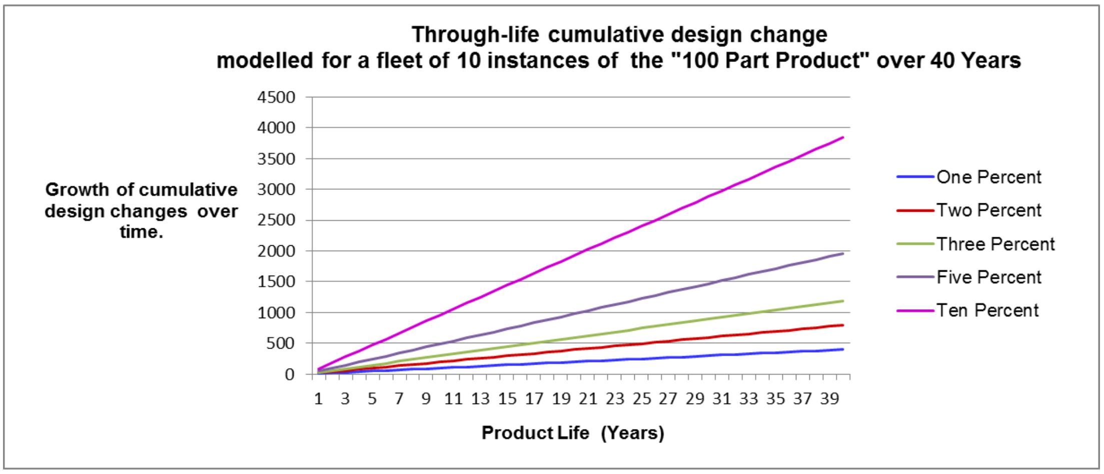


Figure 4.5: Through-life growth of cumulative modifications across the fleet of 10 products

4.4.2 Model Output with 1% Annual Design Change

4.4.2.1 Through-life Design Change (1% annual change)

The design change module of the model looks at which parts within each product have been modified away from the original design. Figure 4.6 illustrates that with an annual rate of design change of 1%, after 40 years between 65% and 72% of parts within the fleet are left unmodified.

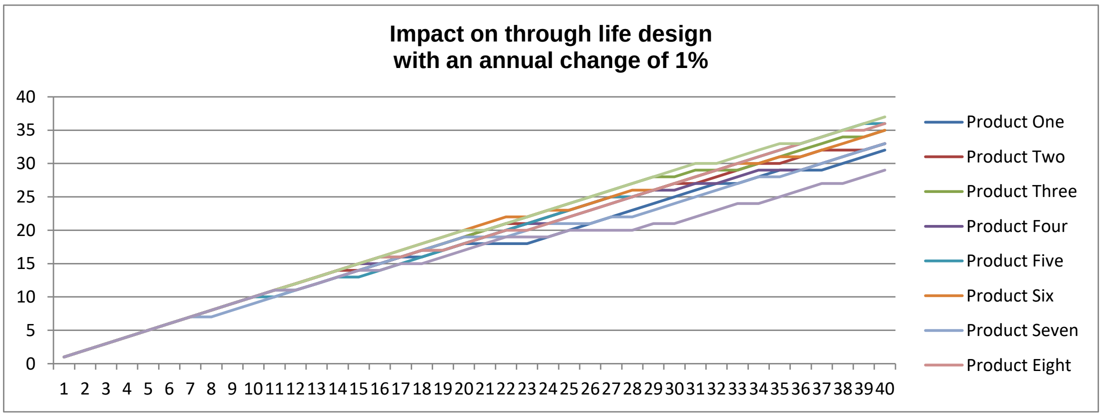


Figure 4.6: Through-life design change 1%

4.4.2.2 Design Divergence (1% annual change)

The divergence module compares the designs of Products Two to Ten with the design of Product One and counts the number of differences. This analysis shows that, over the 40 year life, the product designs within the fleet have diverged by between 40% and 50%. This is represented by the distance between the X axis and the plotted data. The variance in the data is represented by the spread of the plotted data (in the Y axis) and varies between 5% and 10%. Figure 4.7 illustrates the design divergence that was identified.

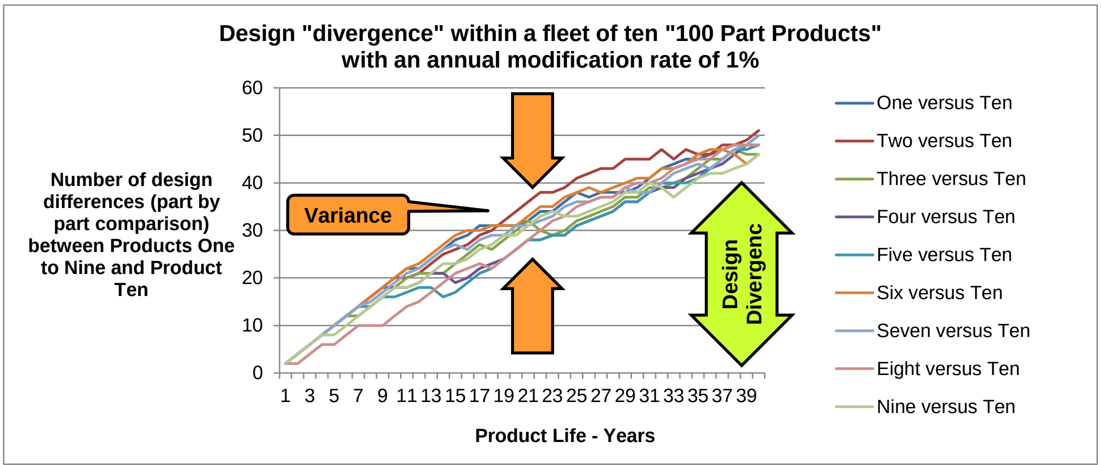


Figure 4.7: Through-life design divergence of fleet compared to Product Ten (1%)

This analysis identified that when the level of through-life design change was set at 1%, the model showed a gradual growth in design divergence that reaches 40% to 50% after 40 years. This supported the observations of industry specialists.

An initial concern with the results, related to the observed clustering of product designs that indicate 40% to 50% design divergence after 40 years, in particular, why the design lines of each product in the fleet are not spread evenly to show a range of design divergence between 0% and 50%.

At one extreme, after one round of the modification process (which represents the end of first year of product support) all products within the fleet might have the same part modified (such as part number 1). In this event, all products would have received the same modification and so remain identical and there would be no design difference or “divergence”. A single parts/ maintenance catalogue would be sufficient to support the whole fleet.

At the other extreme, after one round of the modification process (which represents the end of the first year of product support) all products within the fleet might have received a different modification. In this event there would be a design difference of 1% between each of the products. The designs will have diverged and the parts catalogue/ maintenance manual will need to list 110 parts rather than the 100 it listed when the products were new and the designs the same. To provide an alternative perspective a further comparison was undertaken of the design differences in the fleet, this time between Product 10 and Products One to Nine. This analysis, presented in Figure 4.8, provided a similar result which also displayed clustering of lines that indicated 40% to 50% design divergence after 40 years.

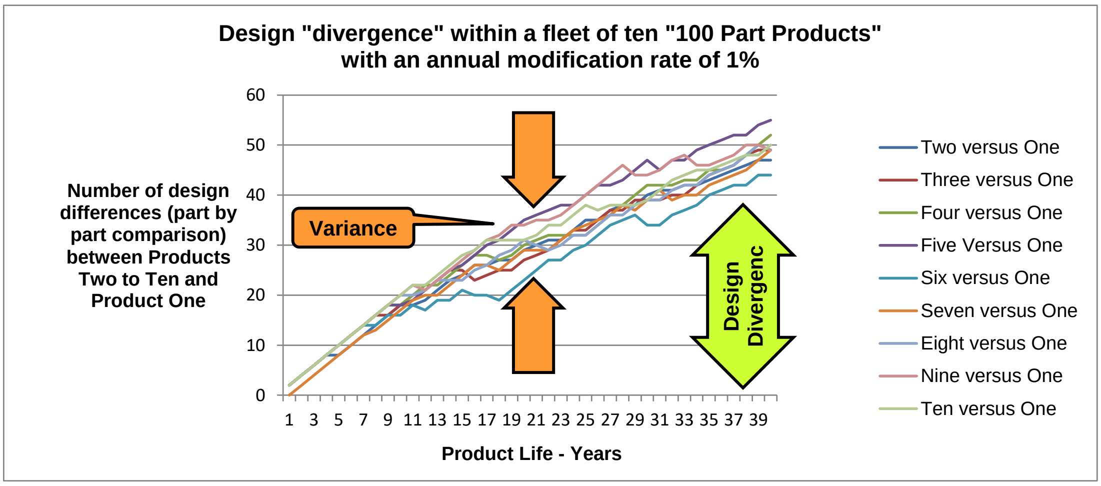


Figure 4.8: Through-life design divergence of fleet compared to Product One (1%)

The fact that both comparisons provide a similar result indicates the model offers a realistic analysis of the design changes evident in industry.

4.4.3 Model Output with 2% Annual Design Change

4.4.3.1 Through-life Design Change (2% annual change)

The design change module of the model looks at which parts within each product have been modified away from the original design. Figure 4.9 illustrates that with an annual rate of design change of 2%, after 40 years between 42% and 47% of parts within the fleet are left unmodified.

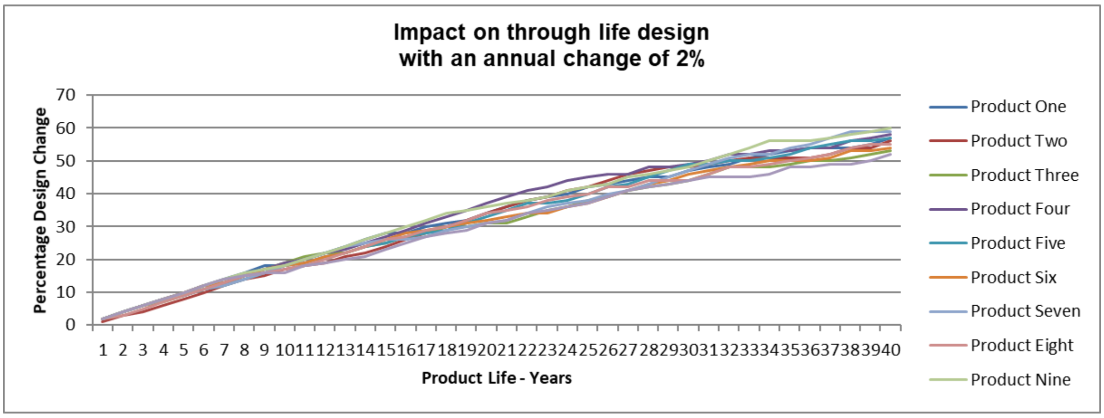


Figure 4.9: Through-life design change 2%

4.4.3.2 Design Divergence (2% annual change)

The divergence module compares the designs of Products Two to Ten with the design of Product One and counts the number of differences. This analysis shows that, over the 40 year life, the product designs within the fleet have diverged by between 60% and 70%. This is represented by the distance between the X axis and the plotted data. The variance in the data is represented by the spread of the plotted data (in the Y axis) and varies between 6% and 13%. Figure 4.10 illustrates the design divergence that was identified.

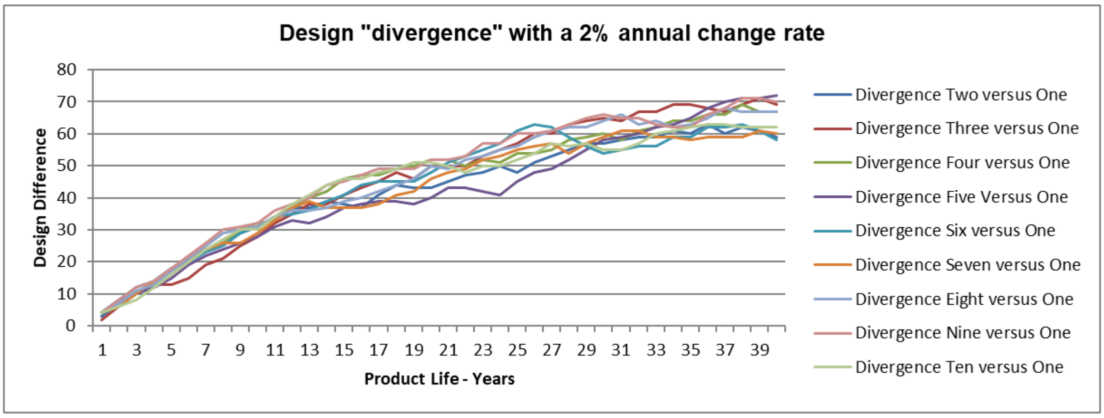


Figure 4.10: Through-life design divergence 2%

4.4.4 Model Output with 3% Annual Design Change

4.4.4.1 Through-life Design Change (3% annual change)

The design change module of the model looks at which parts within each product have been modified away from the original design. Figure 4.11 illustrates that with an annual rate of design change of 3%, after 40 years between 25% and 35% of parts within the fleet are left unmodified.

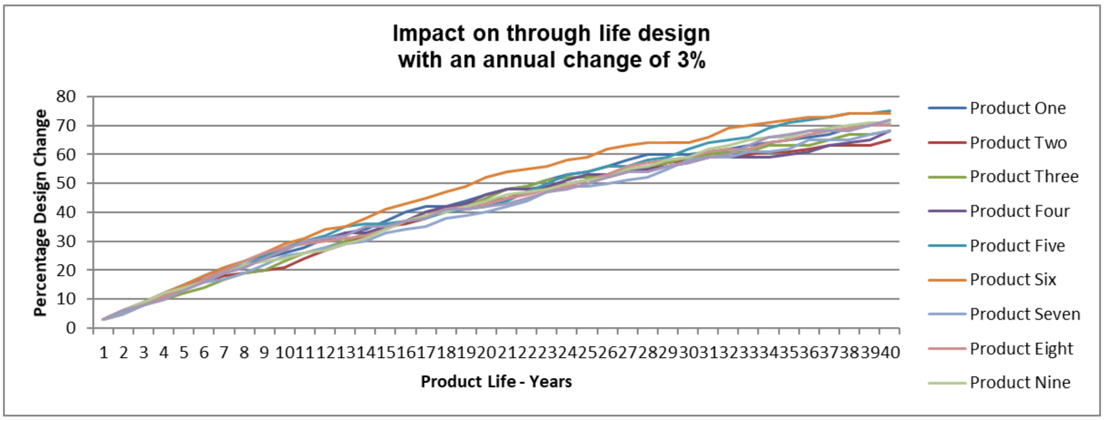


Figure 4.11: Through-life design change 3%

4.4.4.2 Design Divergence (3% annual change)

The divergence module compares the designs of Products Two to Ten with the design of Product One and counts the number of differences. This analysis shows that, over the 40 year life, the product designs within the fleet have diverged by between 65% and 80%. This is represented by the distance between the X axis and the plotted data. The variance in the data is represented by the spread of the plotted data (in the Y axis) and varies between 10% and 15%. Figure 4.12 illustrates the design divergence that was identified.

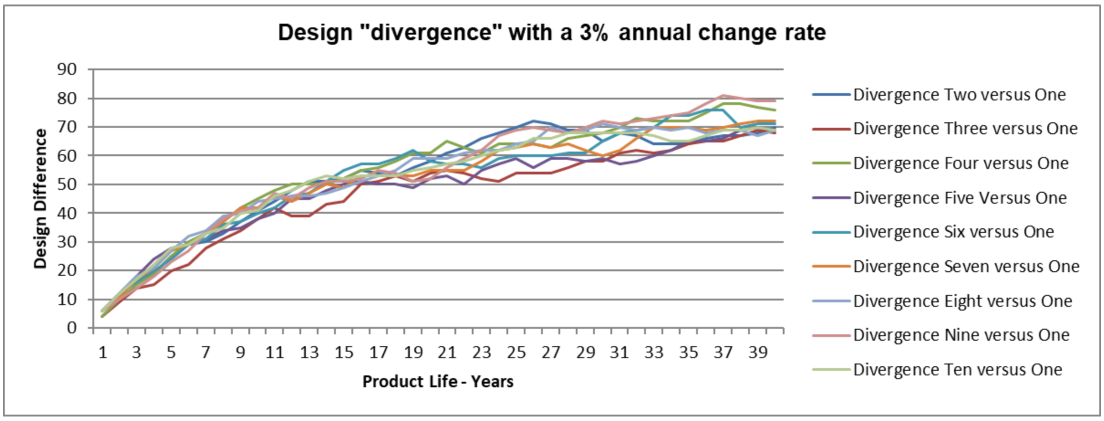


Figure 4.12: Through-life design divergence 3%

4.4.5 Model Output with 5% Annual Design Change

4.4.5.1 Through-life Design Change (5% annual change)

The design change module of the model looks at which parts within each product have been modified away from the original design. Figure 4.13 illustrates that with an annual rate of design change of 5%, after 40 years between 10% and 20% of parts within the fleet are left unmodified.

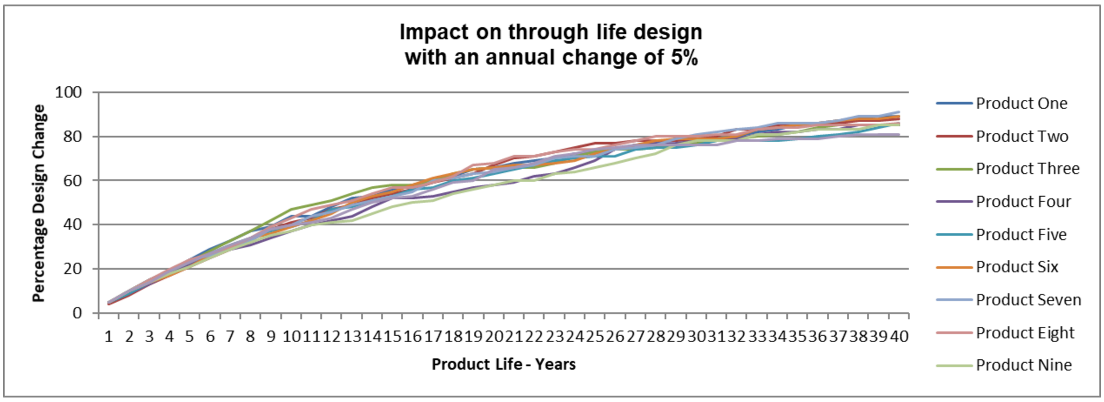


Figure 4.13: Through-life design change 5%

4.4.5.2 Design Divergence (5% annual change)

The divergence module compares the designs of Products Two to Ten with the design of Product One and counts the number of differences. This analysis shows that, over the 40 year life, the product designs within the fleet have diverged by between 75% and 85%. This is represented by the distance between the X axis and the plotted data. The variance in the data is represented by the spread of the plotted data (in the Y axis) and varies between 5% and 13%. Figure 4.14 illustrates the design divergence that was identified.

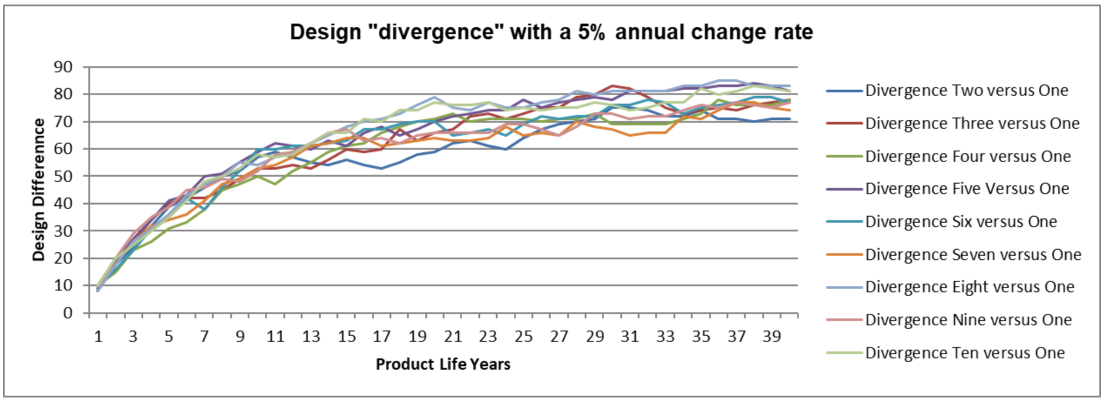


Figure 4.14: Through-life design divergence 5%

4.4.6 Model Output with 10% Annual Design Change

The design change module of the model looks at which parts within each product have been modified away from the original design. Figure 4.15 illustrates that with an annual rate of design change of 10%, after 40 years no parts in any of the products within the fleet remain unmodified.

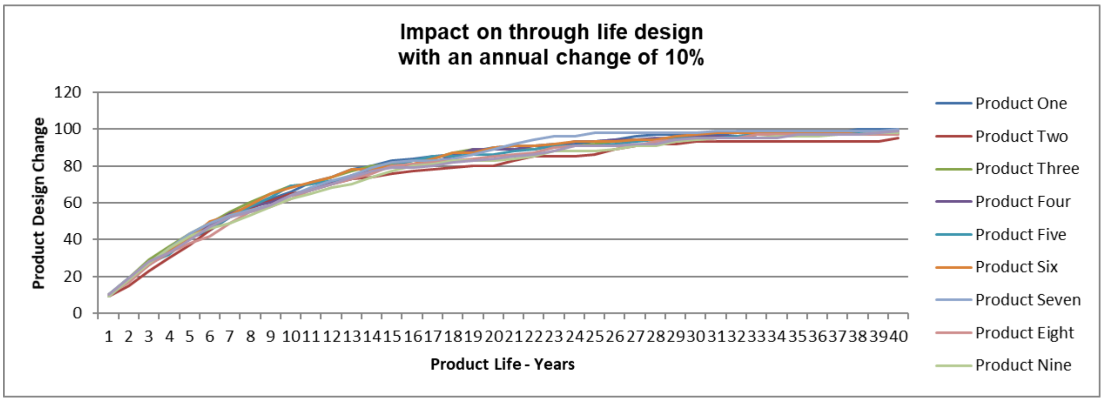


Figure 4.15: Through-life design change 10%

4.4.6.1 Design Divergence (10% annual change)

The divergence module compares the designs of Products Two to Ten with the design of Product One and counts the number of differences. This analysis shows that, over the 40 year life, the product designs within the fleet have diverged by between 75% and 90%. This is represented by the distance between the X axis and the plotted data. The variance in the data is represented by the spread of the plotted data (in the Y axis) and varies between 8% and 16%. Figure 4.16 illustrates the design divergence that was identified.

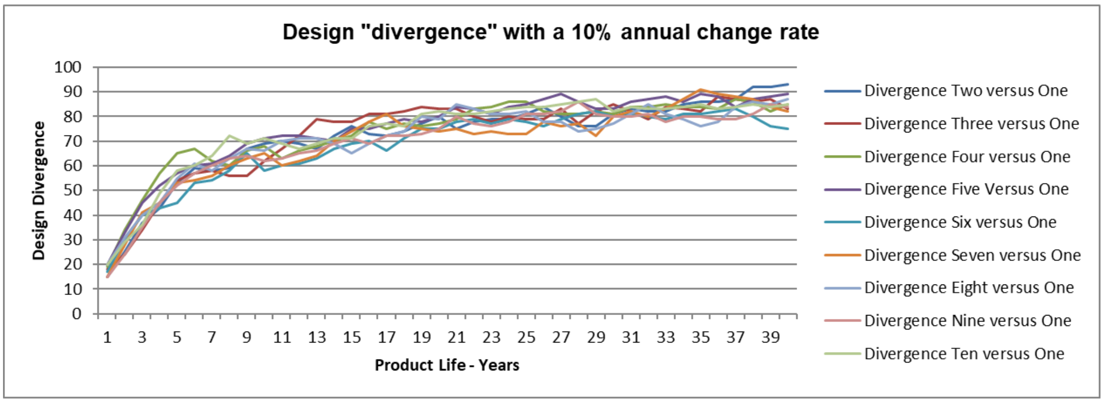


Figure 4.16: Through-life design divergence 10%

4.4.7 Part Number Analysis

To gain a better perspective of the design complexity generated by design change, an analysis was undertaken of the numbers of part revisions in circulation at any time.

4.4.7.1 Part Number One Revisions in Circulation (10% annual change)

With a 10% annual rate of design change and the life of the model reduced to 37 years an analysis of part number ones was undertaken. This analysis is provided in Figure 4.17 and shows how the number of revision "1.0" gradually fell while the number of "1.1", and subsequent revisions grew. By year 36 a single 1.8 variant has entered circulation. This illustrates that shortly (within a couple of years) of the start of the operating life of the product, maintenance engineers already have many choices available to them depending on the configuration of the product in the fleet.

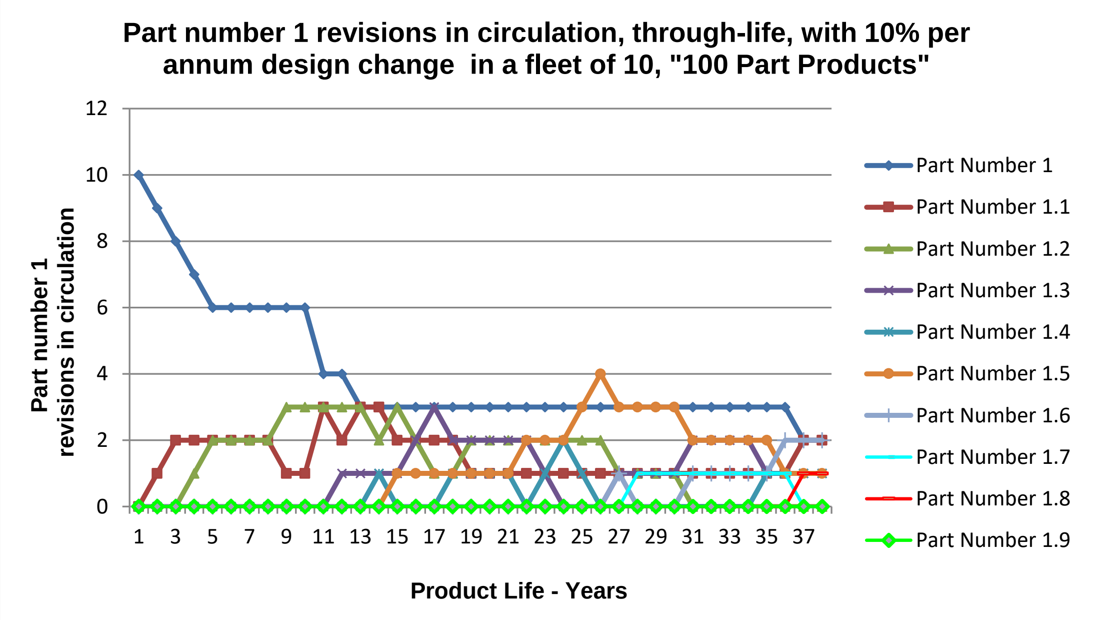


Figure 4.17: Part number ones in circulation 10% annual design change

4.4.7.2 Part Number One Revisions in Circulation (1% annual change)

With a 1% annual rate of design change and the life of the model set to 40 years a separate analysis of part number ones was undertaken. This analysis is provided in Figure 4.18 and shows how the number of revision "1.0" gradually fell while the number of "1.1", and subsequent revisions grew. This illustrates the significant reduction in part one revisions in circulation as the simulation progressed. In this example, multiple revisions are not evident until the second half of the fleet's operating life. Thus the burden of information search for maintenance processes and parts compatibility analysis is less than for higher levels of design change. It is interesting to see that the number of 1.1 variants increases to one in year 24 and then falls to zero as the part is modified to variant 1.2 in the subsequent year another 1.0 variant part is modified, closely followed by a second to increase the population to two in year 40. This provides a valuable insight into an aspect of fleet management that faces engineers when they need to undertake maintenance decisions.

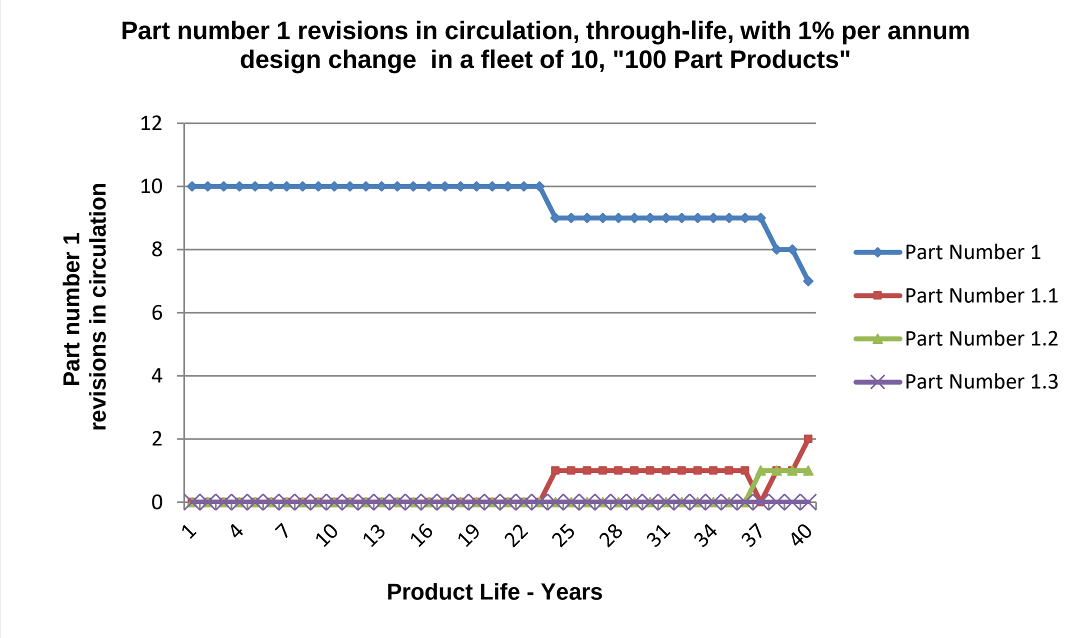


Figure 4.18: Part number ones in circulation 1% annual design change

4.4.7.3 Comparative Analysis of Part Number One Revisions

A final analysis compared the different numbers of part number revisions in circulation for the fleet of 10, “100 part products”. This analysis, provided in Figure 4.19, confirms the different growth rates in the number of design revisions in circulation for each of the scenarios modelled: 1%, 2%, 3%, 5% and 10% annual design change.

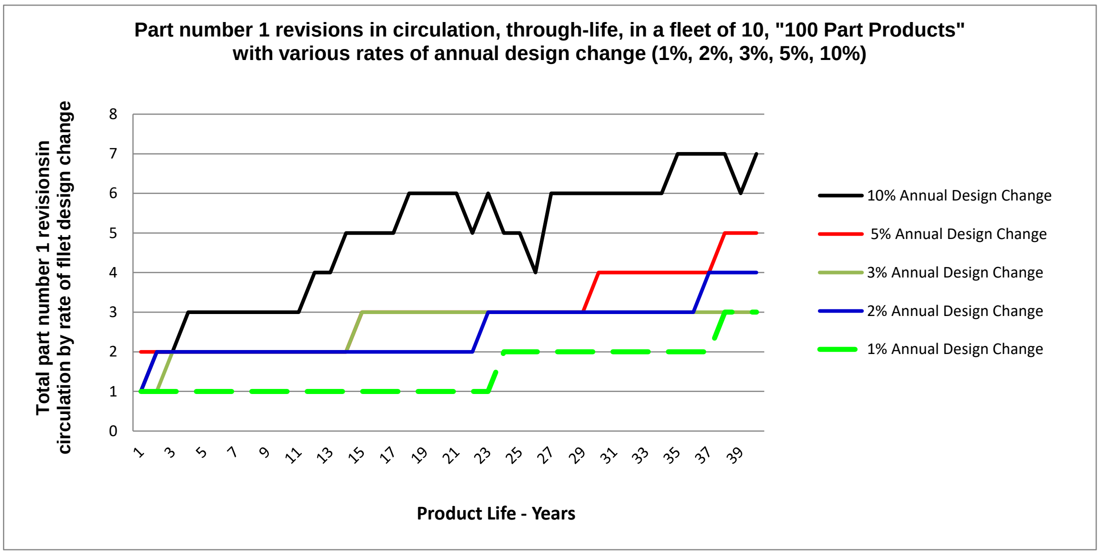


Figure 4.19: Part number 1 revisions in circulation, through-life

4.4.8 Modelling Summary

While the concept of a fleet of ten "100 part products" is a significant simplification of real world scenarios, the model was able to demonstrate the design divergence observed by industry specialists in fleets of civil aircraft. It also helped to explain the design variations observed across product fleets in other HVLL products.

It was found that when the level of through-life design change was set at 1%, the model showed a gradual growth in design divergence that reaches 40% to 50% after 40 years. The modelling approach undertaken in Phase One thus appears to confirm the design divergence concept and quantify the rates of annual design change required to achieve the parameters observed.

The Phase One model has enabled an important concept to be identified that describes the design behavior exhibited by product fleets. As a consequence the model has helped to generate a greater understanding of the complex information issues involved in through-life product management. This insight will help to support the management techniques, processes and ICT systems necessary to support the evolution of future product management strategies.

As a consequence, the modelling complies with the scientific method which can be summarised by the four following essentials: an initial observation and description of a phenomenon or group of phenomena; second, the formulation of a hypothesis to explain the phenomena; third, the use of the hypothesis to predict quantitatively the results of new observations; and finally, the use of an independent experiment to test the phenomena (Cook 2003). A comparison of the results for each model is provided in Table 4.1

Annual Design Change Rate	Divergence After 40 Years	Percentage Variation	Parts remaining unchanged
10	75% and 90%.	8% and 16%	0
5	75% and 85%.	5% and 13%	10% and 20%
3	65% and 80%.	10% and 15%	25% and 35%
2	60% and 70%.	6% and 13%	42% and 47%
1	40% and 50%.	5% and 10%	65% and 72%

Table 4.2: Comparison of modelling results

4.4.9 Implications of Modelling

Maintenance engineers spend as much as 50% of their time searching for and disseminating the information they need for design, diagnosis and rectification processes (Robinson 2010, EU TATAM Project and Gordon 2011). The maintenance of HVLL products is an information intensive process and the output of the model illustrates the complex nature of design variation that maintenance engineers must manage to complete their tasks. While some manufacturers have recognised the design diversity in their manufactured products by offering product centric aftermarket support services, the maintenance of accurate through-life design information in complex, multi stakeholder industries remains a challenge.

For complex products, the product change process spans many organisations. While the need for closer industry integration has been proposed by a number of management disciplines, such as PLM and SCM, meaningful progress has yet to be achieved (Hadaya 2012 and Boehme et al 2012). The attainment of closer integration will require new types of data standard that enable organisations to respond to the era of the Internet of Things and the phenomenon of “Big Data” (Friess 2012). It is inevitable that the current “point solutions” approach to meeting the enterprise architectural requirements will need to evolve to enable organisations to collaborate more easily across industry sectors as “virtual enterprises”.

The model discussed in this chapter seeks to contribute to a deeper understanding of the nature of design variation observed through-life in fleets of HVLL products. To promote discussion of the issues that need to be addressed “Ten Principles” have been proposed (Morris et al 2014). These are fully considered in Chapter 5.

Innovation drives the product design process (beginning of life phase) and continues to a lesser extent during production and operational phases (middle of life phase). Design changes generate significant volumes of information that must be communicated both internally within the enterprise but also externally to customers and suppliers.

The rationale for the investigative approach undertaken to support this thesis was based on the relationship that exists between the volume of information that needs to flow (both within and between organisations) through the supply chain and the number of design modifications that are undertaken as part of the product change process. To quantify the volumes of information that need to flow a number of organisations were asked to estimate the level of design change that their products experience through-life. Having established a number of scenarios from industry specialists a quantitative model was developed to validate the opinions expressed. This “early probe” investigation indicates that the use of more sophisticated modelling techniques may help to further this field of research.

4.5 Model Limitations

While the model was able to support a sample size of 1,000 parts modelled over 40 years, one of the model’s limitations relates to the reduced number of parts used versus a real product which might have hundreds of thousands of parts. In addition all parts face an equal probability of modification. A real product would have modification programmes targeted in a coordinated way at specific product sub systems which would lead to various rates of design change across its constituent parts. For example, software and electronics are likely to experience higher modification rates than major structural assemblies.

Furthermore, it is important to highlight that the analysis is based on a two-dimensional perspective that considers part number (design) changes over time; however, the management of through-life design change uses multi-dimensional information that includes:

- Information on a product's structure that identifies how parts physically relate to each other. For example, parent/child information that enables parts to be related to higher level sub-assemblies and assemblies (Ullah et al 2017). This information can be used to support decision-making regarding whether parts or assemblies are compatible with the particular configuration of end products;
- Information that indicates how parts are related by modifications, design changes or revisions helps to identify alternative spares when inventory is exhausted;
- System information that enables engineers to view how parts are related by function such as braking, control, power, instrumentation and so on;
- Information on relationships between different stages of a product's design: as intended, as manufactured, or as maintained.

Additional features of the model that prevented further detailed analysis related to the limitations of Microsoft Excel. The products and their parts were created in the worksheets of a spreadsheet workbook. Each product fleet was created in a worksheet as a series of arrays - 100 rows for the parts with 40 columns for the years. Each worksheet had ten arrays and additional computations and manipulations of the model results was undertaken in separate worksheets. While Excel offers many sophisticated features, this approach to modelling offered little flexibility for adjusting the number of parts allocated to each product or the number of products in the fleet. Further analysis would require a more sophisticated tool (Flath and Stein 2018).

4.6 Chapter 4 Summary

The purpose of the modelling described in this chapter seeks to replicate the observations of industry specialists that indicated that the designs of HVLL products diverge as the result of through-life design change. A variety of rates of design change were modelled and the rate that most closely matched the industry observations was 1%. In addition, the modelling illustrates the growth of the volume of information required to manage product fleets as they age. The design divergence phenomenon enables a greater understanding of why the labour costs associated with information search are considered significant. Finally, part number analysis is undertaken to illustrate numerical behavior of the model at the part level.

Chapter Five: Future Design Management

5.1 Future Problem Solving

The area of concern this research has set out, relates to the need to improve through-life support for HVLL products in the context of adaptations to industry structure and practice. While the capabilities of networked ICT have grown, there remains a need to improve support to through-life design management processes. To problem solve in this context requires a frame of reference that helps individuals to develop a mental structure of the issues that they must consider when developing solution options (Cook et al, 2003; Amitabh & Sahay, 2008).

5.1.1 Design Divergence Concept

The design divergence identified by the Phase One modelling can be considered as an emergent property of a fleet of complex products as this behavior is not evident when one considers the designs of a single HVLL product instance. This provides evidence that a fleet of products can be viewed as a system. (Checkland, 1988).

The initial impetus for the work arose from the need to improve the configuration management of train design information. Design information includes the relationships that exist between parent and child assemblies as well as earlier and subsequent design variants. The information must enable identification of those items produced under manufacturing batch or production run and then by individual product instances where this is appropriate.

To enable organisations to operate more effectively in their respective roles the accessibility of design information to all product stakeholders. The challenge of undertaking the role of 'design authority' rests on two capabilities. The first is the possession of technical expertise in the 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. Design engineers who participate in collaborative problem solving require design information that is accurate and not impaired by updates that are triggered by design changes.

5.1.2 Ten Principles

It is apparent that the ability of organisations to operate effectively is increasingly defined by their ability to manage information. There are a number of related dimensions that need to be considered: problem governance, process control, information relationships, standards, skills and the need for internal and external integration. This research proposes there is a need to promote discussion of closer alignment between through-life design management processes, ICT and the management models used to guide decision making might be achieved (Erol 2017). A workshop held by a major train manufacturer on 20 - 21 Sep 2011 was established to identify key steps required to improve configuration management of design information. The company had identified that the Institute of Configuration Management listed 112 process requirements. It had also reviewed ANSI-649, which was product focused, similar to ISO 10007 and listed 42 high level principles. The company concluded that a more concise list of 10 principles was required and made some proposals. However, the author reviewed the 10 points the company proposed and concluded that they were insufficiently precise or sufficiently encompassing to support meaningful progress. This created a requirement for the Ten Principles proposed by this research, that more precisely address the different perspectives of the overall nature of the product change management challenge. They are intended to provide a world view appreciation of the prominent issues. Taken individually they are not new, however, when viewed collectively they represent an integrated approach to provide greater clarity on the nature and magnitude of the challenges to be addressed. The Ten Principals are provided below and the underpinning evidence to support each one is presented in Table 5.1 (Morris et al 2015).

- **Principle One:** The business impact of inaccurate product information should be better understood and monitored by business stakeholders and shareholders.
- **Principle Two:** 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.
- **Principle Three:** Product characteristics should be designed and monitored to ensure they comply with legislation, standards and customer requirements.
- **Principle Four:** 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.
- **Principle Five:** 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.
- **Principle Six:** 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).
- **Principle Seven:** A common system of terminology (taxonomy) for product information and processes should be established and incorporated into information systems, documentation, parts and product labels.
- **Principle Eight:** 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 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.

- **Principle Nine:** 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.
- **Principle Ten:** 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.

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	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)
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	Ullah et al (2017), 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;	Mattos and Laurindo (2017), 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; 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;	Mattos and Laurindo (2017), Lucero et al (2017), 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)

Table 5.1: Ten Principles – underpinning evidence

5.1.3 Interdependencies between the Ten Principles

The through-life product management of HVLL products is a complex field that requires sophisticated problem solving techniques to rationalize the system of system challenges. However, a simple framework (heuristic) can prove to be a valuable aid to progress. The Ten Principles support the need to provide stakeholders with an integrated approach to consider the design management process. Figure 5.1 provides a hierarchical perspective of the through-life design environment with markets, society and governments at the top and with the underpinning information technology required to support through-life management at the bottom. It builds on Figure 1.1 by identifying important contextual factors.

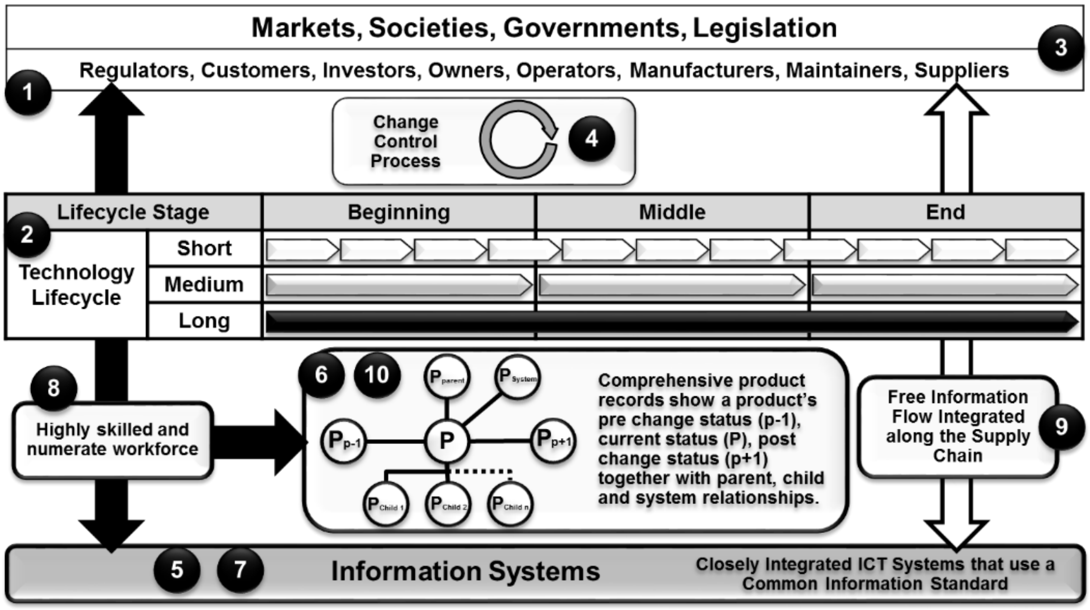


Figure 5.1: Utilisation of the Ten Principles to support improvements to through-life HVLL product design

In a complex field such as covered by Figure 5.1 precision is difficult and so it is possible only to provide a guide to the interacting factors. Nevertheless Principles One to Three predominantly address issues of design governance and are positioned in the Figure accordingly. For example Principle Three covers the need for HVLL products to be managed from a system of systems perspective. Principles Three, Four and Five have a focus on process control. Principle Six addresses the need for relational information and linkages that support, assembled structure, design change and the relationships that establish membership of a particular system. For example, where a component is a member of one or more systems, such as propulsion, braking, control, electrical or hydraulic system. Principle Seven addresses the need for standardized terminology required to support the development of a standard industry data model. Principle Nine addresses the need for integrated information flows both within and between organisations. Finally Principle Ten seeks to provide a perspective that helps people to problem solve in time.

Table 5.2 provides a tabular perspective of the prominent interdependencies that exist between the Ten Principles and therefore illustrate the integrated approach they seek to support. In a complex domain such as this one could justifiably claim that all principles have bilateral relationship with each other. However, this would not offer the sense of direction that problem solving requires.

Interdependencies between the Ten Principles		1	2	3	4	5	6	7	8	9	10
		Principle One enables	Principle Two enables	Principle Three enables	Principle Four enables	Principle Five enables	Principle Six enables	Principle Seven enables	Principle Eight enables	Principle Nine enables	Principle Ten enables
1	Principle One is supported by		X	X	X				X		X
2	Principle Two is supported by				X		X		X		X
3	Principle Three is supported by		X		X				X		X
4	Principle Four is supported by					X	X	X	X	X	X
5	Principle Five is supported by							X		X	
6	Principle Six is supported by							X	X		
7	Principle Seven is supported by										
8	Principle Eight is supported by										
9	Principle Nine is supported by							X			
10	Principle Ten is supported by				X		X				

Table 5.2: Tabular view of Interdependencies between the Ten Principles

Principle One is the most important as it enables decision makers to take a proactive approach to through-life product management by assessing the impact of inaccuracies in design information. Principle One is supported by all the other principles; however, the prominent ones are those that place an emphasis on managing or reviewing processes and information which are Principles Two, Three, Four, Eight and Ten.

Principle Two addresses the need to take a system of systems approach to through-life management. This Principle enables Principles One and Three (monitor the compliance of product characteristics) and is supported by Principles Four, Six, Eight and Ten. This addresses the need for: a single integrated change process; relational design information; skills; and, finally the ability to view design changes in the context of time.

Principle Three addresses the requirement to monitor the compliance of product characteristics. This is an important stakeholder function and so Principle Three enables Principle One. Principle Three requires a system of system perspective, single integrated change process, skilled people and the ability to view changes in time. It is therefore supported by Two, Four, Eight and Ten.

Principle Four stipulates the need for a single integrated change process. This is a concept that describes a way of creating a relationship between a product entity and its related design information, through-life from the beginning to middle and onto end-of-life. The prominent issues that would need to be addressed to achieve this are a single point of data entry, relational information, standardized terminology, skilled staff and fully integrated information flow in the supply chain – within and between organisations. This Principle Four is supported by Principles Five, Six, Seven, Eight and Nine. Principle Four enables: stakeholders to monitor impact of inaccurate information; through-life product characteristics to be monitored; products to be managed from a system of systems perspective; and the presentation of design changes in the context of time. Thus Principle Four enables Principles One, Two, Three and Ten.

Principle Five stipulates the need for a single point of data entry. This concept stems from the need to achieve ensure that the quality of data entry is consistent and complies with the required standards. Principle Five enables Principle Four and is supported by Principle Nine which refers to integration of information flows both within and between organisations.

Principle Six states the requirement for relational information. Principle Six is supported by the need for standardized terminology to enable easier ICT integration. Principle Six enables the system of system management approach, single integrated change process and also the presentation of information in a time perspective. Thus Principle Six enables Principles Two, Four and Ten.

Principle Seven requires standardized terminology and is a foundation principle because it is not enabled by others. Principle Seven enables the single integrated change process, single point of data entry, relational information and finally integrated information flows, both within and between organisations. Thus Principle Seven enables Principles Four, Five, Six and Nine.

Principle Eight is also a foundation principle because it is not enabled by others and recognizes that significantly higher skills are required to manage the complex multi-dimensional issues associated with HVLL products. Principle Eight arguably enables all the other principles, however, the prominent ones are One, Two, Three Four and Six.

Principle Nine (integrated information flow in the supply chain) predominantly enables the creation of the single integrated change process. Principle Nine requires organisations to remove or find a way through commercial and organizational barriers to information flow and is supported by Principle Seven - terminology standardization.

Principle Ten enables improved problem solving by stipulating the need to present design changes in the context of time. It is enabled by relational information, and a single integrated change processes. Thus Principle Ten is supported by Principles Four and Six and enables Principles One, Two, Three and Four. The interrelationships described above are summarized in Figure 5.2. To aid the reader, the lines that indicate the influence of one principle on another are colour. Thus the lines that show how Principle 4 (orange circle) influences other principles are also coloured orange.

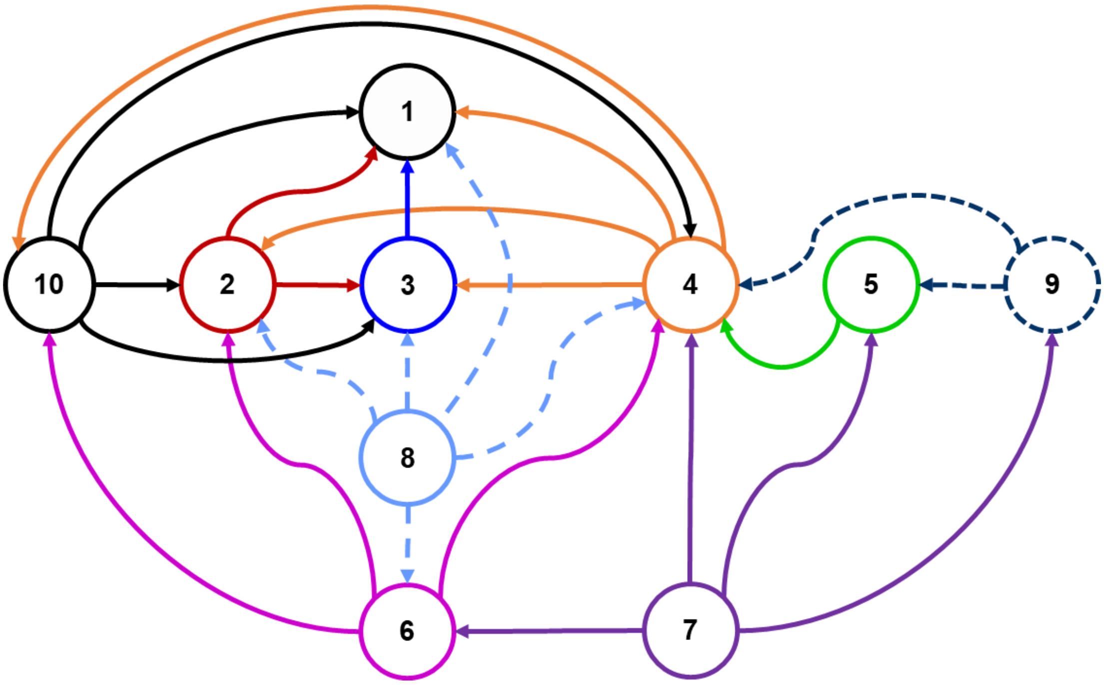


Figure 5.2: Interdependencies between the Ten Principles

5.2 Future Information Architecture

Significant volumes of information are generated during product development which are then embedded within catalogues, bills of materials, inventory, assembly, test, operation and maintenance instructions. Whenever a design is modified, there is a need to communicate relevant information to customers and suppliers. In addition the modification process creates numerous versions of the same product. While OEMs typically have a structured approach to managing the internal product design change process, many experience difficulties with communicating change information in a way that coherently supports their businesses and customers. This process is supported by a variety of software applications that are implemented to support the prominent process areas, or focus points. To improve through-life product management, the way ICT systems manage design information must be changed. Improved software application interoperability is an important priority (Corella 2013). This will require a departure from the current “point solution” architecture approach where applications are implemented to support specific functional areas of a business such as design, maintenance, manufacturing and operations. The current approach has a significant reliance on users to enter product information directly into individual systems, with little control as to the quality of that information (Boehme et al 2012; Xu and Liu 2011).

These issues would be resolved if product information could flow more easily across organisations and be made more accessible to those who needed it. One of the barriers to progress is that the software applications used to support each of the enterprise functional areas (design, manufacturing, operation, maintenance and so on) use slightly different terminology (taxonomy) and database structures (ontology). As a consequence, the rich fully featured enterprise information flows that are required to make efficiency improvements remain out of reach. To overcome the lack of close semantic alignment between different software products requires data mapping and integration activity that increases the time and costs of implementing enterprise ICT (Erol 2017).

If ICT systems were more closely integrated, the product change process would be better supported, product information flow would be improved and accuracy increased. The closer integration of systems to enable “system of systems” management would also provide improved search functionality. This requires an information architecture that utilises some kind of standard industry data model or common information structure (taxonomy/ontology). Such an architecture would enable information and knowledge to be more rapidly deployed to those who need it. So, today one might purchase a stand-alone product management related software product; however, if the ideas in this research were taken forward, it would be possible for organisations to buy software that offered the superior information management characteristics required to enable a more holistic and strategic approach to managing products through-life.

In addition, it will be possible to implement such information technology faster, cheaper and. 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 the Ten Principles is to stimulate discussions in this direction. It is envisaged that such discussions will require the collaboration of PLM/ERP and other ICT system developers, OEMs and researchers in this field.

Figure 5.3 provides a simple illustration of the applications architecture required to support the management of product information to provide through-life support. It identifies prominent business processes that require specialist information. The figure illustrates the need for significant design information reuse across organisations that manufacture and maintain products (Agaram 2017; Ferreira et al 2017). This is represented by the need for core product information and processes under each distinct activity. For example, one can consider the lifecycle management process from the perspective of the "bill of materials" (BOM) which is the list of components and parts required to support product creation. Conventionally there are usually considered to be two prominent "BOMs" the engineering BOM (EBOM) produced by designers and the manufacturing BOM (MBOM) used by production. However, procurement teams also need a list of components that need to be bought from suppliers and there is a need for a list of components and parts required to provide maintenance support. As a consequence, there are many different BOMs each required for different activity areas.

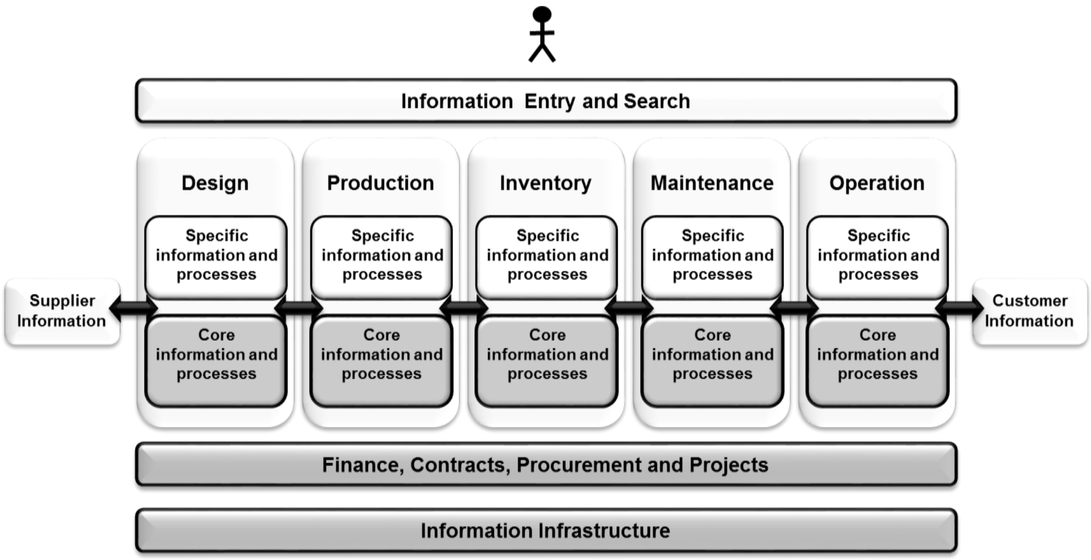


Figure 5.3: Potential future applications architecture.

The simplified perspective in Figure 5.3 presents five perspectives of design information. Design involves the activities required to develop a product that meets a specification or requirement. These activities include product visualization, options analysis, prototyping, testing and analysis. For complex products, the design process must consider the operational and physical interactions between different systems. For example, 3D CAD tools help to model how parts and assemblies will interact when they are assembled. Design must also consider how products will be supported and maintained.

The production process is concerned with creating a product from the designs. Production and design teams must work closely together to ensure that products are designed in a way that is consistent with the economic operation of the business and an organisation's production capabilities. Production specific activities must also consider the tooling, assembly methods, compliance testing and workflows required to deliver a finished product.

The inventory function must ensure that not only is sufficient inventory is available to support the production line but also the maintenance activity required to ensure continued operation. Inventory management requires the core product indexation information relating to each component such as part number, cost and the relationships that exist between product components as illustrated in Figures 1.1 and 5.1. The calculation of optimized inventories is achieved through complex modelling of operating scenarios. While the modelling activity and output is very specialist to the inventory management function, the inputs to this process require core product information. When relationship information is lost from the inventory systems, spares can be held in inventory yet not accessible to maintenance engineers. This situation arises because related parts cannot be identified by search functions when the relationship links are missing.

The maintenance process requires sufficient design information to support product repair instructions, tooling and testing. Ensuring that maintenance information is accurate is difficult because of the diversity in product designs. The divergence of designs described by this research illustrates the challenges engineers face when searching for information. The nature of these difficulties is illustrated by the Spaghetti Team problem solving behaviour described in Chapter 3, Figure 3.55.

Operating parameters and processes of HVLL products are often impacted by design changes, particularly when they are performance affecting. The indexing required to ensure operational information is communicated to product operators such as pilots and train drivers relies on core product information.

In summary, to achieve the 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 the closer process integration across complex organisations (West and Blackburn 2017).

To make progress there is a need to develop an improved understanding of the barriers to progress. This includes the assessment of the impact made by the effect of inaccurate information and the benefits of improvement. To facilitate such developments industries must consider the role of information in their business model. Research is required to better understand how organisations might offer through-life product management in collaboration with other organisations using a shared or pooled information environment.

5.3 Chapter 5 Summary

Chapter 5 has proposed Ten Principles to support the more effective problem solving that is believed necessary to support improvements to the through-life management of HVLL products. The key research issue identified at the outset of this investigation related to the need to improve the alignment between the design change process and underlying information systems. The Ten Principles is a framework of ideas that could help product managers navigate industry challenges associated with developing solutions. The observation of design divergence demonstrates that designs of product fleets display emergent properties that provide evidence of systemic properties. The phenomenon of design divergence represents an additional dimension to this field. One benefit that might arise from the application of the Ten Principles is the development of a new breed of information technology that is developed to a common information standard.

Chapter Six: Validation of the Ten Principles

6.1 Validation Model

To progress this research and validate some of the concepts proposed within the Ten Principles a second model was created using Matlab (a software development environment produced by Mathworks - www.mathworks.com). This was undertaken collaboratively, with additional programming expertise that created a model under the direction of the author. The intention was to provide a way to further explore in a quantitative manner the phenomena associated with design change and demonstrate the efficacy of deploying enhanced management approaches, using the Ten Principles. The specification of the scenarios to be modelled and the underpinning concepts, were the sole responsibility of the author, as was the eventual application of the model to produce the quantitative data and associated analysis presented in this thesis. The model listing is available from the Cardiff School of Engineering data storage resource associated with this thesis.

The validation model sought to increase the number of variables to the computations and enable investigation of the impact of linked changes at three levels of hierarchy, fleet, product and part. The number of fleets was thus increased from one to two with each managed by a separate workshop with independent parts list and inventory holding. An OEM master design was also added and referred to as the master parts list (MPL). This added complexity was traded-off with a reduction in the overall sample size of parts. Instead of 10 products with 100 parts (sample size of 1,000), the validation model had two fleets of 5 products, each product having 10 parts (sample size 100).

6.1.1 Scenario details

The Ten Principles seek to describe a future industrial situation (scenario) whereby up-to-date design information is able to smoothly flow through the supply chain so that it is freely available to all stakeholders and participants in the design change process. The validation model builds on the previous analysis by enabling the designs of two product fleets to be compared as they change through-life. The key feature of this model is that each fleet is maintained by a different workshop with an independent support policy in terms of inventory holdings and parts list. The master design for both fleets is maintained by the original product manufacturer also called OEM. The model can be therefore be summarised as follows:

- The model enables the examination of through-life design changes on two operating product fleets. The option exists to set the parameters of both fleets to the same value, thereby creating a single fleet of ten products. This option was used in the initial stages of this modelling regime to establish synergy with the previous modelling activities.

- A product manufacturer continually develops product enhancements which are incorporated into its OEM master design record as modifications. These modifications are then passed on to the product operators that each have a fleet of 5 products.
- Each product operator has a workshop managed with reference to a parts list and a warehouse that can be used to store spare parts as inventory;
- The product operators also have a parts list that provides a single list of the 10 parts used to maintain the product fleet. The lists are updated by the workshop - independently of the manufacturer and the other workshop.

Figure 6.1 provides a pictorial representation of the model which will be described in subsequent sections.

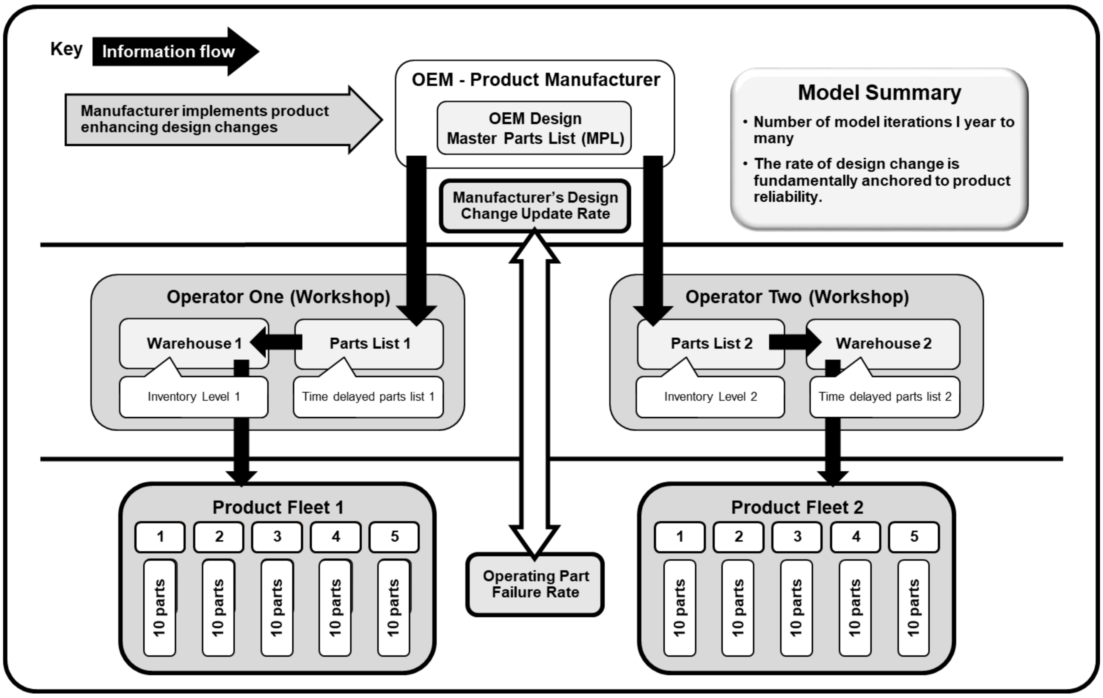


Figure 6.1: Validation Model - Structure

6.1.2 Model concept

The model incorporates the following concepts:

- The model calculates the through-life impact of design changes on two fleets of 5 operating products and each product has 10 parts. The fleets are managed by two separate operators each with their own workshop. However, setting the parameters operator one and two to the same values creates a fleet of 10 products
- The model makes calculations on an iterative basis. Each iteration represents a period of time (month/year);

- There is a two phase approach to implementing design changes to the operating products. The first phase relates to the modifications (product enhancements) the manufacturer makes to the master design record. The second phase relates to the implementation of these modifications into the operating products;
- Design changes are only incorporated into the operating products after a part has failed;
- Parts held in the initial inventory holding (if one has been set) will be at the same design standard as the starting design of each product and the initial master design record. A modification to an operating product only occurs when the inventory levels have fallen to zero;
- If there is no inventory, a part is installed at the design revision specified in the workshop's parts list;
- The period of time between the point at which the manufacturer changes the OEM's MPL and the point at which modifications are incorporated into the operating product fleets can be varied. Increasing the quantity of spares inventory delays the incorporation of modifications and so too does delaying manufacturer's updates to the parts lists.

6.1.3 Variables

The model has the following variable attributes:

- The number of cycles the model calculates can be varied from one cycle to many;
- The model can be set-up to repeat its calculations of a particular scenario from once to many times. The natural variations in data between a repeat run of the same scenario can be used to extrapolate the analysis to larger scenarios;
- The percentage probability that the manufacturer will modify each part's design can be adjusted. Manufacturer's modifications are recorded in the design master – MPL;
- The percentage probability that each part fitted to the products will fail every month can be adjusted. This is independent of the probability that a modification will be made to each part within the manufacturer's design;
- The inventory level at each workshop can be set independently and applies to all parts at each workshop. The lowest value of inventory that can be set is "1";
- The accuracy of the operators' parts lists can be varied by creating a time delay between the lists and the OEM's MPL. At the start of the simulation, the parts lists are both identical to the master design. However, if a time delay is set, the parts lists are not updated with the modifications made to the master design until the time delay is reached. For example, if the delay is set to "2", part number "1.1" would not be published in the list for two iterations (time periods/cycles) of the model. The impact of the time delay variable is to enable the creation

of a gradual degradation in the accuracy of the manuals. Updates to each workshop's parts list can be delayed independently from "1" cycle delay (lowest value) to many cycles.

6.1.4 Validation Model Operation

The model operates as follows:

- At the start of the simulation the parts listed in the manuals are the same as those listed in the manufacturer's master design record.
- For each time period, the model first implements design changes to the manufacturer's master record. Each of the ten parts is examined and modified in accordance with the probability variable set for the scenario;
- The model then looks at part one in product one and calculates whether it has failed. If it has failed it is replaced by a part from inventory. In the event there is no inventory it is replaced by a part to the specification of the parts list. If part one has not failed the model continues to the next part and repeats the process for subsequent parts before repeating the process for the next and subsequent products.

Figure 6.2 provides an illustration of the operation of the validation model as a flow chart.

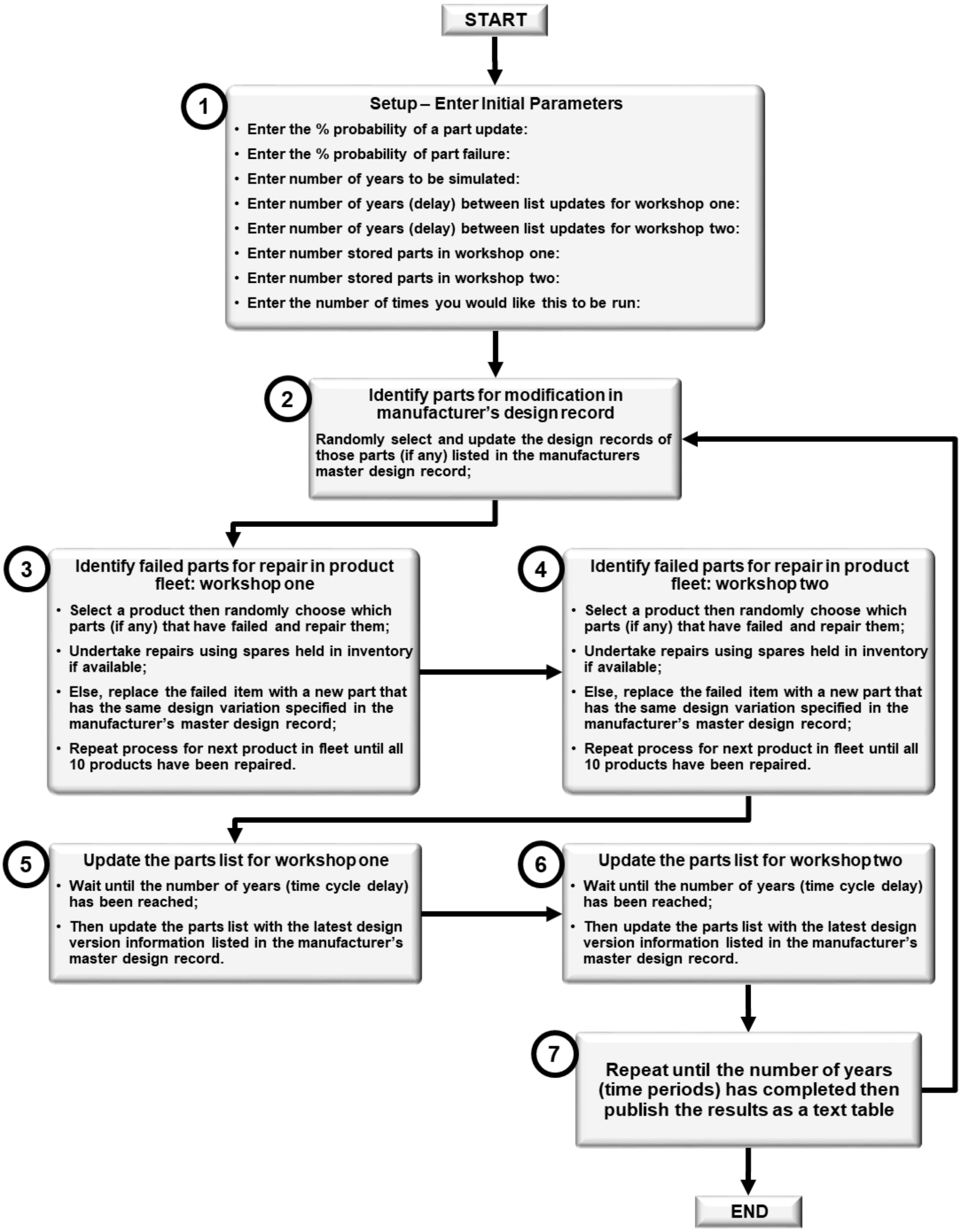


Figure 6.2: Flow diagram to illustrate the operation of the validation model

6.2 Validation Modelling

6.2.1 Overview

The model was run several times to compare the behaviour of a product fleet (P1 to P5) supported in the "supply chain of the future" by Workshop One, with a product fleet (P6 to P10) supported in the "supply chain of the today" by Workshop Two.

This comparison was achieved by providing Workshop One with access to current design information and spares at the latest modification status (parts list delayed by only one year and inventory set at one). The time delays of updates to the parts list and inventory levels for Workshop Two were then set at higher levels and an investigation conducted. The model was run four times with variables adjusted to reflect key features of the research:

- The inventory settings were adjusted to reflect implementation of design changes as identified in Figures 2.1 and 2.2 which were obtained from the NAO Modifying Defence Equipment Report (NAO 1998);
- Rates of design change were varied from 5% to 20% to reflect various levels of design change evident in different types of technology. For example structural components such as the fuselage and vehicle bodies experience very little change, yet electronic components show design change of as much as 20% per annum (industry feedback recorded in Table 3.6). Figure 3.54 also provides raw data on design change in train fleets.
- Delaying information flow from the manufacturer to the operators' parts lists reflects the current information architectures found in industry and identified in Figure 2.5;
- The "supply chain of the future" settings, reflect the aspirational nature of the US Smart Manufacturing Leadership Coalition (SMLC 2011).

Simulation	Workshop One		Workshop Two		Comments
	Parts List Delay	Inventory Level	Parts List Delay	Inventory Level	
1	1	1	3	5	Representative scenario
2	1	1	5	5	Parts list delay increased with representative inventory
3	1	1	5	10	Inventory High
4	1	1	10	3	Parts list significantly delayed with inventory low

Table 6.1: Summary of simulations

Figure 6.3 shows the through-life cumulative design change achieved by the validation model.

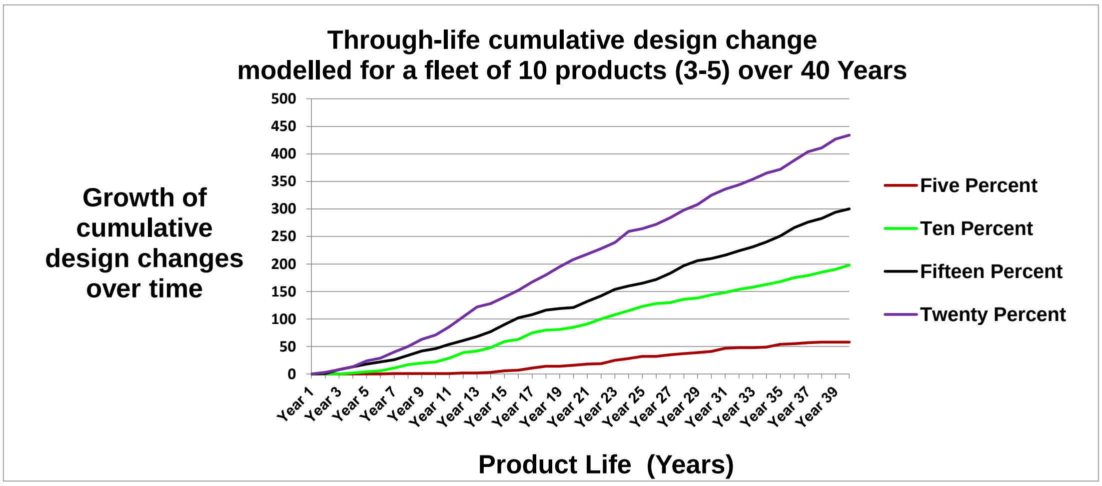


Figure 6.3: The rates of design change produced by the validation model

6.2.2 Simulation One

To expose the effect of inventory and parts list delays, different settings were used for each workshop. Within the constraints of the model, Workshop One was established as a "supply chain of the future". The parts list was set to be updated one year after design modifications were implemented by the manufacturer. This was the fastest update allowed by the model. The inventory level was also set at one, which was also the lowest setting. Both settings were consistent with the aspirations of the Ten Principles.

Workshop Two was setup as the "supply chain of today". The parts list was set to be updated 3 years after design modifications were implemented by the manufacturer and the inventory level was set at 5 years which reflected the typical lifespan of electronic items. The model was run four times with different levels of annual design change: 5%, 10%, 15% and 20%. The settings and associated simulation parameters of model are provided in Table 6.2.

	Duration (Years)	OEM's Annual Design Change (%)	Annual Through-Life Design Change (%)	W1 List Delay	W1 Inv	W2 List Delay	W2 Inv	No. Unique Parts	Total Design Changes
Run One	40	5	5	1	1	3	5	18	76
Run Two	40	10	10	1	1	3	5	21	153
Run Three	40	15	15	1	1	3	5	21	240
Run Four	40	20	20	1	1	3	5	19	313

Table 6.2: Parameters for Simulation One

6.2.2.1 Model Performance – Simulation One

To ensure the Phase One and validation modelling approaches were consistent, the ability of both models to support the process was compared. Figure 6.3 illustrates broadly linear rates of design change across the product lifecycle that is consistent with the Phase One approach. Variations in the linearity can be attributed to the smaller sample size of 100 parts versus 1,000 in Phase One and the probabilistic nature of the change algorithm.

6.2.2.2 Model Output – Simulation One

Figure 6.4 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 5% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

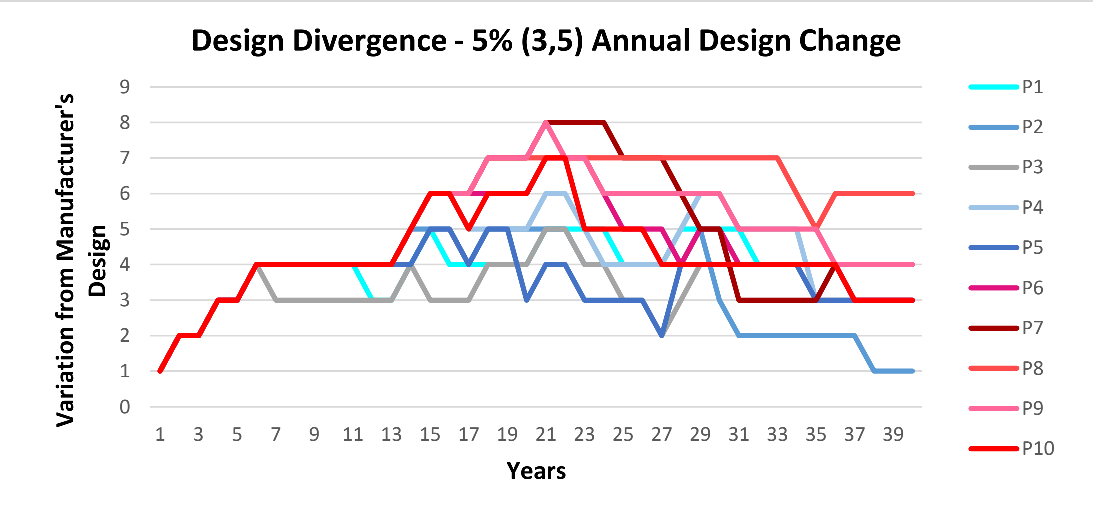


Figure 6.4: Simulation One Annual Design Change 5% (3,5)

Figure 6.5 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 10% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less/equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

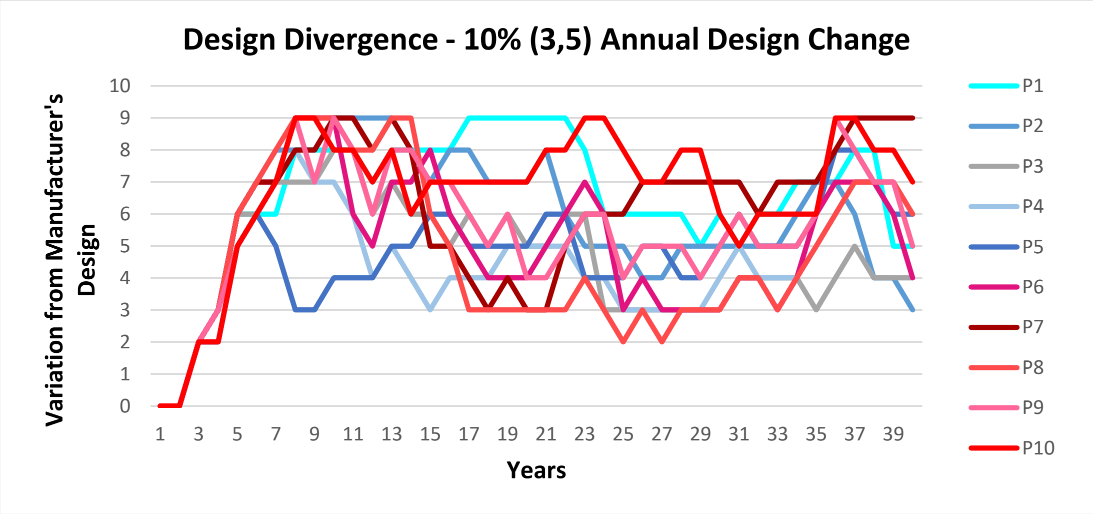


Figure 6.5: Simulation One Annual Design Change 10% (3,5)

Figure 6.6 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 15% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

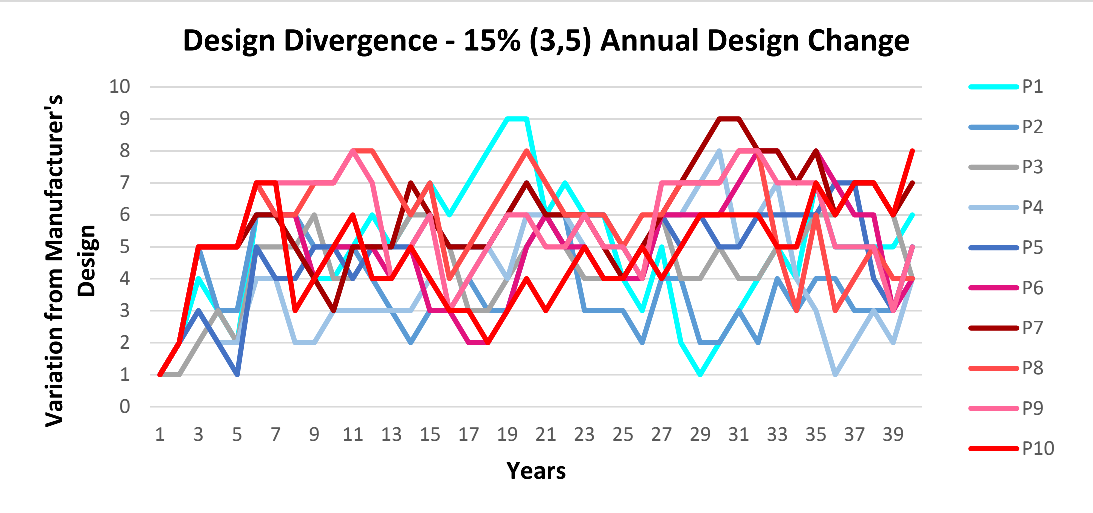


Figure 6.6: Simulation One Annual Design Change 15% (3,5)

Figure 6.7 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 20% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

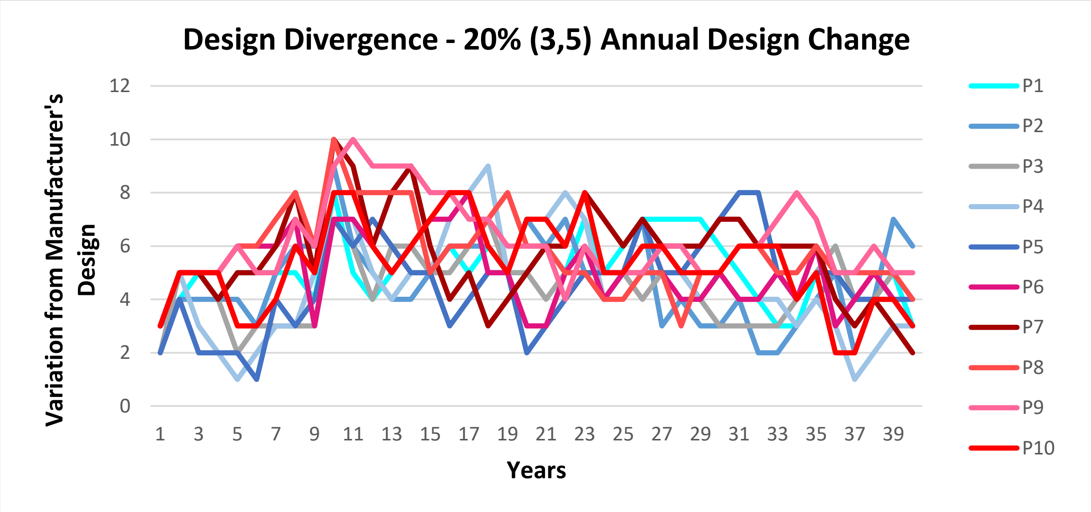


Figure 6.7: Simulation One Annual Design Change 20% (3,5)

6.2.3 Simulation Two

To expose the effect of inventory and parts list delays, different settings were used for each workshop. Within the constraints of the model, Workshop One was established as a "supply chain of the future". The parts list was set to be updated one year after design modifications were implemented by the manufacturer. This was the fastest update allowed by the model. The inventory level was also set a one, which was also the lowest level allowed. Both settings were consistent with the aspirations of the Ten Principles.

Workshop Two was setup as the "supply chain of today". The parts list was set to be updated 5 years after design modifications were implemented by the manufacturer and the inventory level was set at 5 years which reflected the typical lifespan of electronic items. The model was run four times with different levels of annual design change: 5%, 10%, 15% and 20%. The settings and associated simulation parameters of model are provided in Table 6.3.

	Duration (Years)	OEM's Annual Design Change (%)	Annual Through-Life Design Change (%)	W1 List Delay	W1 Inv	W2 List Delay	W2 Inv	No. Unique Parts	Total Design Changes
Run One	40	5	5	1	1	5	5	17	86
Run Two	40	10	10	1	1	5	5	23	170
Run Three	40	15	15	1	1	5	5	23	234
Run Four	40	20	20	1	1	5	5	23	313

Table 6.3: Parameters for Simulation Two

6.2.3.1 Model Output – Simulation Two

Figure 6.8 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 5% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

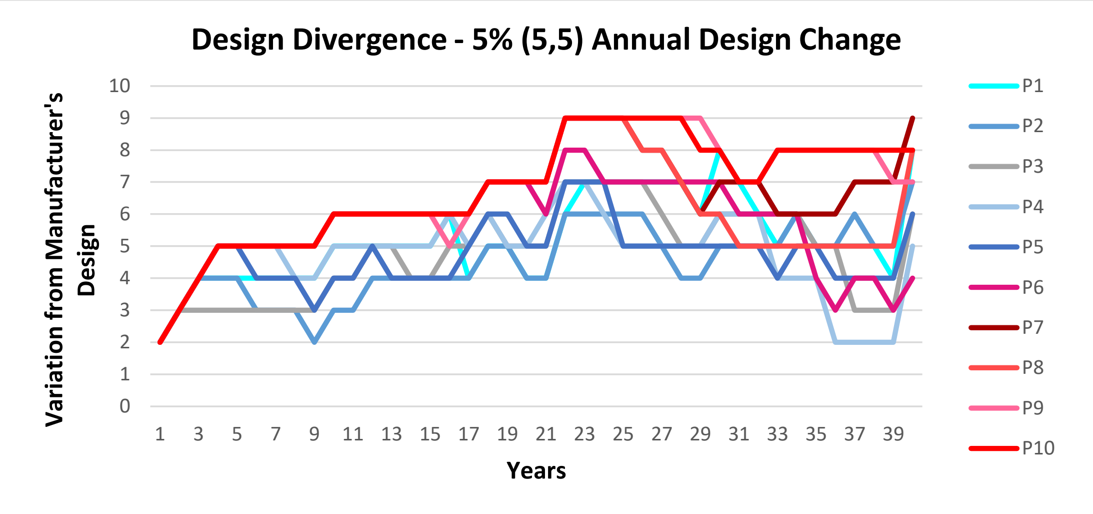


Figure 6.8: Simulation Two Annual Design Change 5% (5,5)

Figure 6.9 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 10% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

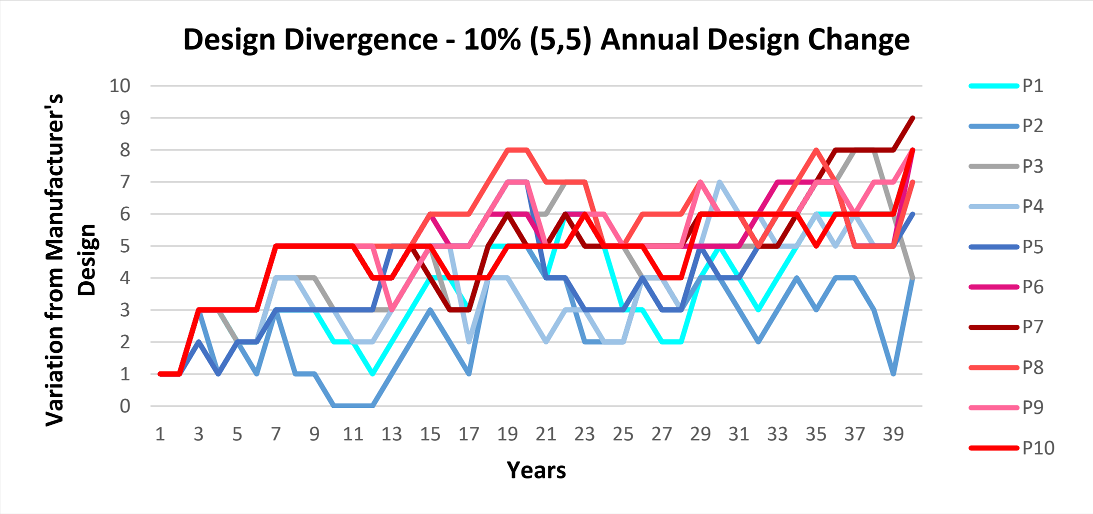


Figure 6.9: Simulation Two Annual Design Change 10% (5,5)

Figure 6.10 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 15% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less or equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

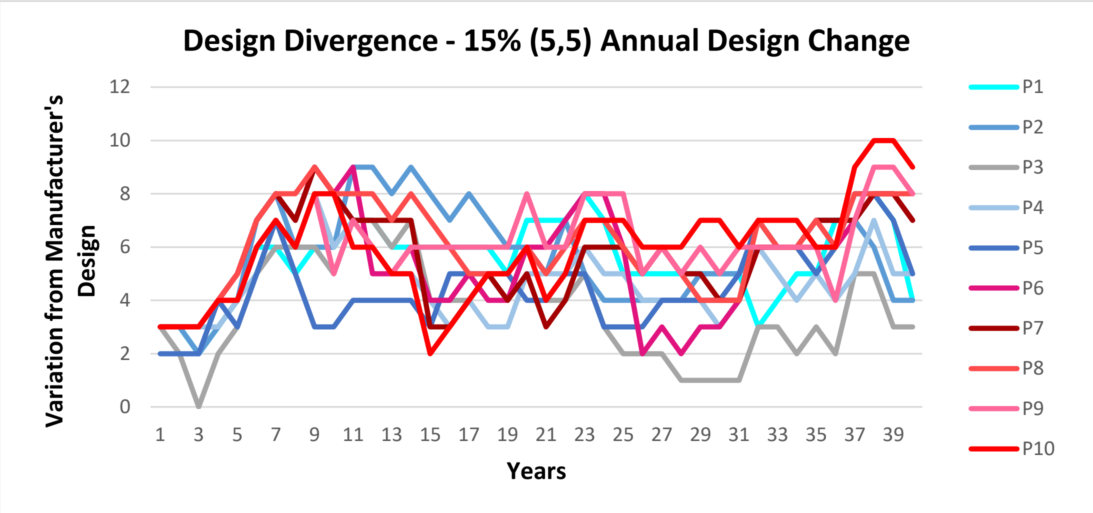


Figure 6.10: Simulation Two Annual Design Change 15% (5,5)

Figure 6.11 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 20% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

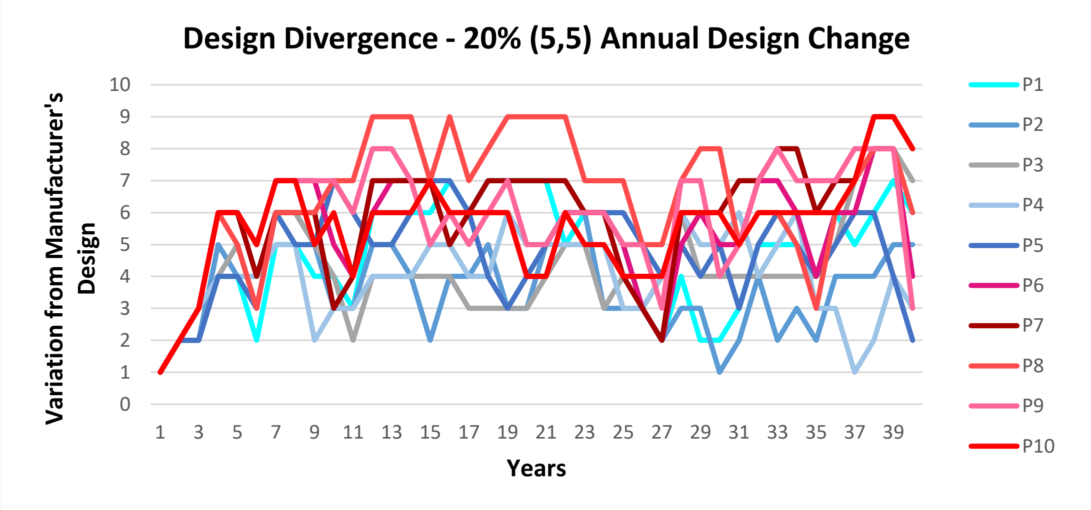


Figure 6.11: Simulation Two Annual Design Change 20% (5,5)

6.2.4 Simulation Three

To expose the effect of inventory and parts list delays, different settings were used for each workshop. Within the constraints of the model, Workshop One was established as a “supply chain of the future”. The parts list was set to be updated one year after design modifications were implemented by the manufacturer. This was the fastest update allowed by the model. The inventory level was also set a one, which was also the lowest level allowed. Both settings were consistent with the aspirations of the Ten Principles.

Workshop Two was setup as the “supply chain of today”. The parts list was set to be updated 5 years after design modifications were implemented by the manufacturer and the inventory level was set at 10 years which reflected the typical lifespan of electronic items.

The model was run four times with different levels of annual design change: 5%, 10%, 15% and 20%. The settings and associated simulation parameters of model are provided in Table 6.4.

	Duration (Years)	OEM’s Annual Design Change (%)	Annual Through-Life Design Change (%)	W1 List Delay	W1 Inv	W2 List Delay	W2 Inv	No. Unique Parts	Total Design Changes
Run One	40	5	5	1	1	5	10	17	86
Run Two	40	10	10	1	1	5	10	20	174
Run Three	40	15	15	1	1	5	10	22	227
Run Four	40	20	20	1	1	5	10	20	303

Table 6.4: Parameters for Simulation Three

6.2.4.1 Model Output – Simulation Three

Figure 6.13 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 5% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

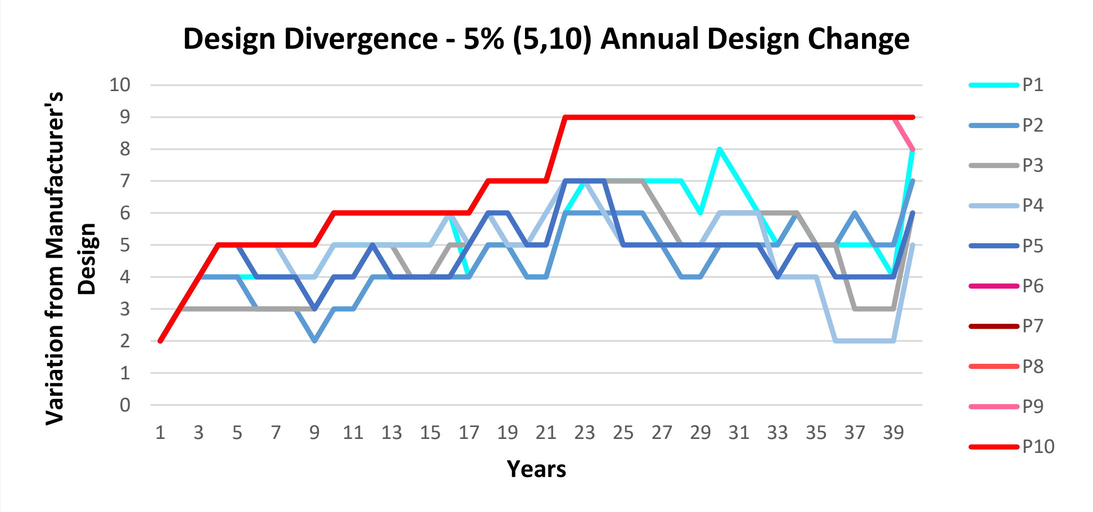


Figure 6.13: Simulation Three Annual Design Change 5% (5,10)

Figure 6.14 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 10% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

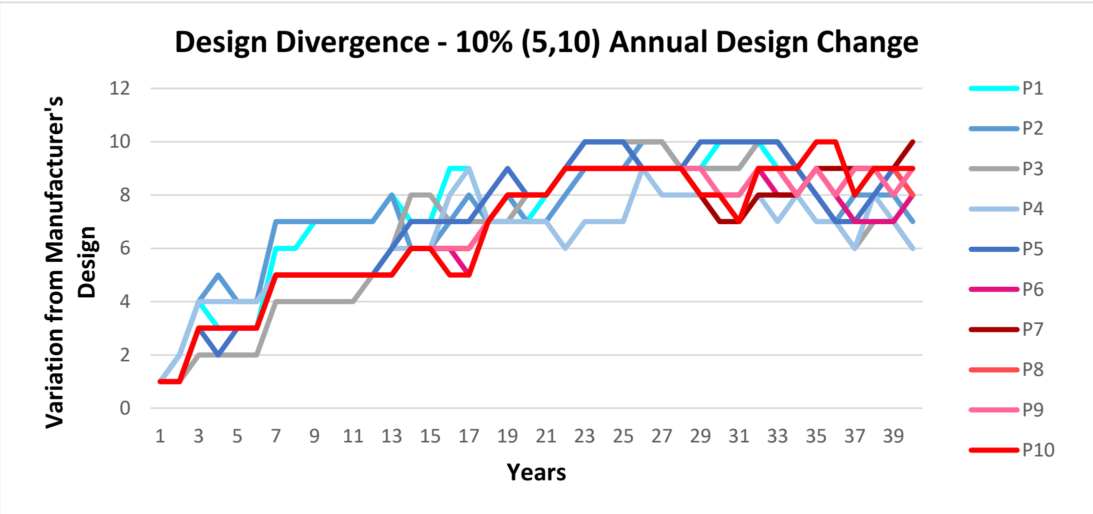


Figure 6.14: Simulation Three Annual Design Change 10% (5,10)

Figure 6.15 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 15% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

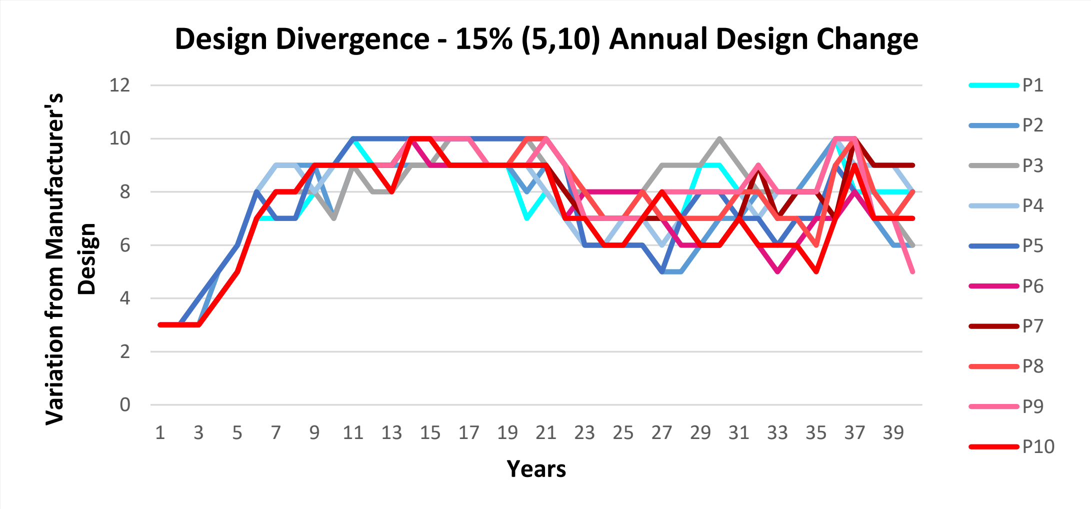


Figure 6.15: Simulation Three Annual Design Change 15% (5,10)

Figure 6.16 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 20% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit equivalent deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

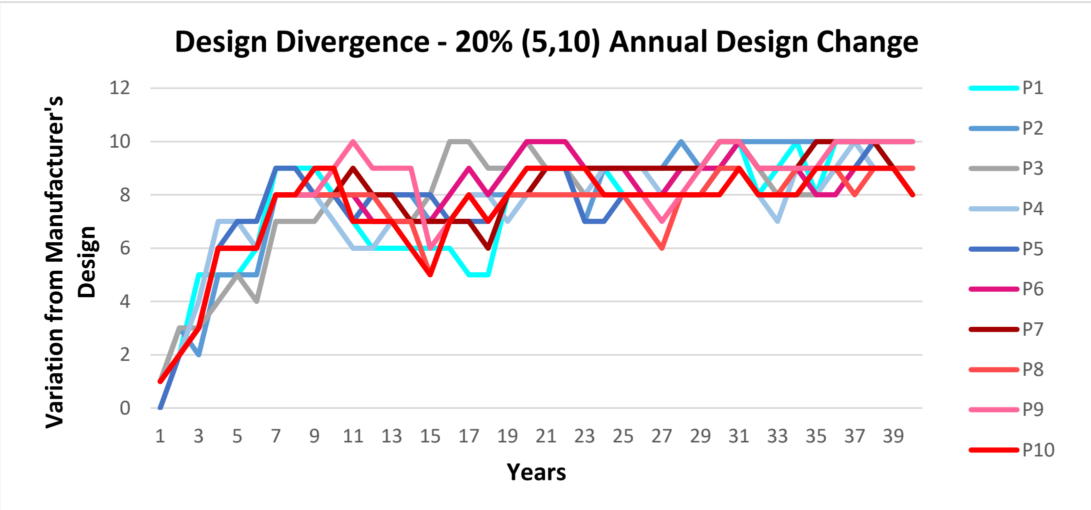


Figure 6.16: Simulation Three Annual Design Change 20% (5,10)

6.2.5 Simulation Four

To expose the effect of inventory and parts list delays, different settings were used for each workshop. Within the constraints of the model, Workshop One was established as a "supply chain of the future". The parts list was set to be updated one year after design modifications were implemented by the manufacturer. This was the fastest update allowed by the model. The inventory level was also set at one, the lowest level allowed. Both settings were consistent with the aspirations of the Ten Principles.

Workshop Two was setup as the "supply chain of today". The parts list was set to be updated 10 years after design modifications were implemented by the manufacturer and the inventory level was set at 3 years, which reflected the typical lifespan of electronic items.

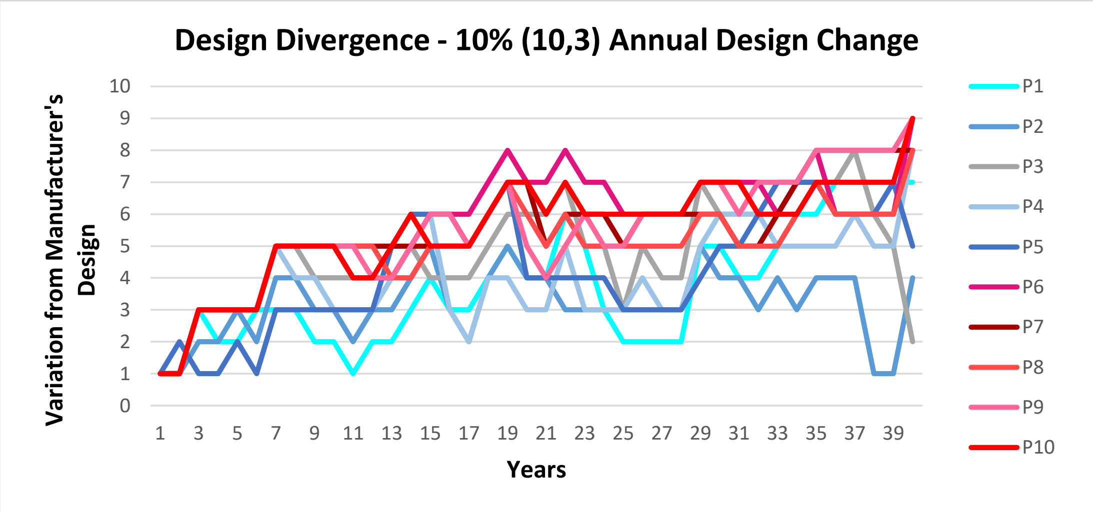
The model was run four times with different levels of annual design change: 5%, 10%, 15% and 20%. The settings and associated simulation parameters of model are provided in Table 6.4.

	Duration (Years)	OEM's Annual Design Change (%)	Annual Through-Life Design Change (%)	W1 List Delay	W1 Inv	W2 List Delay	W2 Inv	No. Unique Parts	Total Design Changes
Run One	40	5	5	1	1	10	3	17	86
Run Two	40	10	10	1	1	10	3	22	171
Run Three	40	15	15	1	1	10	3	22	228
Run Four	40	20	20	1	1	10	3	20	317

Table 6.5: Parameters for Simulation Four

6.2.5.1 Model Output – Simulation Four

Figure 6.16 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 5% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by the "supply chain of today". (Workshop Two). The results show that Products 1 to 5 (Workshop One) exhibit significantly less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.



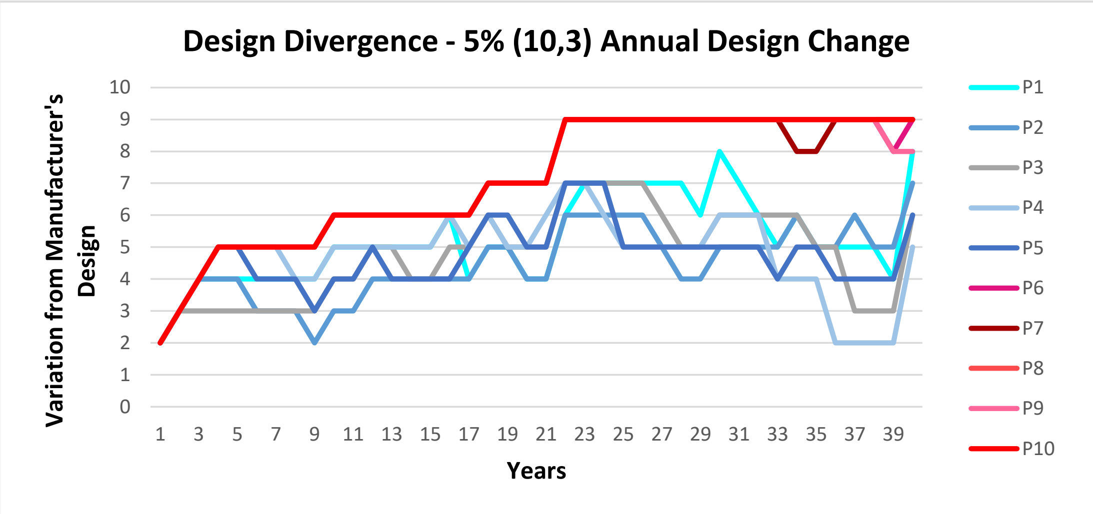


Figure 6.16: Simulation Four Annual Design Change 5% (10,3)

Figure 6.17 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 10% per annum. Products 1 to 5 (blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (red/pink) were supported by the "supply chain of today". (Workshop Two). The results show that Products 1 to 5 (Workshop One) exhibit significantly less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

Figure 6.17: Simulation Four Annual Design Change 10% (10,3)

Figure 6.18 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 15% per annum. Products 1 to 5 (blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit less deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

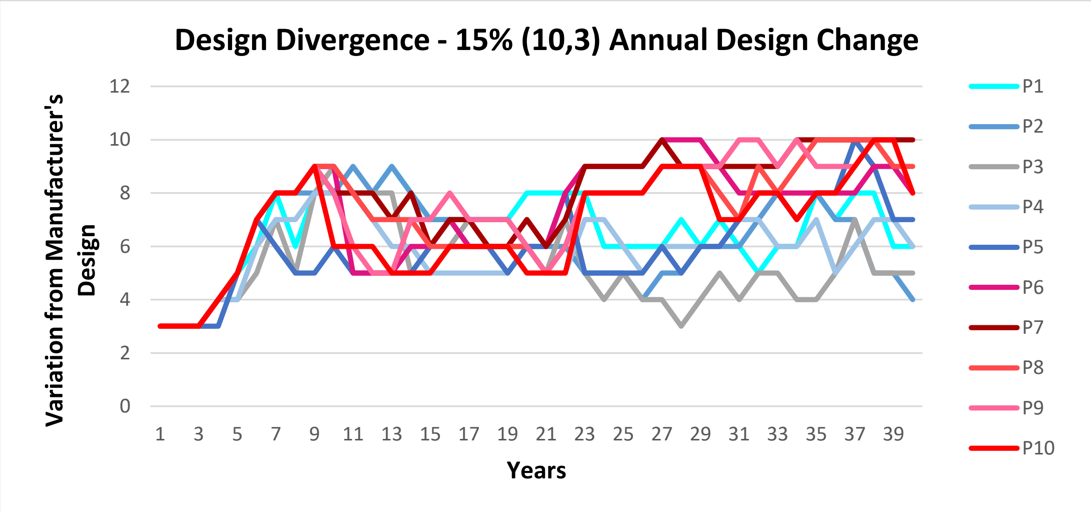


Figure 6.18: Simulation Four Annual Design Change 15% (10,3)

Figure 6.19 illustrates how the designs of each product vary in relation to the manufacturer's design with design change set at 20% per annum. Products 1 to 5 (P1 to P5 and coloured blue/grey) were supported by the "supply chain of the future" (Workshop One). Products 6 to 10 (P6 to P10 and coloured red/pink) were supported by (Workshop Two) the "supply chain of today". The results show that Products 1 to 5 (Workshop One) exhibit deviation/ divergence from the manufacturer's design compared with Products 6 to 10.

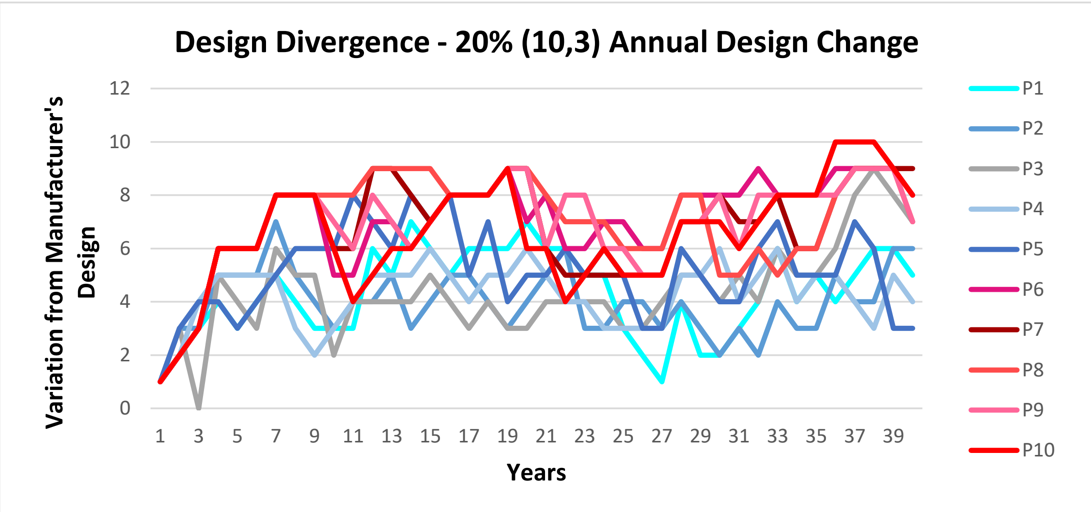


Figure 6.19: Simulation Four Annual Design Change 20% (10,3)

6.3 Analysis of Results

6.3.1 Design Divergence

Different settings were used for each workshop to expose the effect of inventory and parts list delays. The four simulations were each established to demonstrate the design advantage provided to the first product fleet (Workshop One - P1 to P5). The design advantage is represented in the results by lower levels of design divergence between the first product fleet and the manufacturer's design. It must be stressed that the statistical nature of the analysis means that high volumes of information are generated which cannot be presented in a meaningful way in this report. The results presented provide an illustration taken in time.

The simulation settings aimed to reduce design advantage for the second product fleet (P6 to 10) by increasing both the inventory levels and the time delays incurred before the parts list was updated. These settings reflect the evidence of the current situation in industry identified in the literature review and industry investigation. Due to the mathematics of the model, the modelling impact of increasing inventory and parts list delays is similar, that is to delay design modifications reaching implementation on products. However, the effect of inventory only delays the flow of information while inventory is held. Delays of information to the parts lists is sustained for the duration of the simulation. The differential effect of these variables is to increase the design variation between one product fleet and the other.

The results of the simulations showed that while the first product fleet exhibited lower levels of design divergence from the OEM design than the second, the overall picture was mixed with a number of charts showing equivalent divergence between the first and second product fleet and the manufacturer's design. The results are provided in Table 6.6.

Simulation	Workshop Two		Annual Design Change %	Deviation of Product One to 5 versus 6 to 10 versus Manufacturer's Design	Comments
	Parts List Delay	Inventory Level			
1	3	5	5	Compared to manufacture P1 to P5 show less divergence than P6 to P10	Representative scenario
			10	Compared to manufacture P1 to P5 show marginally less/equivalent divergence with P6 to P10	
			15	Compared to manufacture P1 to P5 show equivalent divergence with P6 to P10	

Simulation	Workshop Two		Annual Design Change %	Deviation of Product One to 5 versus 6 to 10 versus Manufacturer's Design	Comments
	Parts List Delay	Inventory Level			
			20	Compared to manufacture P1 to P5 show equivalent divergence with P6 to P10	
2	5	5	5	Compared to manufacture P1 to P5 show marginally less divergence than P6 to P10	Parts list delay increased with representative inventory
			10	Compared to manufacture P1 to P5 show marginally less divergence than P6 to P10	
			15	Compared to manufacture P1 to P5 show marginally less divergence than P6 to P10	
			20	Compared to manufacture P1 to P5 show marginally less divergence than P6 to P10	
3	5	10	5	Compared to manufacture P1 to P5 show significantly less divergence than P6 to P10	Inventory high compared with parts list delay
			10	Compared to manufacture P1 to P5 show equivalent divergence than P6 to P10	
			15	Compared to manufacture P1 to P5 show significantly less divergence than P6 to P10	
			20	Compared to manufacture P1 to P5 show significantly less divergence than P6 to P10	
4	10	3	5	Compared to manufacture P1 to P5 show significantly less divergence than to P6 to P10	Parts list significantly delayed with inventory low
			10	Compared to manufacture P1 to P5 show significantly less divergence than P6 to P10	
			15	Compared to manufacture P1 to P5 show less divergence than P6 to P10	
			20	Compared to manufacture P1 to P5 show less divergence than P6 to P10	

Table 6.6: Summary of simulation results

The reason for the lack of a clear and compelling difference between the performance of the designs of both the first and second product fleets could be for several reasons. Firstly statistical variation – it could be that significantly more data is required to detect an effect. Secondly, both workshop designs were measured against the latest version of the manufacturer's design as it evolved over the 40 year simulation. The evolving version of the manufacturer's design was in itself a moving target but nevertheless represented a common reference point for both product fleets. Consideration of the various factors at play in the simulation identified that:

- Increasing inventory levels held the design of the second product fleet closer to the original manufacturer's design that existed at the start of the simulation;
- Increasing the time delay incurred before parts were updated in the parts list also held the design of the second product fleet closer to the original manufacturer's design. The parts list delay lasted for the duration of the simulation;

Setting delays to the parts lists and increasing the inventory slowed the level of change to the second product fleet, the analysis shows the degree of divergence between the manufacturer's design and the two product fleets.

6.3.2 Part Number Two Analysis

To develop a deeper understanding of how the model operated, an analysis was undertaken of the design changes made to "part number two" across the four simulations. This included an examination of:

- When in the product lifecycle design changes were made;
- How design changes were implemented, for example consecutively or with jumps in the sequence of revisions or modifications.

This analysis is summarized in Table 6.7 and is based on data provided at the end of this thesis.

Workshop Two (Fleet 2) Simulation Settings – Parts List Delay and Inventory		**20%**		**15%**		**10%**		**5%**	
		Fleet 1 (Future)	**Fleet 2 (Today)**	**Fleet 1 (Future)**	**Fleet 2 (Today)**	**Fleet 1 (Future)**	**Fleet 2 (Today)**	**Fleet 1 (Future)**	**Fleet 2 (Today)**
3-5	First Change	2 Yr 3	1 Yr 8	2 Yr 11	2 Yr 13	1 Yr 7	1 Yr 10	2 Yr 23	1 Yr 28
	Two jumps	2	7	6		4	4		1
	Three Jumps	2	2	1	9				1
	Four Jumps	2	1						
	Five Jumps			1	1				
	Six Jumps		1						
	Seven Jumps	1							
5-5	First Change	2 Yr 12	1 Yr 15	1 Yr 8	2 Yr 11	1 Yr 23	1 Yr 29	1 Yr 25	1 Yr 31
	Two jumps	7	6	4	7	3	2	2	1
	Three Jumps	3	5	3			1		
	Four Jumps								
	Five Jumps								
	Six Jumps								
	Seven Jumps								

	First Change	2 Yr 3	1 Yr 9	1 Yr 23	1 Yr 25	2 Yr 2	1 Yr 28	1 Yr 25	-
	Two jumps	8	6	2	3	2		2	
	Three Jumps	1	1		1	2	2		
5-10	Four Jumps	1	4				2		
	Five Jumps	1							
	Six Jumps								
	Seven Jumps								
	First Change	2 Yr 11	2 Yr 21	1 Yr 7	2 Yr 10	1 Yr 22	1 Yr 31	1 Yr 25	-
	Two jumps	5	1	4	8	3	4	2	
	Three Jumps	3		1					
10-3	Four Jumps			3					
	Five Jumps		5						
	Six Jumps								
	Seven Jumps								

Table 6.7: Simulations 1 to 4 - Part Number Two Design Changes

While taking a pure focus on “part number 2”, offers a narrow representation of a much broader body of data, important observations can nevertheless still be made about the nature of the design changes arising across the four simulations.

From the Part Number Two results presented in Table 6.7 (analysis of four separate simulations) it is possible to gain a sense of the challenges faced by a large organisations (product operator or manufacturer providing support) when managing a portfolio of product fleets. Such a scenario could be used to envisage the approach organisations might take in the future to managing product design information. The limitations of currently available technology are such that today, organisations are unable to easily take a portfolio perspective, as is represented by Table 6.7, of the designs for which they are responsible. If this capability were available, the design information and knowledge would be accessible would have the potential to transform the management of resources.

Furthermore, the variation in change rates presented in Table 6.7 can also be used to envisage how the design implications arising from the combined use of different technologies might be better managed. For example as evidenced by the NAO Modifying Defence Equipment Report (NAO 1998), industry feedback received (Table 3.6) and raw data gathered (Figure 3.54).

From the data in Table 6.7, it can be seen that as the design rates of change reduce from 20% per annum in the first, left hand column to 15%, 10% and then 5%, the first design changes are made increasingly later in the product lifecycle. Furthermore, as might be expected, design changes are implemented earlier to Fleet 1 (products P1 to 5) which represents the “supply chain of the future”, than changes are made to Fleet 2 products (P6 to

10). The delayed design changes to Fleet 2 products arises due to the information delays in the passage of manufacturer's design information to the parts lists and increased inventory levels that were set.

- The inventory settings were adjusted to reflect implementation of design changes as identified in Figures 2.1 and 2.2 which were obtained from the NAO modifying defence equipment report (NAO 1998);
- Rates of design change were varied from 5% to 20% to reflect various levels of design change evident in different types of technology. For example structural components such as the fuselage and vehicle bodies experience very little change, yet electronic components change show design of as much as 20% per annum (industry feedback recorded in Table 3.6). Figure 3.54 also provides raw data on design change in train fleets.

The incidence of non-sequential design changes are summarized in Table 6.8. These arise in the model due to the interactions between the manufacturer's design, inventory levels and delays in information being published to parts catalogues. In industry non-sequential implementation of modifications might arise from decisions that prioritize some design changes/modifications over others or where there are compatibility issues that require a series of modifications to be skipped. Some modifications may be deemed non-essential for example.

Workshop Two (Fleet 2) Simulation Settings – Parts List Delay and Inventory	20%		15%		10%		5%	
	Fleet 1 (Future)	Fleet 2 (Today)	Fleet 1 (Future)	Fleet 2 (Today)	Fleet 1 (Future)	Fleet 2 (Today)	Fleet 1 (Future)	Fleet 2 (Today)
3-5	7	11	8	10	4	4	-	2
5-5	10	11	7	7	3	3	2	1
5-10	11	11	2	4	4	4	2	-
10-3	8	6	8	8	3	4	2	-

Table 6.8: Simulations 1 to 4 - Part Number Two Non-Sequential Design Changes

6.3.2.1 Part Number Two Analysis: Workshop Two - Parts List Delay 3, Inventory 5

Figure 6.20 provides a graphical illustration of the part number 2s for both product fleets over 40 cycles. The simulation was run with a three cycle delay to parts list updates and an inventory level set at five for Workshop Two (Fleet Two - red themed legend). Workshop One (grey themed legend) had no inventory and received immediate updates to the parts list from the OEM. The blue line represents the OEM master parts list which always leads the revision status. This illustrates that information from the OEM is always the most current and therefore leads other design information elsewhere in the supply chain. Thus the product designs and parts information in the product fleet lag that of the OEM. Figure 6.20 shows that modifications to Fleet Two products are delayed until year 8 and setting aside statistical variation, a contributory factor will have been the delays to design changes established by the parts list and inventory settings.

The jump modification (pink – Workshop Two) shows a revision leap of six (2.00 to 2.06 in year 16) that is consistent with the analysis presented in Tables 6.7 and 6.8. This might be representative of a reliable electronic component that has become obsolete after many years and needs to be updated to the latest standard of technology. The flagged OEM delay modification (grey - Workshop One) shows a significant OEM delay of 7 (2.00 to 2.07 in year 29) this is an exception.

The designs of the product fleets on the whole closely match that of the OEM because of the minimal inventory settings and delays to parts list information. A final point to note is that this simulation starts with a single part number 2 but ends with four, part number 2 variants (2.07, 2.08, 2.09 and 2.10). This represents a fourfold increase in the volume of design information that engineers must search through to identify the part they require. These part number variants are the keys that enable the organisation of other categories of information required to manage the product fleets through-life (design, manufacture, inventory and maintenance) amongst others. If the impact of missing succession links (Figures 1.1 and 5.1) are also considered then it becomes easier to understand the amount of time spend engineers spend searching for information.

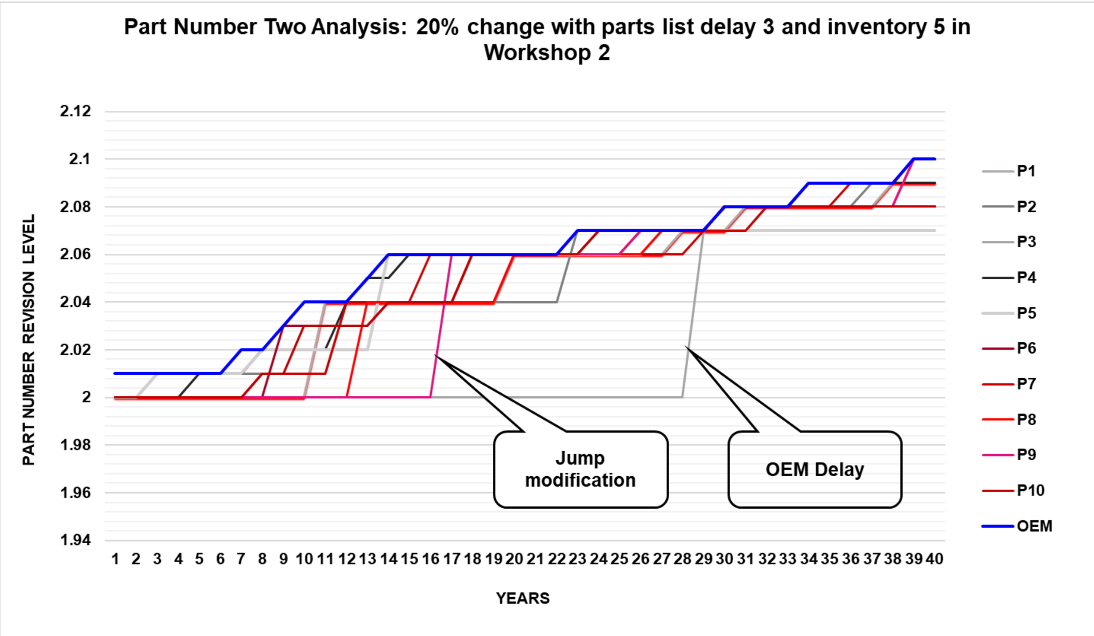


Figure 6.20: Part number 2 analysis with 3 cycle delay to parts list updates and inventory set at 5 for Workshop Two

6.3.2.2 Part Number Two Analysis: Workshop Two - Parts List Delay 5, Inventory 5

Figure 6.21 illustrates the part number 2s for both product fleets over 40 cycles. The simulation was run with a five cycle delay to parts list updates and inventory set at 5 for Workshop Two (red themed legend). Workshop One (grey themed legend) had no inventory and immediate updates to the parts list from the OEM. The blue line represents the OEM master parts list. Figure 6.21 shows that modifications to Fleet Two products are delayed until year 16, a 5 year delay versus Workshop One Fleet One products and this is caused by the parts list and inventory settings.

In this simulation, the statistical variation meant that there were no OEM updates until cycle 12, but in that cycle, two products in fleet 1 (Workshop One) received the latest revision. As expected the product designs and parts information in the product fleet lags that of the OEM. The identified jump modification (grey - Workshop One) shows a revision leap of three (2.02 to 2.05 in year 19) in product fleet one that is consistent with the analysis presented in Tables 6.7 and 6.8.

The flagged OEM delay modification (pink – Workshop Two) shows an OEM delay of 1 (2.05 to 2.06 in year 35). A final point to note is that this simulation starts with a single part number 2 but ends with two, part number 2 variants (2.06 and 2.07). This represents a doubling in the volume of design information that engineers must search through to identify the part they require.

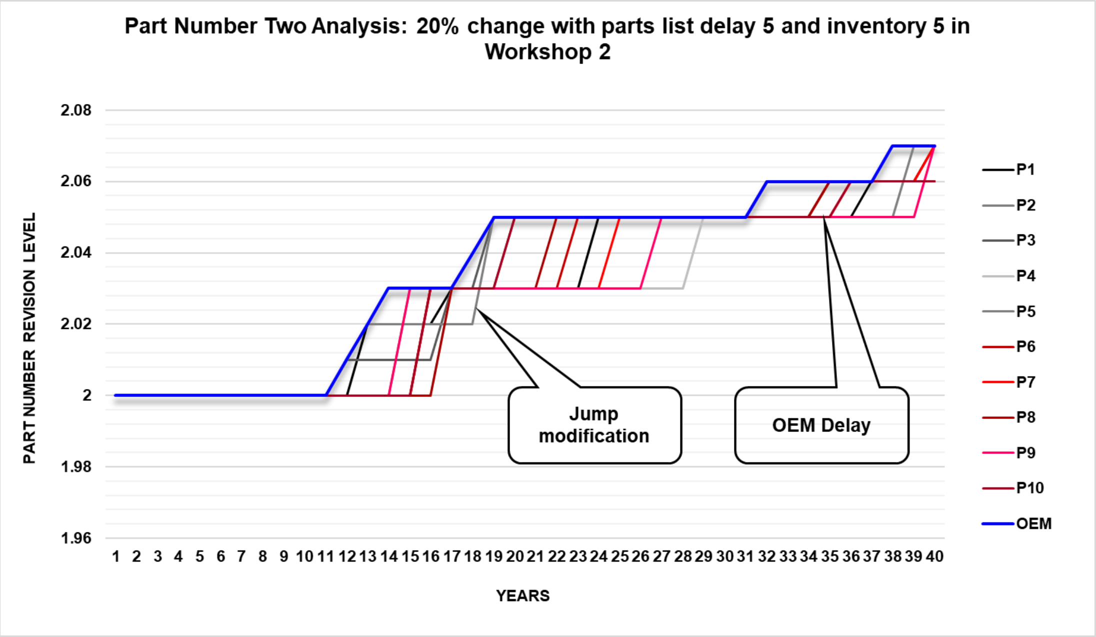


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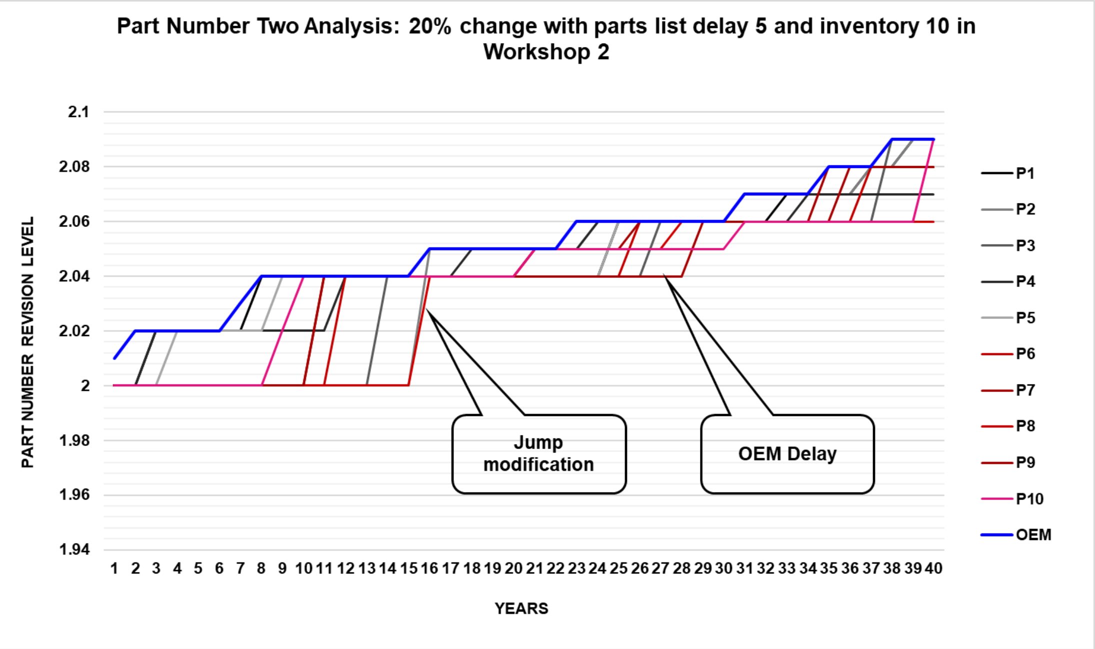
Figure 6.21: Part number 2 analysis with 5 cycle delay to parts list updates and inventory set at 5 for Workshop Two

6.3.2.3 Part Number Two Analysis: Workshop Two - Parts List Delay 5, Inventory 10

Figure 6.22 shows the part number 2 changes for both product fleets over 40 cycles. The simulation was run with a five cycle delay to parts list updates and inventory set at ten for Workshop Two (Fleet Two - red themed legend). Workshop 1 (grey themed legend) had no inventory and experienced immediate updates to the parts list from the OEM. Figure 6.22 shows that modifications to Fleet Two products are delayed until year 10, a 10 year delay versus Workshop One Fleet One products and this reflects the inventory settings.

As expected the product designs and parts information in the product fleet lags that of the OEM. The illustrated jump modification (pink - Workshop Two) in this example, shows a revision leap of four (2.00 to 2.04 in year 16) in product eight of fleet two and is consistent with the analysis presented in Tables 6.7 and 6.8.

The flagged OEM delay modification (pink – Workshop Two) shows an OEM delay of 2 (2.04 to 2.06 in year 29). A final point to note is that this simulation starts with a single part number 2 but ends with three, part number 2 variants (2.06, 2.07, 2.08 and 2.09). This represents a fourfold increase in the volume of design information that engineers must search through to identify the part they require. This provides further evidence of the nature of the challenges created by design changes that product managers must overcome to make



efficiency and quality improvements in their product change processes.

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Figure 6.22: Part number 2 analysis with 5 cycle delay to parts list updates and inventory set at 10 for Workshop Two

6.3.2.4 Part Number Two Analysis: Workshop Two - Parts List Delay 10, Inventory 3

Figure 6.23 illustrates the part number 2s for both product fleets over 40 cycles. The simulation was run with a ten cycle delay to parts list updates and inventory set at three for Workshop Two (red themed legend). Workshop 1 (grey themed legend) had no inventory and immediate updates to the parts list from the OEM. The blue line represents the OEM master parts list. In this simulation, the statistical variation in the simulation meant there were no modifications until year 11 at which point products three and five (Workshop One) received modifications to part number 2 revision level 2.01. Figure 6.23 shows that modifications to Fleet Two products are delayed until year 20, a 10 year delay versus Workshop One Fleet One products and this reflects the delay of updates to the parts list.

The illustrated jump modification (pink - Workshop Two) in this example, shows a revision leap of five (2.00 to 2.05 in year 24) with product seven in Workshop Two. The flagged OEM delay modification (grey – Workshop One) shows an OEM delay of 2 (2.03 to 2.05) with fleet 1 product 4, Workshop One in year 28. Finally, this simulation starts with a single part number 2 but ends with three, part number 2 variants (2.05, 2.06 and 2.07). This represents a threefold increase in the volume of design information that engineers must search through to identify the part they require. From these charts it can be seen that a significant volume of data is produced. This excludes the relational information illustrated in Figures 1.1 and 5.1. The volume of data is such that to represent it in a meaningful way in this report is extremely difficult. The part two data used in this analysis is presented in Appendix One.

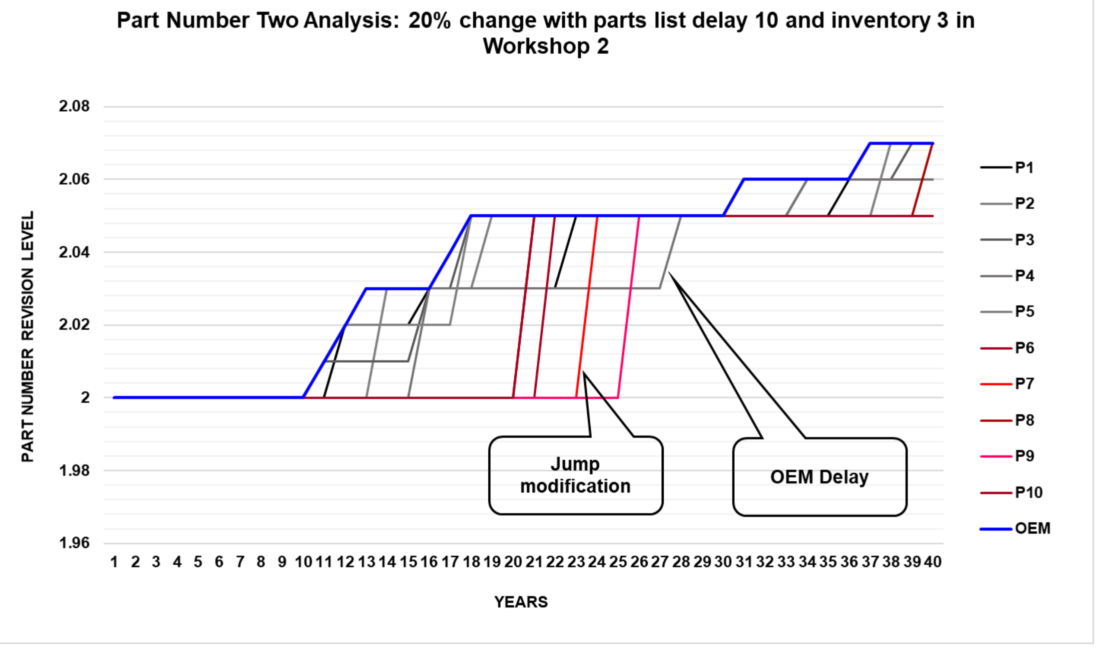

Figure 6.23: Part number 2 analysis with 10 cycle delay to parts list updates and inventory set at 3 for Workshop Two

6.3.3 Validation Model Limitations

The analysis undertaken in the validation modelling is based on the data of single run simulations for a given set of parameters with a limited sample size. The validation model had two fleets of 5 products, each product having 10 parts (sample size 100) and was able to support analysis of a 40 year lifecycle. A broader understanding could be established with a more sophisticated modelling approach that was able to collate patterns of variation across greater numbers of simulations run with the same parameters. Nevertheless, some of the effects observed in the Phase Two modelling help to illustrate what is happening at a macro level in industry. One of the validation model's limitations relates to the reduced number of parts used versus a real product. While the Matlab model was able to support more sophisticated scenarios than the spreadsheet used to validate the design divergence, this was at the expense of the sample size of parts which was reduced from 1,000 to 100.

In addition, all parts face an equal probability of modification whereas a real product would have modification programmes targeted in a coordinated way at specific product sub systems which would cause a variety of design change rates to be experienced within a single product. For example, software and electronics are likely to experience higher modification rates than major structural assemblies.

The features of the model that prevented further, more detailed analysis related to the limitation on the number of parts in each product, the number of products in each fleet and even the number of fleets. While Matlab offered many sophisticated features, the model developed offered little flexibility for adjusting the scale and complexity of the simulation.

Finally, it is important to highlight that the analysis in both modelling phases is based on a two dimensional perspective that considers part number (design) changes over time; however, the management of through-life design change uses multi-dimensional information that includes the following information:

- Information on a product's structure that indicates how parts physically relate to each other. For example parent/child information that enables parts to be related to higher level sub-assemblies and assemblies. This information can be used to support decision-making regarding whether parts or assemblies are compatible with the particular configuration of end products;
- Information that indicates how parts are related by modifications, design changes or revisions helps to identify alternative spares when inventory is exhausted;
- System information that enables engineers to view how parts are related by function such as braking, control, power, instrumentation and so on;
- Information on relationships between different stages of a product's design: as intended, as manufactured, as maintained and also any intentions for further development.

6.4 Chapter 6 Summary

The purpose of the validation modelling has been to illustrate the benefits of the Ten Principles. A model was created that enabled some of the practices described in the Principles to be applied in a differential way to a supply chain where two product fleets were separately supported by two workshops. The workshop supported by the supply chain of the future experienced less design divergence from the OEM's design than the supply chain of the past supported by the supply chain of the past – where inventory and time delays were present.

Chapter Seven: Drawing together the Ten Principles

The issues that affect through-life management of design changes in HVLL products are complex, however, a simple framework of ideas could prove to be a valuable aid to progress. Such a summary should be set in the context of other problem solving approaches that have emerged with the invention of new technologies. These include those that are encapsulated in the fields of systems engineering, strategic thinking, soft systems methodology and control engineering.

Taken individually the Ten Principles are not new, however when viewed collectively they represent an integrated approach that it is hoped will help product managers to develop strategies that will enable them to address the complex challenges in industry. The Principles exclude consideration of the commercial interests (market barriers to change) industrial, political or legislative arrangements that are likely to be required to implement them.

The Ten Principles are intended to be aspirational and provide better clarity on the nature of the challenges that need to be addressed in light of the growth of outsourcing and increasing dependence on networked information technology. .

7.1 Principle One

The business impact of inaccurate product information should be better understood and monitored by business stakeholders and shareholders.

Principle One is the first and most important in terms of deriving benefits from this research. Business leaders are ultimately concerned with marshalling the resources at their disposal to achieve success. The resources required to manage HVLL products through-life include knowledge, information, skilled people, finances and finally the products themselves. The first step towards understanding the business impact of inaccurate information is to understand the nature of the relationship between product information and business outputs.

This research was motivated by a recognition of the business problems that arise due to inaccuracies in product information. This led to a deeper understanding of the complex relationships that exist between products related by design change and the impact of inaccuracies on inventory management. The absence of succession or alternatives links between products related by design change can be cause by many reasons including poor processes, a lack of skills and inadequate ICT. Other information errors can impact the ability to manage design configuration and product safety. These topics extend to product confidence, business confidence and, ultimately, business viability.

The industry survey identified that inaccurate information was the respondents' greatest concern and the Spaghetti Team effect that was subsequently identified, helps to explain the consequential impact on through-life management. The industry consultation provided evidence of the phenomenon of design divergence that was substantiated by the simulation modelling.

The modelling validated the observations of design divergence in product fleets that were made by industry specialists. The design divergence provided evidence of the complex systemic relationships that exist within the significant volumes of information required to manage product fleets. While the creation of the Ten Principles is a positive contribution, to provide meaning they need to be set into a broader context. The case study analysis of the evolution of warship designs from The Tudor era to the Industrial Revolution illustrates the impact of technological innovation on engineering problem solving. To make progress there remains a need for evidence based guidance to enable business leaders, product managers and engineers to respond to changes in industry practice that are required in the light of new innovations.

Principle One is supported by all nine principles, however, the most significant are Principles Two, Three, Four, Eight and Ten.

7.2 Principle Two

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.

The modelling in support of this research is limited to three levels of hierarchy, fleet, product and part and examines design changes over time, tracked by part numbers. The information required to support HVLL products is significantly more complex because it is multi-dimensional in nature and includes the relationship information necessary to record physical structure, the design revisions that are related by modification and functional membership of systems.

The relatively simple modelling undertaken by this research enabled the concept of diverging designs to be identified. The divergence phenomenon is significant because it provides evidence that the designs of HVLL products exhibit emergent systemic properties when considered from a fleet management perspective. This must be set in the context of the greater design complexity that relates to the relational information illustrated in Figures 1.1 and 5.1. This knowledge highlights the need to consider the wider system implications of any design modifications that are being planned in the course of the through-life management.

To enable the continued design integrity and safe operation, one modification may require consequential design changes to other related system components such as production, maintenance and operating processes. This is the logic that underpins the need for this principle. The simulations illustrate that it is possible to influence the level of divergence by adjusting the modelling parameters. The ability to adopt a system of systems approach when planning design changes would be significantly aided if the transparency of complex design structures that exist within HVLL products were improved. The part number level analysis of the modelling results illustrates what might be possible if tools were available to model configuration compatibilities.

Principle Two enables Principles One and Three and is supported by Principles Four, Six, Eight and Ten.

7.3 Principle Three

Product characteristics should be designed and monitored to ensure they comply with legislation, standards and customer requirements.

Complex products are invariably operated in highly regulated environments with stringent safety requirements and so it is critical to be able to maintain high levels of design integrity. This requirement underpins the need to be able to improve the ability of stakeholders to monitor design compliance with requirements whether they are functional, regulatory or motivated by other stakeholder needs.

During the industry consultation respondents expressed frustration at the length of time taken to manage designs through reviews before they are released for use. This issue reflects the complex stakeholder environments in which HVLL products are managed and where participants include: manufacturers, maintainers, owners, suppliers, regulators and operators. The availability of a holistic automated information management solution that provides stakeholders with greater transparency of the through-life product management information they require, has the potential to be of significant benefit.

The modelling identified the significant volumes of data required to manage HVLL products through-life. The underlying complexities generated by design divergence was illustrated by the part number level analysis. The examination of through-life part numbering changes shows how configuration management conflicts can arise, such as when a reliable component has been fitted to a product for many years but then is replaced by a component with a design that has the latest modification status.

Principle Three enables Principle One and is supported by Principles Two, Four Eight and Ten.

7.4 Principle Four

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.

The concept of a single integrated change process describes a way of creating a relationship between a product entity and its related design information, as it moves through the design process and on to manufacture and operation (beginning, middle and end-of-life).

In the survey, barriers to information flow was identified as the third greatest concern and this issue remains a prominent challenge. Yet the need to communicate design information in an efficient and timely manner to those people who have a role to play in design decision making is a key objective. Improving transparency of the design change process and the complex relationships that exist to support physical and systems structure has the potential to offer significant opportunities for improving design management.

The part level analysis of the modelling results illustrates the complex nature of underlying data this is required to manage and maintain product configurations through-life. The importance of Principle Four is signified by the fact that while it does not connect to all principles it is the most connected with other principles (total 10).

Principle Four enables Principles One, Two, Three and Ten and is supported by Principles Five, Six, Seven, Eight, Nine and Ten.

7.5 Principle Five

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.

The industry survey identified that inaccurate information was the greatest concern. Further feedback identified that most employees are not able to distinguish master data in one system, from data held in another. The current designs of ICT systems, utilise a system of point solutions to support specific process areas such as design, manufacturing, inventory management and maintenance. The decentralized and loosely connected nature of such systems presents barriers to information search, impairs accuracy and increases cost. However, the need to improve performance, demands consistent information, rapid records availability and greater accuracy.

There is a need to establish a mechanism that enables users to enter data in a consistent way that improves the quality and availability of accurate information to those operating in the same product support environment. The comparative analysis in the modelling, Workshop One – supply "chain of the future", versus Workshop Two "supply chain of today", illustrates the performance differences.

The current situation in industry offers poor control of information quality. To make progress with the attainment of this principle requires consideration of information systems boundaries and those boundaries associated with design influence which must be set in the context of the management of commercial interests and intellectual property rights.

Principle Five enables Principle Four and is supported by Principles Seven and Nine.

7.6 Principle Six

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).

HVLL product design information is relational and includes: assembled structure, system structure and design change traceability. Parent/child information enables parts to be related to higher level assemblies and sub-assemblies. The time spent searching for information was identified as the fourth most important issue in the survey. Improving the transparency of the relational nature of this complex multi-dimensional information would support superior levels of search and decision-making. For example, it would help with consideration of whether parts or assemblies are compatible with the particular configuration of end products as the part number analysis helps to illustrate.

The challenges of problem solving in the context of HVLL through-life support is explained by the concept of the Spaghetti Team. This concept describes the way people collaborate temporarily in an informal way to resolve technical problems that arise from discrepancies in product information. The modelling illustrates the complex design variations that can be created amongst product fleets. This variation means that as products age, it is increasingly likely that maintenance engineers, product managers and operators will be faced with design scenarios without accurately matching maintenance or operating documentation. Such problems are usually discovered by one individual but often lead to the temporary creation of substantial informal problem solving teams that can extend across the supply chain.

The modelling undertaken presented a two dimensional analysis of part number (design) changes over time. If the design divergence phenomenon that was identified were investigated in other product information dimensions the volume and complexity would increase exponentially. This fact illustrates the challenges that product managers and engineers are faced with, when providing through-life support and justifies the need for this principle.

Principle Six enables Principles Two, Four and Ten and is enabled by Principles Seven and Eight.

7.7 Principle Seven

A common system of terminology (taxonomy) for product information and processes should be established and incorporated into information systems, documentation, parts and product labels.

The industry consultation identified the need to remove barriers to information flow in the supply chain. Significant volumes of information are generated during product development and then embedded within many through-life support processes. Whenever a design is modified, amendments must be communicated through-out the supply chain and incorporated into documentation, processes and systems. The modelling undertaken by this research has explored the complex nature of this information and generated evidence that helps to quantify the nature of the information difficulties faced by industry.

Currently, enterprise ICT architectures consist of a series of “point solutions” that support specific process areas. This represents a collection of loosely coupled information systems and implementing new solutions is time consuming and expensive. However, if a common industry data model were developed and embedded by enterprise ICT software vendors in their products, the costs and time of implementing and upgrading enterprise ICT solutions could be significantly reduced. While the benefits of standardized information are well recognised the standards currently in place are superficial in relation to what is required to make meaningful progress.

The development of new information standards is a critical enabler of the journey to improve transparency of the complex relationships that exist in HVLL product design information. This principle is therefore central to any initiative to enable the rich fully featured enterprise information flows that are required to make significant efficiency improvements possible.

Principle Seven together with Principle Eight is not enabled by other principles and therefore provides a foundation for this integrated approach. Principle Seven enables Principles Four, Five, Six and Nine.

7.8 Principle Eight

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 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.

To improve the through-life management of complex products requires a significantly greater understanding of the complexity of information. Increasingly higher skill levels are required to effectively manage the complex multi-dimensional information structures involved.

While skills were not identified as a top five priority in the survey and subsequent industry consultation, the significant impact of poor skills is evident. Greater discipline is required to manage design information accurately. The need for skills improvement is created by the growth in complexity of design information required to efficiently manage product fleets. Evidence to support the need for greater precision in the rules for allocating configuration information is underpinned by the modelling.

Principle Eight together with Principle Seven is not enabled by other principles and therefore provides a foundation for this integrated approach. Principle Eight is relevant to all principles but most directly enables Principles One, Two, Three, Four and Six.

7.9 Principle Nine

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.

The role of accurate information in supply chains and the benefits of closer collaboration between supply chain participants have been long recognized. Jay Forrester's work in the 1950s with GE is frequently cited. The survey identified product information flow as a top five priority. The validation modelling illustrated the differences in design behavior between the product fleets that were supported by the “supply chain of the Future” and the “supply chain of today”. The impact of delays increases the challenges of through-life product management and the observed Spaghetti Team effect is one symptom.

Principle Nine enables Principles Four and Five and is enabled by Principle Seven.

7.10 Principle Ten

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.

As product complexity has increased, engineers have developed problem solving strategies to support product development, for example modular design, concurrent engineering and control engineering. Approaches to problem solving have identified the need to create a mental structure of the problem to be solved. This includes a description of the current and future state - an ability to “think in time”.

The evolution of warship designs from The Tudor era to the Industrial Revolution illustrated how engineering problem solving practices have evolved in response technological innovations. The Spaghetti Team concept illustrates the huge cost in terms of engineers’ time that is currently expended in the course of inefficient problem solving behavior.

The identification of design divergence helps to enable a deeper understanding of the information behaviours associated with managing HVLL product fleets that engineers can utilize when creating a mental picture of the design related problems that arise.

Principle Ten enables Principles One, Two, Three and Four and is supported by Principles Four and Six.

7.11 Chapter 7 Summary

Chapter 7 sets out to demonstrate how the research undertaken provides evidence for the validity of each of the Ten Principles. Evidence from the industry survey, the discussions with industry specialists, Phase One Modelling, Validation Modelling and interdependencies between the Ten Principles are collated against each of the Ten Principles. This analysis sets out to demonstrate that the Principles are fit for purpose.

Chapter Eight: Conclusion

8.1 Research Initiation

To establish problems that were being experienced with the management of product information in industry, including part numbers, the Author initiated contact with some major manufacturing organisations. These included Bombardier Transportation, Rolls-Royce, The Ford Motor Company and BAE Systems. The organisations expressed frustration with the challenges they were experiencing with coordinating the design information that was generated as products were modified. To explore the issues of concern, the Author devised an investigative approach that identified four important perspectives of the product change process: innovation and industry lifecycle; product information; management models and thought systems; and finally, information technology. To provide a foundation for the investigation the research initiated and designed an industry survey and follow-up by discussing the results with industry specialists. The survey approach was validated by the Journal of Engineering Design. The research brought together a large number of related problems associated with design management and has presented them as a single coherent body of knowledge;

8.2 Investigation

To progress an investigation, the Author devised an approach that identified four important perspectives of the product change process: innovation and industry lifecycle; product information; management models and thought systems; and finally, information technology. A review of published literature on the field of design change, identified significant research interest in the respective fields identified by the research approach but the central issue of product change management was not fully defined and remains relatively unexplored. Product knowledge is increasingly being used to derive competitive advantage from information on through-life product performance. Furthermore, the increasing use of embedded software in products enables systems to be upgraded more frequently.

The research was started with the support of a large train manufacturer that both manufactured rolling-stock and provided outsourced maintenance services for the trains it had sold to rail operators. The flow of product information through the supply chain was vitally important and problems regularly arose as the result of design changes made by parts suppliers that were poorly communicated through the supply chain. An additional feature of the UK's rail industry related to the leased ownership model that was used. The companies that owned the trains (lessors) were also interested in the through-life management of rolling stock as well as the OEMs, rail operators and regulators.

To provide a foundation for the investigation, the Author initiated and designed an industry survey which was followed-up with detailed discussions with industry specialists. The survey approach was validated by the literature review and reported in a paper that was published in the Journal of Engineering Design. The survey and subsequent consultation identified that the design configuration records of older products were observed to be less accurate than those that were newly manufactured. A six week investigation with aircraft manufacturers and airlines identified a significant body of opinion that suggested that the designs of aircraft diverged as they aged. This phenomenon was subsequently validated by two simulation models that were created to investigate the impact of through-life design change on product fleets in accordance with the scientific method. This modelling was able to substantiate that designs of HVLL products diverge from the designs of other similar products when managed as a fleet.

A workshop in 2011 held by the train manufacturer reviewed the key principles of prominent standards used to manage design configuration. These included ANSI/EIA 649-B, ICM CMII and ISO 10007:2003 Quality management systems — Guidelines for configuration management. Collectively these offered many principles for good practice but failed to address the very closely related issues of design problem solving, information management and ICT. This led the Author to conclude that there was a need to provide product managers and engineers with guidance that related more closely to the knowledge related challenges of managing design information through-life.

Onboard systems are generating growing volumes of information that record products' operating performance. This information is then reported to central control centres where teams are able to collectively utilize more efficient product fleet management approaches. This illustrates a dimension of the growth of the service economy which in conjunction with outsourcing has changed industry working practices.

This thesis has shown that the need to improve product information flow in the supply chain is greater than ever and that Jay Forrester's observations (1950s) of the need for information sharing between supply chain participants remain a priority.

8.3 Ten Principles

Ten Principles have been proposed to support the improved problem solving required to resolve the complex industry challenges associated with through-life product management. The need for the Ten Principles arises from a requirement to better align ICT to design management practice for HVLL products. Individually these are not new concepts but collectively they encapsulate the broad issues that needed to be addressed. While the Ten Principles are a positive contribution, to provide meaning they needed to be set into a broader context.

A visit to the National Maritime Museum made by the Author in April 2016 identified a number of exhibits that illustrated the evolution of warship designs from the Tudor era to the Industrial Revolution. An interesting dimension was that the main exhibits which were the Mary Rose, HMS Victory and HMS Warrior were all HVLL products that had experienced operating lives of several decades in a similar way to modern HVLL products. Engineering problem solving practices continually evolve in response technological innovations. The emergence of the gun turret to replace the gun deck was an example of a disruptive technology that can be linked to the emergence of engineering working practices used today. Concurrent engineering, systems engineering and control engineering are examples of engineering disciplines and practices that have arisen from the need for engineers to better manage new technology.

The current challenges for product managers relates to the changes in industry practice that have arisen from the need to derive competitive advantage from knowledge and that have been enabled by the growth in capabilities of networked ICT. This field is complex and a framework of ideas would help product managers to navigate industry challenges. The phenomenon of design divergence represents an additional dimension to this field. Design divergence is an emergent systemic property that is exhibited by fleets of HVLL products over time. Design divergence cannot be identified by examining a single product on its own. Together, knowledge of the Ten Principles and concept of design divergence is proposed as a positive contribution to engineering theory and practice.

8.4 Future State

In the future, networked technology will enable the seamless flow of information in real time between supply chain participants. This will require technology that uses a common information model. Engineers and product managers will be able to rapidly access the information they need to make design changes to the HVLL products they manage. Industry stakeholders will be able to monitor product performance and business performance from sophisticated analytical capabilities that have been developed to interrogate the underlying data that is generated from product and supply chain performance. The potential benefits in terms of industrial competitiveness that might be achieved are considered to be significant.

8.5 Further Development and Next Steps

To make improvements to the through-life management of complex products represents a significant and multi-faceted challenge. Further research is required to generate the knowledge to enable industries adopt the innovations being introduced in the context of the digital economy. This will require coordinated activity by governments, market regulators and industry participants.

8.6 Research Contributions

This thesis has made the following contributions to research:

- The observation of the property of diverging designs within HVLL product fleets is a significant phenomenon because it provides evidence that the designs of HVLL products exhibit emergent systemic properties when considered from a fleet management perspective. This behaviour is not evident from consideration of the design of a single HVLL product instance.
- The Ten Principles collectively represent an integrated approach to improve the through-life management of HVLL products and provide greater clarity on the nature and magnitude of the challenges to be addressed. Knowledge and information are derived from data. The Ten Principles promote the informative use of design change data in a way that supports better management. The Ten Principles enable the combination of a large number of related problems associated with design management and present them as a single coherent perspective.

8.7 Papers

8.7.1 Published Journal Paper

Assessing the challenges of managing product design change through-life, Journal of Engineering Design, Volume 27, Issue 1-3, 2016.

8.7.2 Published Conference Papers

- SDM'2016 the Third International Conference on Sustainable Design and Manufacturing (5 & 6 April 2016 Chania, Crete, Greece);
- SDM'2015 the Second International Conference on Sustainable Design and Manufacturing (12 to 14 April 2015 Seville, Spain);
- SDM'2014 the International Conference on Sustainable Design and Manufacturing (28 to 30 April 2014 Cardiff, Wales, UK);

8.7.3 Submitted Papers

- Problem Solving in Design: from the Industrial Revolution to 21st Century, International Journal of Information Management;
- Modelling paper, Computers in Engineering

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Appendix One: Phase Two Modelling – Part Two Data

3-5 Simulation

Simulation 3-5 5%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2.01	2	2.01	2	2	2	2	2	2
Year 24	2	2.01	2	2.01	2	2	2	2	2	2
Year 25	2	2.01	2	2.01	2	2	2	2	2	2
Year 26	2	2.01	2	2.01	2	2	2	2	2	2
Year 27	2	2.01	2.01	2.01	2	2	2	2	2	2
Year 28	2	2.01	2.01	2.01	2	2.01	2	2	2	2
Year 29	2	2.01	2.01	2.01	2	2.01	2	2.01	2	2
Year 30	2	2.01	2.01	2.01	2	2.01	2	2.01	2	2
Year 31	2	2.01	2.01	2.01	2	2.01	2.02	2.01	2	2
Year 32	2	2.01	2.01	2.01	2	2.01	2.02	2.01	2	2
Year 33	2	2.01	2.01	2.01	2	2.01	2.02	2.01	2	2
Year 34	2	2.01	2.01	2.01	2	2.01	2.02	2.01	2	2
Year 35	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2	2
Year 36	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2.03	2
Year 37	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2.03	2
Year 38	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2.03	2
Year 39	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2.03	2
Year 40	2	2.01	2.01	2.02	2	2.01	2.02	2.02	2.03	2

Simulation 3-5 10%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2.01	2	2	2	2	2	2	2	2	2
Year 8	2.01	2	2	2	2.01	2	2	2	2	2
Year 9	2.01	2	2	2	2.01	2	2	2	2	2
Year 10	2.01	2	2	2	2.01	2	2	2	2	2.01
Year 11	2.01	2	2	2	2.01	2.01	2	2	2	2.01
Year 12	2.01	2	2	2	2.01	2.01	2	2	2.01	2.01
Year 13	2.01	2	2	2	2.01	2.01	2	2	2.01	2.01
Year 14	2.01	2	2	2	2.01	2.01	2	2	2.01	2.01
Year 15	2.01	2	2	2	2.01	2.02	2	2.02	2.01	2.01
Year 16	2.01	2	2	2	2.01	2.02	2	2.02	2.01	2.01
Year 17	2.01	2	2	2.02	2.01	2.02	2	2.02	2.01	2.01
Year 18	2.01	2	2	2.02	2.01	2.02	2	2.02	2.01	2.01
Year 19	2.01	2	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 20	2.01	2	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 21	2.01	2	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 22	2.01	2	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 23	2.01	2.02	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 24	2.02	2.02	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 25	2.02	2.02	2	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 26	2.02	2.02	2.02	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 27	2.02	2.02	2.02	2.02	2.01	2.02	2	2.02	2.02	2.01
Year 28	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.01
Year 29	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.01
Year 30	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 31	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 32	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 33	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 34	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 35	2.02	2.02	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 36	2.03	2.03	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 37	2.03	2.03	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 38	2.03	2.04	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 39	2.03	2.04	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02
Year 40	2.03	2.04	2.02	2.04	2.02	2.04	2	2.02	2.04	2.04

Simulation 3-5 15%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2.01	2	2.01	2	2	2	2	2
Year 12	2	2	2.01	2	2.01	2	2	2	2	2
Year 13	2	2	2.01	2	2.01	2	2	2.02	2.02	2
Year 14	2	2.02	2.01	2	2.01	2	2	2.02	2.02	2
Year 15	2	2.02	2.01	2	2.01	2.02	2	2.02	2.02	2.02
Year 16	2.02	2.02	2.02	2.02	2.01	2.02	2	2.02	2.02	2.02
Year 17	2.02	2.02	2.02	2.02	2.01	2.02	2	2.02	2.02	2.02
Year 18	2.02	2.02	2.04	2.02	2.01	2.02	2	2.02	2.02	2.04
Year 19	2.02	2.04	2.04	2.02	2.01	2.02	2	2.02	2.02	2.04
Year 20	2.02	2.04	2.04	2.02	2.01	2.02	2	2.02	2.02	2.04
Year 21	2.02	2.04	2.04	2.02	2.01	2.02	2	2.04	2.02	2.04
Year 22	2.02	2.04	2.04	2.02	2.01	2.04	2	2.04	2.02	2.04
Year 23	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.02	2.04
Year 24	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.02	2.04
Year 25	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.02	2.04
Year 26	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 27	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 28	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 29	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 30	2.04	2.04	2.04	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 31	2.04	2.04	2.05	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 32	2.04	2.04	2.05	2.02	2.01	2.04	2	2.04	2.04	2.04
Year 33	2.04	2.04	2.05	2.02	2.01	2.04	2	2.04	2.05	2.04
Year 34	2.04	2.05	2.05	2.05	2.01	2.04	2	2.05	2.05	2.04
Year 35	2.04	2.05	2.05	2.05	2.01	2.04	2.05	2.05	2.05	2.04
Year 36	2.04	2.05	2.05	2.05	2.01	2.04	2.05	2.05	2.05	2.04
Year 37	2.04	2.05	2.05	2.05	2.01	2.04	2.05	2.05	2.05	2.04
Year 38	2.04	2.05	2.05	2.05	2.06	2.04	2.06	2.05	2.05	2.04
Year 39	2.04	2.05	2.06	2.05	2.06	2.06	2.06	2.05	2.06	2.04
Year 40	2.04	2.05	2.06	2.05	2.06	2.06	2.06	2.06	2.06	2.04

Simulation 3-5 20%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2.01	2	2	2.01	2	2	2	2	2
Year 4	2	2.01	2	2	2.01	2	2	2	2	2
Year 5	2	2.01	2	2.01	2.01	2	2	2	2	2
Year 6	2	2.01	2	2.01	2.01	2	2	2	2	2
Year 7	2	2.01	2	2.01	2.01	2	2	2	2	2
Year 8	2	2.01	2	2.02	2.02	2	2.01	2	2	2.01
Year 9	2	2.01	2	2.02	2.02	2.03	2.01	2	2	2.01
Year 10	2	2.01	2	2.02	2.02	2.03	2.01	2	2	2.03
Year 11	2.04	2.01	2	2.02	2.02	2.03	2.01	2	2	2.03
Year 12	2.04	2.04	2	2.04	2.02	2.03	2.04	2	2	2.03
Year 13	2.04	2.04	2	2.05	2.02	2.03	2.04	2.04	2	2.03
Year 14	2.04	2.04	2	2.05	2.06	2.04	2.04	2.04	2	2.04
Year 15	2.04	2.04	2	2.06	2.06	2.04	2.04	2.04	2	2.04
Year 16	2.04	2.04	2	2.06	2.06	2.04	2.06	2.04	2	2.04
Year 17	2.04	2.04	2	2.06	2.06	2.04	2.06	2.04	2.06	2.04
Year 18	2.04	2.04	2	2.06	2.06	2.06	2.06	2.04	2.06	2.06
Year 19	2.04	2.04	2	2.06	2.06	2.06	2.06	2.04	2.06	2.06
Year 20	2.06	2.04	2	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 21	2.06	2.04	2	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 22	2.06	2.04	2	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 23	2.06	2.07	2	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 24	2.06	2.07	2	2.07	2.06	2.06	2.06	2.06	2.06	2.07
Year 25	2.06	2.07	2	2.07	2.06	2.06	2.06	2.06	2.06	2.07
Year 26	2.06	2.07	2	2.07	2.06	2.07	2.06	2.06	2.07	2.07
Year 27	2.06	2.07	2	2.07	2.07	2.07	2.06	2.07	2.07	2.07
Year 28	2.07	2.07	2	2.07	2.07	2.07	2.06	2.07	2.07	2.07
Year 29	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07
Year 30	2.07	2.07	2.08	2.08	2.07	2.08	2.07	2.08	2.08	2.08
Year 31	2.08	2.07	2.08	2.08	2.07	2.08	2.07	2.08	2.08	2.08
Year 32	2.08	2.08	2.08	2.08	2.07	2.08	2.08	2.08	2.08	2.08
Year 33	2.08	2.08	2.08	2.08	2.07	2.08	2.08	2.08	2.08	2.08
Year 34	2.08	2.08	2.08	2.09	2.07	2.08	2.08	2.08	2.08	2.08
Year 35	2.08	2.08	2.08	2.09	2.07	2.08	2.09	2.08	2.08	2.08
Year 36	2.08	2.08	2.08	2.09	2.07	2.08	2.09	2.08	2.08	2.08
Year 37	2.08	2.09	2.08	2.09	2.07	2.08	2.09	2.08	2.08	2.08
Year 38	2.09	2.09	2.08	2.09	2.07	2.08	2.09	2.08	2.08	2.08
Year 39	2.09	2.09	2.08	2.09	2.07	2.08	2.1	2.1	2.1	2.08
Year 40	2.09	2.09	2.08	2.09	2.07	2.08	2.1	2.1	2.1	2.08

5-5 Simulation

Simulation 5-5 5%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2	2	2	2	2	2	2	2	2
Year 24	2	2	2	2	2	2	2	2	2	2
Year 25	2	2	2	2	2.01	2	2	2	2	2
Year 26	2	2	2	2	2.01	2	2	2	2	2
Year 27	2	2.01	2	2	2.01	2	2	2	2	2
Year 28	2	2.01	2	2	2.01	2	2	2	2	2
Year 29	2	2.01	2	2	2.01	2	2	2	2	2
Year 30	2	2.01	2	2	2.01	2	2	2	2	2
Year 31	2	2.01	2	2	2.01	2	2	2	2.01	2
Year 32	2.01	2.01	2	2	2.01	2	2	2	2.01	2
Year 33	2.01	2.01	2	2	2.01	2	2	2	2.01	2
Year 34	2.01	2.01	2	2	2.01	2	2	2	2.01	2
Year 35	2.01	2.01	2	2	2.01	2.02	2	2	2.01	2
Year 36	2.01	2.01	2	2	2.01	2.02	2	2	2.01	2
Year 37	2.01	2.01	2.02	2.02	2.01	2.02	2	2	2.01	2
Year 38	2.01	2.02	2.02	2.02	2.01	2.02	2	2	2.01	2
Year 39	2.01	2.02	2.02	2.02	2.01	2.02	2	2	2.01	2
Year 40	2.01	2.02	2.02	2.02	2.01	2.02	2	2	2.01	2

Simulation 5-5 10%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2.01	2	2	2	2	2	2	2	2
Year 24	2	2.01	2	2.01	2	2	2	2	2	2
Year 25	2	2.01	2	2.01	2	2	2	2	2	2
Year 26	2	2.01	2	2.01	2	2	2	2	2	2
Year 27	2	2.01	2	2.01	2	2	2	2	2	2
Year 28	2	2.01	2.01	2.01	2	2	2	2	2	2
Year 29	2	2.01	2.01	2.01	2	2.01	2	2	2	2
Year 30	2	2.02	2.02	2.01	2	2.01	2	2.02	2	2
Year 31	2.02	2.02	2.02	2.01	2	2.01	2	2.02	2	2
Year 32	2.02	2.02	2.02	2.01	2	2.01	2.02	2.02	2	2
Year 33	2.02	2.02	2.02	2.01	2	2.01	2.02	2.02	2	2
Year 34	2.02	2.02	2.02	2.01	2	2.02	2.02	2.02	2	2
Year 35	2.02	2.02	2.02	2.01	2	2.02	2.02	2.02	2	2
Year 36	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2	2
Year 37	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2.03	2
Year 38	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2.03	2
Year 39	2.02	2.04	2.03	2.03	2	2.02	2.03	2.03	2.03	2
Year 40	2.02	2.04	2.04	2.03	2	2.02	2.03	2.03	2.03	2

Simulation 5-5 15%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2.02	2	2	2	2	2	2	2	2	2
Year 9	2.02	2	2	2	2.02	2	2	2	2	2
Year 10	2.02	2	2	2	2.02	2	2	2	2	2
Year 11	2.02	2	2	2	2.02	2	2.02	2	2	2.02
Year 12	2.02	2	2	2	2.02	2.02	2.02	2	2	2.02
Year 13	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 14	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 15	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 16	2.02	2	2	2	2.02	2.02	2.02	2.02	2.02	2.02
Year 17	2.02	2	2	2	2.02	2.02	2.02	2.02	2.02	2.02
Year 18	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 19	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 20	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 21	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.02
Year 22	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.02
Year 23	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 24	2.02	2.04	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 25	2.04	2.04	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 26	2.04	2.04	2	2.03	2.02	2.04	2.02	2.03	2.04	2.03
Year 27	2.04	2.04	2.04	2.03	2.02	2.04	2.02	2.03	2.04	2.03
Year 28	2.04	2.04	2.04	2.03	2.02	2.04	2.02	2.04	2.04	2.03
Year 29	2.04	2.04	2.04	2.03	2.04	2.04	2.04	2.04	2.04	2.03
Year 30	2.04	2.04	2.04	2.03	2.04	2.04	2.04	2.04	2.04	2.03
Year 31	2.04	2.04	2.04	2.03	2.04	2.04	2.04	2.04	2.04	2.04
Year 32	2.04	2.04	2.04	2.03	2.04	2.04	2.04	2.04	2.04	2.04
Year 33	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 34	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 35	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 36	2.05	2.05	2.04	2.04	2.04	2.05	2.04	2.04	2.05	2.04
Year 37	2.05	2.05	2.04	2.04	2.04	2.05	2.05	2.04	2.05	2.04
Year 38	2.06	2.06	2.04	2.04	2.04	2.05	2.05	2.04	2.05	2.04
Year 39	2.06	2.06	2.04	2.04	2.04	2.05	2.05	2.04	2.05	2.04
Year 40	2.06	2.06	2.04	2.04	2.04	2.05	2.05	2.04	2.05	2.06

Simulation 5-5 20%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2.01	2	2.01	2	2	2	2	2
Year 13	2.02	2	2.01	2	2.02	2	2	2	2	2
Year 14	2.02	2	2.01	2	2.02	2	2	2	2	2
Year 15	2.02	2.03	2.01	2	2.02	2	2	2	2.03	2
Year 16	2.02	2.03	2.01	2	2.02	2.03	2.03	2	2.03	2.03
Year 17	2.03	2.03	2.03	2.03	2.02	2.03	2.03	2.03	2.03	2.03
Year 18	2.03	2.03	2.03	2.03	2.02	2.03	2.03	2.03	2.03	2.03
Year 19	2.03	2.03	2.05	2.03	2.05	2.03	2.03	2.03	2.03	2.03
Year 20	2.03	2.05	2.05	2.03	2.05	2.03	2.03	2.03	2.03	2.05
Year 21	2.03	2.05	2.05	2.03	2.05	2.03	2.03	2.03	2.03	2.05
Year 22	2.03	2.05	2.05	2.03	2.05	2.03	2.03	2.03	2.03	2.05
Year 23	2.03	2.05	2.05	2.03	2.05	2.05	2.03	2.05	2.03	2.05
Year 24	2.05	2.05	2.05	2.03	2.05	2.05	2.03	2.05	2.03	2.05
Year 25	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.03	2.05
Year 26	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.03	2.05
Year 27	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.05	2.05
Year 28	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.05	2.05
Year 29	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 30	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 31	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 32	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 33	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 34	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.06	2.05	2.05
Year 35	2.05	2.06	2.06	2.06	2.05	2.06	2.06	2.06	2.05	2.05
Year 36	2.05	2.06	2.06	2.06	2.05	2.06	2.06	2.06	2.05	2.06
Year 37	2.06	2.06	2.06	2.06	2.05	2.06	2.06	2.06	2.05	2.06
Year 38	2.06	2.06	2.06	2.06	2.05	2.06	2.06	2.06	2.05	2.06
Year 39	2.06	2.06	2.06	2.06	2.07	2.06	2.06	2.06	2.05	2.06
Year 40	2.06	2.06	2.07	2.06	2.07	2.07	2.07	2.06	2.07	2.06

5-10 Simulation

Simulation 5-10 20%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2.02	2	2	2.02	2	2	2	2	2	2
Year 4	2.02	2	2	2.02	2.02	2	2	2	2	2
Year 5	2.02	2	2	2.02	2.02	2	2	2	2	2
Year 6	2.02	2	2	2.02	2.02	2	2	2	2	2
Year 7	2.02	2	2	2.02	2.02	2	2	2	2	2
Year 8	2.04	2	2	2.02	2.02	2	2	2	2	2
Year 9	2.04	2	2	2.02	2.04	2	2	2	2	2.02
Year 10	2.04	2	2	2.02	2.04	2	2	2	2	2.04
Year 11	2.04	2	2	2.02	2.04	2	2.04	2	2.04	2.04
Year 12	2.04	2	2	2.04	2.04	2.04	2.04	2	2.04	2.04
Year 13	2.04	2	2	2.04	2.04	2.04	2.04	2	2.04	2.04
Year 14	2.04	2	2.04	2.04	2.04	2.04	2.04	2	2.04	2.04
Year 15	2.04	2	2.04	2.04	2.04	2.04	2.04	2	2.04	2.04
Year 16	2.04	2.05	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 17	2.04	2.05	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 18	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.04	2.04	2.04
Year 19	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.04	2.04	2.04
Year 20	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.04	2.04	2.04
Year 21	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.05	2.05	2.05
Year 22	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.05	2.05	2.05
Year 23	2.04	2.05	2.04	2.05	2.04	2.04	2.04	2.05	2.05	2.05
Year 24	2.04	2.06	2.04	2.06	2.04	2.04	2.04	2.05	2.05	2.05
Year 25	2.06	2.06	2.04	2.06	2.06	2.04	2.04	2.05	2.05	2.05
Year 26	2.06	2.06	2.04	2.06	2.06	2.06	2.04	2.05	2.06	2.05
Year 27	2.06	2.06	2.06	2.06	2.06	2.06	2.04	2.05	2.06	2.05
Year 28	2.06	2.06	2.06	2.06	2.06	2.06	2.04	2.06	2.06	2.05
Year 29	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.05
Year 30	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.05
Year 31	2.06	2.07	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 32	2.06	2.07	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 33	2.07	2.07	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
Year 34	2.07	2.07	2.06	2.07	2.06	2.06	2.06	2.06	2.06	2.06
Year 35	2.07	2.07	2.06	2.07	2.06	2.06	2.08	2.06	2.06	2.06
Year 36	2.07	2.07	2.06	2.07	2.06	2.06	2.08	2.06	2.08	2.06
Year 37	2.08	2.08	2.06	2.07	2.06	2.08	2.08	2.06	2.08	2.06
Year 38	2.08	2.08	2.09	2.07	2.06	2.08	2.08	2.06	2.08	2.06
Year 39	2.09	2.09	2.09	2.07	2.06	2.08	2.08	2.06	2.08	2.06
Year 40	2.09	2.09	2.09	2.07	2.06	2.08	2.08	2.06	2.08	2.09

Simulation 5-10 15%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2.01	2	2	2	2	2	2	2	2
Year 24	2	2.01	2	2.01	2	2	2	2	2	2
Year 25	2	2.01	2	2.01	2	2	2	2	2.01	2
Year 26	2	2.01	2	2.01	2	2	2	2	2.01	2
Year 27	2	2.01	2	2.01	2	2	2	2	2.01	2
Year 28	2	2.01	2.01	2.01	2	2	2	2	2.01	2
Year 29	2	2.01	2.01	2.01	2	2.01	2	2	2.01	2
Year 30	2	2.02	2.02	2.02	2	2.02	2	2.02	2.01	2
Year 31	2.02	2.02	2.02	2.02	2	2.02	2	2.02	2.01	2
Year 32	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02	2.01	2
Year 33	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02	2.01	2
Year 34	2.02	2.02	2.02	2.02	2	2.02	2.02	2.02	2.01	2
Year 35	2.02	2.02	2.02	2.02	2	2.02	2.02	2.03	2.01	2
Year 36	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2.01	2
Year 37	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2.03	2
Year 38	2.02	2.02	2.03	2.03	2	2.02	2.02	2.03	2.03	2
Year 39	2.02	2.04	2.03	2.03	2	2.02	2.03	2.03	2.03	2
Year 40	2.02	2.04	2.04	2.03	2	2.02	2.03	2.03	2.03	2.04

Simulation 5-10 10%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2.01	2.01	2	2	2	2	2	2	2	2
Year 3	2.01	2.01	2	2	2	2	2	2	2	2
Year 4	2.02	2.01	2	2	2	2	2	2	2	2
Year 5	2.02	2.01	2	2	2	2	2	2	2	2
Year 6	2.02	2.02	2	2	2	2	2	2	2	2
Year 7	2.02	2.02	2	2	2	2	2	2	2	2
Year 8	2.02	2.02	2	2	2	2	2	2	2	2
Year 9	2.02	2.02	2	2	2	2	2	2	2	2
Year 10	2.02	2.02	2	2	2	2	2	2	2	2
Year 11	2.02	2.02	2	2	2	2	2	2	2	2
Year 12	2.02	2.02	2	2	2	2	2	2	2	2
Year 13	2.02	2.02	2	2	2	2	2	2	2	2
Year 14	2.02	2.02	2	2	2	2	2	2	2	2
Year 15	2.02	2.02	2	2	2	2	2	2	2	2
Year 16	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 17	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 18	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 19	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 20	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 21	2.02	2.02	2	2.02	2	2	2	2	2	2
Year 22	2.02	2.03	2	2.02	2	2	2	2	2	2
Year 23	2.02	2.03	2	2.02	2	2	2	2	2	2
Year 24	2.02	2.03	2	2.02	2	2	2	2	2	2
Year 25	2.02	2.03	2	2.02	2.03	2	2	2	2	2
Year 26	2.02	2.03	2	2.02	2.03	2	2	2	2	2
Year 27	2.02	2.03	2.03	2.02	2.03	2	2	2	2	2
Year 28	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2	2
Year 29	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2	2
Year 30	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2	2
Year 31	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2.03	2
Year 32	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2.03	2
Year 33	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2.03	2
Year 34	2.03	2.03	2.03	2.02	2.03	2	2	2.03	2.03	2
Year 35	2.03	2.03	2.03	2.04	2.03	2.04	2	2.03	2.03	2
Year 36	2.03	2.03	2.03	2.04	2.03	2.04	2	2.03	2.03	2.04
Year 37	2.03	2.03	2.04	2.04	2.03	2.04	2	2.03	2.03	2.04
Year 38	2.03	2.04	2.04	2.04	2.03	2.04	2	2.03	2.03	2.04
Year 39	2.03	2.04	2.04	2.04	2.03	2.04	2	2.03	2.03	2.04
Year 40	2.03	2.04	2.04	2.04	2.03	2.04	2	2.03	2.03	2.04

Simulation 5-10 5%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2	2	2	2	2	2	2	2	2
Year 24	2	2	2	2	2	2	2	2	2	2
Year 25	2	2	2	2	2.01	2	2	2	2	2
Year 26	2	2	2	2	2.01	2	2	2	2	2
Year 27	2	2.01	2	2	2.01	2	2	2	2	2
Year 28	2	2.01	2	2	2.01	2	2	2	2	2
Year 29	2	2.01	2	2	2.01	2	2	2	2	2
Year 30	2	2.01	2	2	2.01	2	2	2	2	2
Year 31	2	2.01	2	2	2.01	2	2	2	2	2
Year 32	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 33	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 34	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 35	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 36	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 37	2.01	2.01	2.02	2.02	2.01	2	2	2	2	2
Year 38	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2
Year 39	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2
Year 40	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2

10-3 Simulation

Simulation 10-3 20%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2.01	2	2.01	2	2	2	2	2
Year 12	2.02	2	2.01	2	2.02	2	2	2	2	2
Year 13	2.02	2	2.01	2	2.02	2	2	2	2	2
Year 14	2.02	2.03	2.01	2	2.02	2	2	2	2	2
Year 15	2.02	2.03	2.01	2	2.02	2	2	2	2	2
Year 16	2.03	2.03	2.03	2.03	2.02	2	2	2	2	2
Year 17	2.03	2.03	2.03	2.03	2.02	2	2	2	2	2
Year 18	2.03	2.03	2.05	2.03	2.05	2	2	2	2	2
Year 19	2.03	2.05	2.05	2.03	2.05	2	2	2	2	2
Year 20	2.03	2.05	2.05	2.03	2.05	2	2	2	2	2
Year 21	2.03	2.05	2.05	2.03	2.05	2	2	2.05	2	2.05
Year 22	2.03	2.05	2.05	2.03	2.05	2.05	2	2.05	2	2.05
Year 23	2.05	2.05	2.05	2.03	2.05	2.05	2	2.05	2	2.05
Year 24	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2	2.05
Year 25	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2	2.05
Year 26	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.05	2.05
Year 27	2.05	2.05	2.05	2.03	2.05	2.05	2.05	2.05	2.05	2.05
Year 28	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 29	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 30	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 31	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 32	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 33	2.05	2.05	2.06	2.05	2.05	2.05	2.05	2.05	2.05	2.05
Year 34	2.05	2.06	2.06	2.06	2.05	2.05	2.05	2.05	2.05	2.05
Year 35	2.05	2.06	2.06	2.06	2.05	2.05	2.05	2.05	2.05	2.05
Year 36	2.06	2.06	2.06	2.06	2.05	2.05	2.05	2.05	2.05	2.05
Year 37	2.06	2.06	2.06	2.06	2.05	2.05	2.05	2.05	2.05	2.05
Year 38	2.06	2.06	2.06	2.06	2.07	2.05	2.05	2.05	2.05	2.05
Year 39	2.06	2.06	2.07	2.06	2.07	2.05	2.05	2.05	2.05	2.05
Year 40	2.06	2.06	2.07	2.06	2.07	2.05	2.05	2.07	2.05	2.05

Simulation 10-3 15%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2.02	2	2	2	2	2	2	2	2	2
Year 8	2.02	2	2	2	2.02	2	2	2	2	2
Year 9	2.02	2	2	2	2.02	2	2	2	2	2
Year 10	2.02	2	2	2	2.02	2	2.02	2	2	2.02
Year 11	2.02	2	2	2	2.02	2.02	2.02	2	2	2.02
Year 12	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 13	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 14	2.02	2	2	2	2.02	2.02	2.02	2	2.02	2.02
Year 15	2.02	2	2	2	2.02	2.02	2.02	2.02	2.02	2.02
Year 16	2.02	2	2	2	2.02	2.02	2.02	2.02	2.02	2.02
Year 17	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 18	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 19	2.02	2	2	2.03	2.02	2.02	2.02	2.02	2.02	2.02
Year 20	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.02
Year 21	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.02
Year 22	2.02	2	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 23	2.02	2.04	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 24	2.04	2.04	2	2.03	2.02	2.02	2.02	2.03	2.03	2.03
Year 25	2.04	2.04	2	2.03	2.02	2.03	2.02	2.03	2.03	2.03
Year 26	2.04	2.04	2.04	2.03	2.02	2.03	2.02	2.03	2.03	2.03
Year 27	2.04	2.04	2.04	2.03	2.02	2.03	2.02	2.03	2.03	2.03
Year 28	2.04	2.04	2.04	2.03	2.04	2.03	2.03	2.03	2.03	2.03
Year 29	2.04	2.04	2.04	2.03	2.04	2.03	2.03	2.03	2.03	2.03
Year 30	2.04	2.04	2.04	2.03	2.04	2.03	2.03	2.03	2.03	2.04
Year 31	2.04	2.04	2.04	2.03	2.04	2.04	2.03	2.04	2.03	2.04
Year 32	2.04	2.04	2.04	2.03	2.04	2.04	2.03	2.04	2.03	2.04
Year 33	2.04	2.04	2.04	2.04	2.04	2.04	2.03	2.04	2.03	2.04
Year 34	2.04	2.04	2.04	2.04	2.04	2.04	2.03	2.04	2.03	2.04
Year 35	2.04	2.04	2.04	2.04	2.04	2.04	2.03	2.04	2.04	2.04
Year 36	2.05	2.05	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 37	2.05	2.05	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 38	2.06	2.06	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 39	2.06	2.06	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
Year 40	2.06	2.06	2.04	2.06	2.04	2.06	2.04	2.04	2.06	2.06

Simulation 10-3 10%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2.01	2	2	2	2	2	2	2	2
Year 23	2	2.01	2	2.01	2	2	2	2	2	2
Year 24	2	2.01	2	2.01	2	2	2	2	2	2
Year 25	2	2.01	2	2.01	2	2	2	2	2	2
Year 26	2	2.01	2	2.01	2	2	2	2	2	2
Year 27	2	2.01	2.01	2.01	2	2	2	2	2	2
Year 28	2	2.01	2.01	2.01	2	2	2	2	2	2
Year 29	2	2.02	2.02	2.01	2	2	2	2	2	2
Year 30	2.02	2.02	2.02	2.01	2	2	2	2	2	2
Year 31	2.02	2.02	2.02	2.01	2	2	2.02	2	2	2
Year 32	2.02	2.02	2.02	2.01	2	2	2.02	2	2	2
Year 33	2.02	2.02	2.02	2.01	2	2.02	2.02	2.02	2	2
Year 34	2.02	2.02	2.02	2.01	2	2.02	2.02	2.02	2	2
Year 35	2.02	2.02	2.03	2.03	2	2.02	2.02	2.02	2	2
Year 36	2.02	2.02	2.03	2.03	2	2.02	2.02	2.02	2.02	2
Year 37	2.02	2.02	2.03	2.03	2	2.02	2.02	2.02	2.02	2
Year 38	2.02	2.04	2.03	2.03	2	2.02	2.02	2.02	2.02	2
Year 39	2.02	2.04	2.04	2.03	2	2.02	2.02	2.02	2.02	2
Year 40	2.02	2.04	2.04	2.03	2	2.02	2.02	2.02	2.02	2

Simulation 10-3 5%

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Year 1	2	2	2	2	2	2	2	2	2	2
Year 2	2	2	2	2	2	2	2	2	2	2
Year 3	2	2	2	2	2	2	2	2	2	2
Year 4	2	2	2	2	2	2	2	2	2	2
Year 5	2	2	2	2	2	2	2	2	2	2
Year 6	2	2	2	2	2	2	2	2	2	2
Year 7	2	2	2	2	2	2	2	2	2	2
Year 8	2	2	2	2	2	2	2	2	2	2
Year 9	2	2	2	2	2	2	2	2	2	2
Year 10	2	2	2	2	2	2	2	2	2	2
Year 11	2	2	2	2	2	2	2	2	2	2
Year 12	2	2	2	2	2	2	2	2	2	2
Year 13	2	2	2	2	2	2	2	2	2	2
Year 14	2	2	2	2	2	2	2	2	2	2
Year 15	2	2	2	2	2	2	2	2	2	2
Year 16	2	2	2	2	2	2	2	2	2	2
Year 17	2	2	2	2	2	2	2	2	2	2
Year 18	2	2	2	2	2	2	2	2	2	2
Year 19	2	2	2	2	2	2	2	2	2	2
Year 20	2	2	2	2	2	2	2	2	2	2
Year 21	2	2	2	2	2	2	2	2	2	2
Year 22	2	2	2	2	2	2	2	2	2	2
Year 23	2	2	2	2	2	2	2	2	2	2
Year 24	2	2	2	2	2	2	2	2	2	2
Year 25	2	2	2	2	2.01	2	2	2	2	2
Year 26	2	2	2	2	2.01	2	2	2	2	2
Year 27	2	2.01	2	2	2.01	2	2	2	2	2
Year 28	2	2.01	2	2	2.01	2	2	2	2	2
Year 29	2	2.01	2	2	2.01	2	2	2	2	2
Year 30	2	2.01	2	2	2.01	2	2	2	2	2
Year 31	2	2.01	2	2	2.01	2	2	2	2	2
Year 32	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 33	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 34	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 35	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 36	2.01	2.01	2	2	2.01	2	2	2	2	2
Year 37	2.01	2.01	2.02	2.02	2.01	2	2	2	2	2
Year 38	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2
Year 39	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2
Year 40	2.01	2.02	2.02	2.02	2.01	2	2	2	2	2

			Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
3-5																						
	20%	P1	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.06
		P2	2	2	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		P4	2	2	2	2	2.01	2.01	2.01	2.02	2.02	2.02	2.02	2.04	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06
		P5	2	2	2.01	2.01	2.01	2.01	2.01	2.02	2.02	2.02	2.02	2.02	2.02	2.06	2.06	2.06	2.06	2.06	2.06	2.06
		P6	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03	2.04	2.04	2.04	2.04	2.06	2.06	2.06
		P7	2	2	2	2	2	2	2	2.01	2.01	2.01	2.01	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06
		P8	2	2	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.06
		P9	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.06	2.06	2.06	2.06
		P10	2	2	2	2	2	2	2	2.01	2.01	2.03	2.03	2.03	2.03	2.04	2.04	2.04	2.04	2.06	2.06	2.06
	OEM	OEM	2.01	2.01	2.01	2.01	2.01	2.01	2.02	2.02	2.03	2.04	2.04	2.04	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06
5-5																						
	20%	P1	2	2	2	2	2	2	2	2	2	2	2	2	2.02	2.02	2.02	2.02	2.03	2.03	2.03	2.03
		P2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03	2.05
		P3	2	2	2	2	2	2	2	2	2	2	2	2.01	2.01	2.01	2.01	2.01	2.03	2.03	2.05	2.05
		P4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03
		P5	2	2	2	2	2	2	2	2	2	2	2	2.01	2.02	2.02	2.02	2.02	2.02	2.02	2.05	2.05
		P6	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03
		P7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03
		P8	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03
		P9	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03	2.03
		P10	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.05
	OEM	OEM	2	2	2	2	2	2	2	2	2	2	2	2.01	2.02	2.03	2.03	2.03	2.03	2.04	2.05	2.05
5-10																						
	20%	P1	2	2	2.02	2.02	2.02	2.02	2.02	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.05	2.05	2.05	2.05	2.05
		P3	2	2	2	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P4	2	2	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.04	2.04	2.04	2.04	2.04	2.04	2.05	2.05	2.05
		P5	2	2	2	2.02	2.02	2.02	2.02	2.02	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P6	2	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P7	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P8	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04
		P9	2	2	2	2	2	2	2	2	2	2	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
		P10	2	2	2	2	2	2	2	2	2.02	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
	OEM	OEM	2.01	2.02	2.02	2.02	2.02	2.02	2.03	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.05	2.05	2.05	2.05	2.05
10-3																						
	20%	P1	2	2	2	2	2	2	2	2	2	2	2	2.02	2.02	2.02	2.02	2.03	2.03	2.03	2.03	2.03
		P2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03	2.05	2.05
		P3	2	2	2	2	2	2	2	2	2	2	2.01	2.01	2.01	2.01	2.01	2.03	2.03	2.05	2.05	2.05
		P4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.03	2.03	2.03	2.03	2.03
		P5	2	2	2	2	2	2	2	2	2	2	2.01	2.02	2.02	2.02	2.02	2.02	2.02	2.05	2.05	2.05
		P6	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		P7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		P8	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		P9	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		P10	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	OEM	OEM	2	2	2	2	2	2	2	2	2	2	2.01	2.02	2.03	2.03	2.03	2.03	2.04	2.05	2.05	2.05

			Year 21	Year 22	Year 23	Year 24	Year 25	Year 26	Year 27	Year 28	Year 29	Year 30	Year 31	Year 32	Year 33	Year 34	Year 35	Year 36	Year 37	Year 38	Year 39	Year 40
3-5																						
	20%	P1	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.09	2.09	2.09
		P2	2.04	2.04	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.09	2.09	2.09	2.09
		P3	2	2	2	2	2	2	2	2	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08
		P4	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.09	2.09	2.09	2.09	2.09	2.09	2.09
		P5	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.07
		P6	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08
		P7	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.09	2.09	2.09	2.1	2.1
		P8	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.1	2.1
		P9	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.1	2.1
		P10	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08	2.08
	OEM	OEM	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.08	2.09	2.09	2.09	2.09	2.09	2.1	2.1
5-5																						
	20%	P1	2.03	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06
		P2	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06
		P3	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07
		P4	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06
		P5	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.07	2.07
		P6	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.07
		P7	2.03	2.03	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.07
		P8	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06
		P9	2.03	2.03	2.03	2.03	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.07
		P10	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06
	OEM	OEM	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07
5-10																						
	20%	P1	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.08	2.08	2.09	2.09
		P2	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.08	2.08	2.09	2.09
		P3	2.04	2.04	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.09	2.09	2.09
		P4	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.07	2.07	2.07
		P5	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
		P6	2.04	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.08	2.08	2.08	2.08
		P7	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.06	2.06	2.06	2.06	2.06	2.06	2.08	2.08	2.08	2.08	2.08	2.08
		P8	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
		P9	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.08	2.08	2.08	2.08
		P10	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.09
	OEM	OEM	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07	2.08	2.08	2.08	2.09	2.09	2.09
10-3																						
	20%	P1	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06
		P2	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06
		P3	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07
		P4	2.03	2.03	2.03	2.03	2.03	2.03	2.03	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.06
		P5	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.07	2.07	2.07
		P6	2	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
		P7	2	2	2	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
		P8	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.07
		P9	2	2	2	2	2	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
		P10	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05
	OEM	OEM	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.05	2.06	2.06	2.06	2.06	2.06	2.06	2.07	2.07	2.07	2.07