Characterisation of the engineering change management process and relationship with artefact knowledge within the product lifecycle

by

William Rowell

Department of Design, Manufacture and Engineering Management

University of Strathclyde

Glasgow, UK

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ABSTRACT

The management of engineering change occurs throughout product development projects. Currently, this process is well documented during the detailed design and production stages; however, little is known in terms of how the engineering change management process varies at different stages of the product lifecycle. In addition, it is not known how artefact knowledge is used and created during the enactment of the activities within the engineering change management process. Addressing this knowledge gap, this thesis presents the findings from a case study of three engineering projects and a survey of seventy nine engineering practitioners from the wider engineering community. To this end, the research reported in this thesis contributes to knowledge by offering evidence that the engineering change management process is fundamentally similar within the product lifecycle; however, eight characteristics have been found to vary. In addition, this thesis also contributes to knowledge by demonstrating the key relationship between artefact knowledge and the engineering change management process. Based on these findings, six recommendations for future engineering change management practice are offered.

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Chapter 1 - INTRODUCTION

Change, the transformation from a previous to a new state, is inevitable during the development of an engineered artefact (Huang and Mak 1999) and has been described as one of the most powerful driving factors in design (Eckert, Clarkson et al. 2004). During the design and development of engineered artefacts, changes are made, leading to a position in which the new state of the engineered artefact represents an improvement over the old state (Eckert, Clarkson et al. 2004). Whilst different definitions exist, a change that impacts upon the structure of an engineered artefact, once the design has been completed or has been released is generally recognised as an engineering change.

Reflecting the necessity for a design to be complete or released, current theory limits the existence of these engineering changes to the latter stages of detailed design and production (Huang, Yee et al. 2003, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006). This leads to the assumption that engineering change only needs to be managed during these lifecycle stages. However, whilst Bhuiyan et al. (2006) has reported that engineering changes were most prevalent during the transition between the detailed design and production stages, during conceptual design and in-service stages of certain engineering projects, processes for the management of changes to an engineered artefact have been observed. Currently, little is known about processes for the management of engineering changes out with the detailed design and production stages. As such, it is currently unclear whether the process is the same within each of stages the product lifecycle or not and what lessons could be learnt from studying the processes used at different lifecycle stages to improve future engineering change management endeavours.

By comparison, the knowledge intensiveness of the engineering change process is better documented, being reported to be one of the key characteristics of this process (Lee, Ahn et al. 2006). Reflecting this, significant research effort has been expended to develop methods to support knowledge of the artefact within the engineering change management process. Of these, a particular emphasis has been placed on supporting knowledge of the artefact's structure. However, literature defines that knowledge of an existing or putative artefact also relies upon knowledge of its function and behaviour (Qian and Gero 1996). In this context, these knowledge types act as a link between the developed structure of the artefact and the artefact's requirements. As such, during the engineering change management process, due consideration of each type of artefact knowledge must be granted to avoid changes compromising the satisfaction of these requirements. At present, little is known about the relationship between artefact knowledge and the engineering change management process. This leads to a lack of knowledge in terms of when is artefact knowledge used and created during the engineering change management process and how does this contribute to the successful management of engineering changes.

Recognising these knowledge gaps, this thesis presents the findings from a literature review, case study of three distinct cases and a survey of seventy nine engineering practitioners that have been triangulated to contribute towards filling these gaps. To that end, this thesis presents a comparison of engineering change management processes at different stages of the product lifecycle, characterising the nature of the processes and the discussing factors that influence the nature of these processes. This leads towards the development of recommendations on how the engineering change management process could be improved based on these findings. In addition, this thesis presents an overview of the types of artefact knowledge that are used and created during the enactment of the activities that compose the engineering change management process. Based on the findings from this research, recommendations on the support of artefact knowledge during the engineering change management process are offered. In addition, guidance is provided on the future development of engineering change support systems, outlining the types of artefact knowledge that should be supported.

1.1 Scope of the work

The research reported in this thesis focuses on the activities that are enacted during the engineering change management process at different stages of the product lifecycle and the artefact knowledge that is used and created through the enactment of these activities. Reflecting this, the domain of the research work contained within this thesis is bounded by four main considerations:

The type of change

The focus of this research work is based upon engineering change. Whilst there are a number of definitions of engineering change available in literature (see chapter 2, section 2.2 for discussion), this thesis adheres to the following definition for engineering change: a modification to any aspect of an artefact’s structure that had been set during its current development project.

Type of engineering artefact

Research by Pikosz and Malmqvist (1998) and Tavčar and Duhovnik (2005) informs that different types of engineering artefacts can influence the engineering change management process. As such, to mitigate the effects of different types of engineering artefact, the scope of this study is constrained to complex, low quantity, highly customised design-to-order, physical engineering artefacts that represent an innovative level of newness as defined by Tavčar and Duhovnik (2005) (see section 2.4 for discussion on product levels). To illustrate, this includes engineering artefacts such as specialised military equipment and bespoke industrial machinery, rather than general domestic artefacts such as cars and vacuum cleaners or software products.

Activities and artefact knowledge usage and creation

The engineering change management process is composed of a number of interrelated activities. Within this thesis, only the activities that can be associated with the engineering change management process with a high degree of certainty are considered to be part of this process. Based on a literature review, these activities are defined (see section 2.3) and any further activities explicitly described in the subsequent research chapters (chapters 6, 7 and 8) contained within this thesis. In addition, whilst different types of knowledge can be linked to the engineering change management process, this thesis is only concerned with artefact knowledge in the forms of function, behaviour and structure. To define these forms, a review of literature is presented in chapter 3. As such, only artefact knowledge in these forms that are used and created are related to the activities that compose the engineering change management process

Product lifecycle

Literature reports many models that represent the lifecycle of a product. Based on this literature, this thesis takes the product lifecycle to consist of six stages: requirements capture, conceptual design, detailed design, production, in-service and disposal. For clarity, of these the engineering change management process is only studied in the conceptual design, detailed design, production and in-service stages. A further description of these stages is provided in section 2.1.2.

1.2 Aim and objectives

1.2.1 Aim

The primary aim of this thesis is to characterise the variations in the engineering change management process within the product lifecycle and explore the relationship between this process and artefact knowledge. Based on the findings from this study, recommendations for improving existing engineering change management practice shall be offered.

1.2.2 Objectives

In order to achieve this aim, four objectives have been identified as being needed to be met:

1. Synthesise and discuss relevant literature in the field of engineering change management, offering contextual definitions for key terminology in the field, an outline of the knowledge gap addressed in this thesis and the design for the research to fill this knowledge gap
    a. Present a definition of engineering change and the engineering change management process that are adopted throughout the thesis.
    b. Report the activities that compose the engineering change management process.
    c. Report the types of artefact knowledge that are used and created during the enactment of these activities.
    d. Discuss limitations of existing work, present the knowledge gap that this thesis has been prepared to fill and justify why this knowledge is needed.
    e. Design the research methodology so that the research is executed in a controlled and systematic manner.

2. Present empirical evidence of the activities that are enacted during the engineering change management process and the artefact knowledge that is both used and created during the enactment of these activities:
    a. Execute a case study to establish which activities compose the engineering change management process at different stages of the product lifecycle and to establish the types of artefact knowledge that these activities use and create during their enactment.

   b. Cross reference the findings from each of the cases to establish the variations between the enactment of the activities that compose the engineering change management process and the artefact knowledge that these activities use and create.
   c. Execute a survey to determine whether the findings from the case study reflect how engineering change is managed in the wider engineering industry.
   d. Triangulate the results of the case study and survey, presenting evidence of the activities that are enacted during the engineering change management process and the artefact knowledge that is used and created through the enactment of these activities.

3. <u>Present the impact of the research in terms of how the results should influence future engineering change management practice and outline how the sponsoring company has exploited the findings</u>
   a. Offer recommendations for improving the engineering change management process based on the results from the research.
   b. Discuss the implication of the findings, outlining how the findings have been and will be exploited by the sponsoring organisation.

4. <u>Discuss the benefits and limitations of the research findings and approach used to obtain these findings, offering conclusions and avenues for further research:</u>
   a. Analyse the strengths and weaknesses of the main findings, research strategy and research methodology.
   b. Identify avenues for future work that are related to the output of the research.
   c. Explicitly describe the contributions contained within this thesis, including the implications for engineering change management theory and practice.

1.3 Thesis structure

This thesis is organised in three main parts: research problem formalisation; investigation and findings, and discussion and conclusion. The content of these three parts is described below, based upon the chapters of the thesis:

<u>Part I – Research problem formalisation (chapters 2, 3, 4 & 5)</u>

Chapter 2 commences with a review of definitions for engineering change management, discussing the similarities and differences before offering a description of engineering change that is adhered to within this thesis. It then progresses to present a review of literature related to the engineering change management process, reporting the twelve activities that compose the engineering change management process.

Chapter 3 builds upon the activities that have been found to compose the engineering change management process. This chapter details the types of artefact knowledge that are used and created through this process. From this, a model of artefact knowledge usage and creation during the enactment of the activities that compose the engineering change management process is presented.

Chapter 4 commences with a discussion of the limitations associated with current knowledge of the activities that compose the engineering change management process and what types of artefact knowledge are used and created though the enactment of these activities. As such, two research questions are proposed. The first relates to the lack of knowledge of what engineering change management process activities are enacted at different stages of the product lifecycle. The second focuses on the lack of clarity over how artefact knowledge relates to the activities that compose the engineering change management process.

Chapter 5 details the research design that has been adopted to answer the research questions described in the previous chapter. Based upon post-positivism, the triangulated methodology that has been utilised within this research is presented. As such, the use of case study and survey methods are presented and justified.

Part II – Investigation and findings (chapters 6, 7, 8 & 9)

Chapter 6 describes the findings from the individual cases that form the case study, presenting a review of engineering change management processes within these cases. Each case concludes with a summary of the key findings.

Chapter 7 presents a cross case analysis focussing on the variations in the enactment of the activities between the cases and the artefact knowledge that is used and created during the enactment of these activities. In addition, emergent insights based upon the formality and goals of the engineering change management process are also presented.

Chapter 8 presents the findings from a survey within the wider engineering community, executed to triangulate the findings from the case study. As such, a quantitative representation of activity enactment and artefact knowledge usage and creation is offered.

Chapter 9 presents a triangulated description of the activities that compose the engineering change management process at different stages of the product lifecycle and the artefact knowledge that is used and created through the enactment of these activities. Furthermore, any variations in activity enactment are presented along with emergent insights into the formality and goals of the engineering change management process.

Part III –Discussion, research exploitation and conclusion (chapters 10, 11 & 12)

Chapter 10 commences with a presentation of the answers to the research questions based on the triangulated findings from this research. It also, provides a discussion of the work in terms of its strengths and weaknesses in two areas: research strategy and research methodology. In addition, lessons learnt, implications for engineering change management practice and future work are also presented.

Chapter 11 outlines the impact of the research, highlighting how the research has influenced the sponsoring company outlining the four issues that were addressed and three cases in which these were addressed.

Chapter 12 concludes the thesis with a description of the primary and secondary knowledge contributions of the research.

Chapter 2 - ENGINEERING CHANGE AND THE ENGINEERING CHANGE MANAGEMENT PROCESS

Acting as a summary of work in the field of engineering change and engineering change management processes, the intention of this chapter is threefold. Firstly, it acts to inform the reader of some of the key terminology used in the thesis, covering both engineering change and the engineering change management process. Secondly, it reports on previous work in the field, with particular emphasis on the activities that compose the process through which engineering changes are managed. Thirdly, it presents a brief discussion on the knowledge gap that this thesis addresses, of which further elaboration is presented in chapters 3 and 4. As such, prior to reporting the findings from literature, section 2.1 outlines the approach that has been taken for this literature review. Section 2.2 the commences to detail a review of published definitions for the term engineering change, discussing the similarities and differences in these before reporting the definition that is adhered to within this thesis. Following this, section 2.3 proceeds to discuss engineering change management, focussing on the processing of engineering changes and leads to the synthesis of a five phase model of the engineering change management process, composed of twelve distinct activities. This model is then discussed in section 2.4, offering an insight into the knowledge gap that this thesis addresses. Finally, in section 2.7 the chapter is summarised.

2.1 Approach to the literature review

Mulrow (1994) reports that in a range of academic fields, the volume of published literature that relates to a specific subject can be significant, leading to a situation in which it is not possible to read and review all of this work in detail. Recognising this constraint, a range of methods for systematically identifying, evaluating and synthesising relevant articles have been developed, e.g. Greenhalgh (1997). These methods enable the researcher to navigate through the available literature and establish the most salient and critical pieces of work that could influence thinking upon a specific topic.

Within literature on systematic literature reviews, a range of processes have been outlined (Egger and Smith 2008). These processes follow a similar theme in terms of steps that they advocate and the premises upon which they should be applied. At the core of these processes is the definition of explicit search criteria, search locations and objectification of the selection criteria. However, extending this process is a key step in which the quality of the content is quantified and ranked, leading to an explicit definition of the key papers in the field.

Whilst the approach to the literature review that was conducted for this thesis did not follow that of the systematic literature review method advocated by Greenhalgh (1997) in terms of explicitly quantifying the quality of the reviewed literature, the approach followed the initial steps of this process. As such, the following literature review focussed on finding articles in electronic databases that were searched regularly throughout the research period, including: Sciencedirect, Web of Knowledge, Emerald full text and Google Scholar. In addition, a key focus was placed upon engineering design journals as it was recognised that a number of key papers had been published within these. These were predominantly the Journal of Engineering Design, Research in Engineering Design, Design Studies and Artificial Intelligence in Engineering Design and Manufacture. However, reflecting the diverse nature of engineering change research, publications were also found in a range of manufacturing and operations management journals.

During these searches key terms such as engineering change, artefact knowledge and change management processes, were searched within electronic databases to find a range of texts. The abstracts of these papers were then read in the context of the research questions (presented in section 4.4) and those that were deemed to contain a contribution that facilitated an improved understanding of these questions were read in full. Once these papers had been read in full, the references in these papers were checked and any of these that were deemed relevant were obtained and read as well. This process continued until no further papers were found within the references that provided any greater insight into the research questions. In addition, citation alerts were set up so that whenever a paper that had been deemed to be relevant was referenced by a paper that had just been published; an email was sent to the researcher. This enabled the researcher to keep abreast of literature throughout the research period.

2.2 Defining engineering change

As the focus of this research is on engineering change, it is important to define the term engineering change to establish the boundaries of this type of change. Whilst this may seem like a trivial task, actually defining engineering change is not as straight forward as may be first considered, an observation also supported by Jarratt et al. (2011). This is due to both the multiple definitions presented by different authors and the number of authors who present research in this field but who do not detail which of these descriptions that they adhere to e.g. (Balcerak and Dale 1992, Peng and Trappey 1998, Keller, Eckert et al. 2009). Sudin and Ahmed (2009) were the first to present a number of different definitions in a single paper, highlighting the range of these definitions. As a result of these different definitions, clear comparisons between these different papers can be difficult to draw. In the following paragraphs, this lack of comparability is demonstrated through a discussion on the multiple definitions for engineering changes that are reported before the content of these definitions are discussed based upon two commonalities: what changes and definitional constraints. A decomposition of papers that present definitions for engineering change based on these two commonalities can be found in Table 1.

Table 1 - Definitions of engineering change

Author	What changes?	Definition constraints
(Harhalakis 1986)	Fit, form, function, part	-
(Wright 1997)	Component of a product	After the product has entered production
(Huang and Mak 1998) (Huang and Mak 1999) (Huang, Yee et al. 2001) (Huang, Yee et al. 2003)	Component, dimensions, fit, form, function, materials, parts (only in (Huang and Mak 1998)), product	After the design is released (only in (Huang, Yee et al. 2003))
(Terwiesch and Loch 1999) (Loch and Terwiesch 1999)	Drawings, parts, software	That have already been released
(Barzizza, Caridi et al. 2001)	Component part, design, existing product	-
(Tavčar and Duhovnik 2005)	Product's component	After the product has entered production
(Lee, Ahn et al. 2006)	Components, products	After product design is complete
(Habhouba, Desrochers et al. 2007)	Mechanical documents, parts, processes	-
(Kocar and Akgunduz 2010)	Dimensions, fit, form, function, materials, parts	-

Harhalakis (1986) reports engineering change as any modification to a part that affects its form, function or fit. Huang et al. (2001) develop this by adding materials and dimensions of products and constituent components as attributes that if changed can be regarded as an engineering change. Habhouba et al. (2007) define engineering change as changes upon mechanical documents, parts or processes. Some authors term engineering change as an alteration in the design of an existing product or component part (Barzizza, Caridi et al.

2001) whilst others refer to engineering change as an alteration of a component after it has entered production (Tavčar and Duhovnik 2005) or after it has been released by the design department (Loch and Terwiesch 1999). Currently engineering change is used as both a term for development (Huang, Yee et al. 2001, Bhuiyan, Gatard et al. 2006) and rework (Terwiesch and Loch 1999, Tavčar and Duhovnik 2005), with related research projects focussing on the design stage (Clarkson, Simons et al. 2004, Oduguwa, Roy et al. 2006) but also spanning into the manufacturing stage (Do, Choi et al. 2008) of the product lifecycle. Engineering changes have been presented as ranging from simple modifications to wide spread redesigns of product and project management systems (Clarkson, Simons et al. 2004). Organisational changes and strategic changes are not essentially directly related to the design of a product and hence are not usually referred to as engineering changes, however may influence or be influenced by engineering changes (Huang and Mak 1999).

In total thirteen definitions for the term engineering change have been collected. Reviewing these definitions, two commonalities have emerged. Firstly, all the definitions propose examples of items that if changed can refer to engineering changes. As such, thirteen examples are offered: components, design, dimensions, documents, drawings, fits, forms, functions, materials, parts, processes, products and software. Secondly, six of the referenced papers (Wright 1997, Loch and Terwiesch 1999, Terwiesch and Loch 1999, Huang, Yee et al. 2003, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006) place constraints upon the definitions that they offer for engineering change, leading to the position in which only changes to the aforementioned items that satisfy these conditions can be considered to be engineering changes. Based upon the content of these two commonalities, insights into the nature of engineering change can be reported. As such, in the following section the content of these decomposed definitions are discussed and conclusions drawn to provide an insight into the nature of engineering change. Based on these insights, the definition for engineering change that is adhered to within the context set in this thesis is subsequently presented and justified.

2.2.1 What changes?

Based on the twelve items that define what, if modified, can be referred to as an engineering change, different groupings of these terms emerge providing an insight into the nature of engineering change. The first grouping encompasses the terms components, parts and products. Through the use of general descriptors, these terms demonstrates that engineering changes must be enacted upon a product, or a discrete decomposition of that product. Analysing the use of the term product, it was found that the Oxford English Dictionary (2010) defines a product as an object that is created as the result of mental or physical effort. As such, a product represents an object that has been produced. However, this does not mean that the product has to have been through a production process in the traditional manufacturing context as Eder and Hosnedl (2008) report that a product can also be defined as the output of a transformation process. Based on this definition, a design can be considered to be the product of a cognitive process (Peña and Logcher 1992) in the same way that a physical output of a manufacturing process can be considered to be a product. Referring to the usage of the term product in the reviewed definitions of engineering change, the authors do not make a distinction between manufactured products and products of a cognitive process as items that can change. Therefore, engineering change is not limited by affecting only manufactured products but can affect products that are yet to be manufactured as well. Reflecting this, in this thesis, the term engineering artefact is used synonymously to describe either a physical product or a design, where a physical product can be considered to be the physical realisation of a design.

Given the context, the next grouping of terms provides a more detailed description of what it is about the engineering artefact that actually changes. This grouping contains the terms dimensions, fit, form, function and materials. Focussing initially on the term form, literature suggests that form can be described as the surface geometry or shape of outline of an object, related by points in space (Gorti and Sriram 1996, Lai, Lin et al. 2005, Urbanic and ElMaraghy 2009). Based on this definition, it is evident that a modification to the external shape of an object or component could be referred to as an engineering change. In addition to a modification to the form being referred to as an engineering change, modifications to the relationships between the components are also reported to be affected by engineering changes. A modification to the relationships between components is also evident in the use of the term fit, where fit is taken to be the mating between two or more interrelated components (Zhang, McClain et al. 2000). A modification to the dimensions could also be referred to as an engineering change, where, based on work presented by Farmer and Harris (1984) a dimension can be offered as a specific, quantified measure of the size between a datum and a referenced location. In addition, a modification to the materials that the components are either made from or are due to be made from can be referred to as an engineering change. Given the nature of these terms, it can be concluded that an engineering change is a modification to the structure of the engineering artefact where the structure is taken as both the items that compose the engineering artefact and the relationships between these items.

Whilst most of the described terms refer to changes to the structure of an engineering artefact, others terms are also described. Most notably, the function is presented as a property that can change. However, the function of an engineering artefact, defined as its purpose or intention (Hybs and Gero 1992, Qian and Gero 1996, Wang, Duffy et al. 2007), is not part of the structure as such. Instead, Wang et al. (2007) report that the function of an engineering artefact is a construct that is used to rationalise the development of an engineering artefact. As such, a change to the function seems to contradict the previous insight, suggesting that engineering change does not have to affect the structure of an engineering artefact. However, applying this to an example draws out the weakness in this argument, as a brick that has been developed for use in the construction of a building can be used just as effectively to open a nut. This shift in function does not appear to represent an engineering change as adhered to by authors within this field. Instead, a change to the function is considered to be a factor that can initiate a modification to the structure of an engineering artefact but a change to the function that does not result in a change to the structure of an engineering artefact is not considered to be an engineering change per se.

The next grouping encompasses the terms design, documentation and drawings. Fundamentally, these terms describe representations of the engineering artefact. Whilst documents and drawings are instantiated representations of an engineering artefact, Wang et al. (2007) argues that the design of an engineering artefact does not solely exist within an instantiated form. Indeed Wang et al. (2007) proceeds to report that documents and drawings are external to the design domain, being outputs from this cognitive process in the form of information rather than knowledge. Peña and Logcher (1992) refer to this design domain as an extension of the hierarchical decomposition of the engineering artefact that is composed of the design problem that requires to be conceived, described and developed. In such a situation, an engineering change can be concluded to change both the design domain and the instantiated representations of the design domain. However, given the separation of the design domain from the drawings and documents that describe this domain, an engineering change may not result in a modification to both.

The final grouping composes two terms: processes and software. Of these terms, Habhouba et al. (2007) reports that as a result of engineering change management, processes can be modified. This is mirrored by a publication by Huang and Mak (1999) who argue that engineering changes can be as complicated as the entire redesign of manufacturing processes. However, Huang and Mak (1999) proceed to state that only engineering changes that are directly related to the design of an engineering artefact can be referred to as an engineering change. As such, processes associated with the development of an engineering artefact may change as a result of an engineering change, but changes to these processes are not considered to be engineering changes per se. Likewise, Loch and Terwiesch (1999) report software as an item that could change as a result of an engineering change, but do not constrain the definition of engineering change to a modification to the software. As such, an engineering change can result in the modification to software, but within this thesis changes to software are not considered to be engineering change per se as these do not necessarily affect the structure of the engineered artefact.

Summarising what, if modified, can be referred to as an engineering change four insights can be offered:

1. Engineering change enacts upon an engineering artefact.
2. An engineering change is evident as a modification to the structure of an engineering artefact.
3. A change to the function of an engineering artefact can cause an engineering change, but is not an engineering change per se.
4. An engineering change may or may not be evident in the documents, drawings, software or processes associated with the design of the artefact.

2.2.2 Definitional constraints

In addition to defining what, if modified, can be referred to as an engineering change, six of the definitions (Wright 1997, Loch and Terwiesch 1999, Terwiesch and Loch 1999, Huang, Yee et al. 2003, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006) have been found to contain statements that constrain the term engineering change, relating these constraints to the concept of the product lifecycle. Within literature there has been a long standing recognition that the product lifecycle can be decomposed into distinct, yet interrelated stages. A review of literature demonstrates a vast array of models that describe these stages. With examples such as the CADMID cycle (Chandler 2003), total design process (Pugh 1990), Vee-model (Forsberg and Mooz 1991) and waterfall model (Royce 1970), amongst a significant list of others, a range of names and definitions for these stages are reported. Synthesising the similarities between a number of these models, the product lifecycle is taken to consist of six interrelated stages: requirements capture, conceptual design, detailed design, production, in-service and disposal (see Figure 1). Whilst these stages can be considered to be distinct stages throughout a product's lifecycle, actually identifying these stages explicitly can be difficult. As such, for clarity a brief overview of what is involved during each of the stages of is presented:

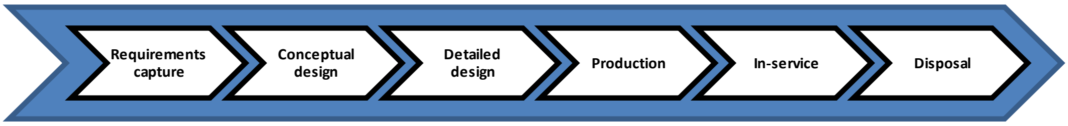


Figure 1 - A model of product lifecycle

- **Requirements capture:** Prior to solution preparation, in the requirements capture stage the desired functional and performance characteristics of the product are established. As such, the requirements detail the intention of the product and can be considered on both a functional and non-functional basis (Roman 1985).
- **Conceptual design:** In the conceptual design stage, the functional and performance characteristics are translated into design parameters that are realised through the creation of a physical solution (Zhang 1999). As such, the physical solution bridges the gap between the function and performance characteristics that are required of a product and the physical form that the product is intended to embody.
- **Detailed design:** In the detail design stage a definitive layout is created, refined and optimised (Pahl and Beitz 1996). In particular the structure of the solution and the shapes, dimensions, tolerances, surface properties and materials of all the individual parts in the solution are fully specified and documented in the assembly drawings, detail drawings and part list (Zhang 1999). Essentially, the output from the detailed design stage should provide all the necessary information to enable production to begin.
- **Production:** The production stage is executed to transfer the abstract representations of the proposed design artefact into a physical product that meets the desired functional and performance characteristics. As such, the production stage involves the manufacturing, assembling and testing of the physical product as well as the creation of production related support systems as needed. The product may be individually produced, assembled, integrated and tested as appropriate or may be mass-produced (Standardisation 2002).

- **In-service:** The in-service phase represents the period after which the product has been delivered to the customer. During this period the product may undergo maintenance, conducive with re-establishing previous performance or incorporating new functionality (Tang and Yun 2008).
- **Disposal:** The disposal stage refers to the removal of the product and related operational and support services. This involves the consideration and preparation of recycling strategies and disposal plans (Tang and Yun 2008).

Relating this back to the definitional constraints presented in Table 1, Wright (1997) and Tavčar and Duhovnik (2005) report an engineering change as occurring after the engineering artefact has entered production, Terwiesch and Loch (1999, 1999) and Huang et al. (2003) report an engineering change as occurring after a design has been released whilst Lee et al. (2006) report and it as occurring after a design is complete. Of these, perhaps the most telling is that of Huang et al. (2003), who only added this constraint to their definition following the publication of three previous papers in which the term engineering change had also been defined (Huang and Mak 1998, Huang and Mak 1999, Huang, Yee et al. 2001). However, what is actually meant by the term released is not discussed and as such it is unclear.

Based on these definitions, engineering change has been considered to exist primarily within the latter stages of the development of an engineering artefact. In particular, phrases such as “after the product design is complete” (Lee, Ahn et al. 2006) or “after the product has entered production” (Wright 1997, Tavčar and Duhovnik 2005) have been used to constrain definitions of engineering change. However, building on some recent research (Keller, Eckert et al. 2009), engineering change can be argued to exist in the earlier stages of engineering artefact development as well; a point further emphasised by Jarratt et al. (2011). Further due to the uncertainty around the usage of the termed “released” (Loch and Terwiesch 1999, Terwiesch and Loch 1999, Huang, Yee et al. 2003) and “complete” (Lee, Ahn et al. 2006), recent developments have indicated that engineering changes can exist as early as within the conceptual design stage (see Figure 2).

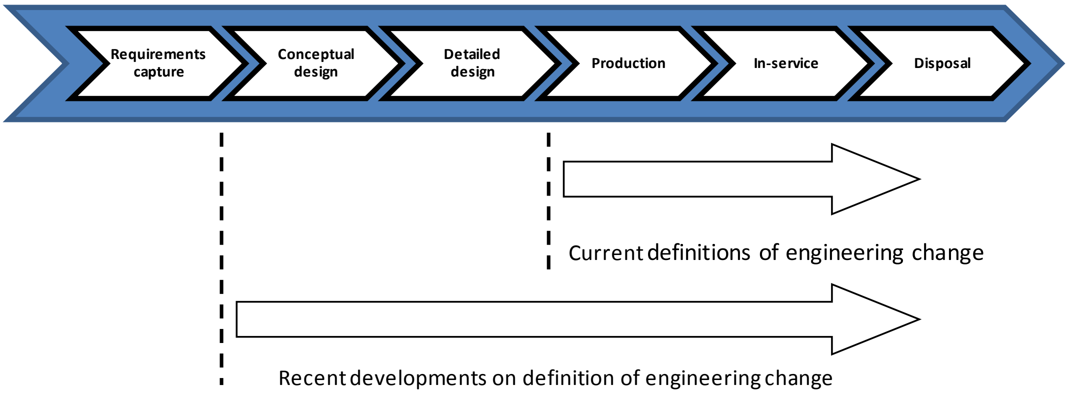


Figure 2 - Definitions of engineering change

Given the realisation that engineering changes are not constrained to specific lifecycle stages, the definitional constraints must be revisited to discuss the nature of these constraints. During the development of an engineering artefact, the artefact proceeds through developmental stages, each with their own unique outputs (Zhang 1999) as outlined previously. Progressing through these stages, decisions are taken that constrain the development of the engineering artefact and enable a greater level of detail to be incorporated. These decisions initially affect the parameters that constrain the major interacting sub-systems, but not the component parameters that compose these sub-systems (Rawson and Tupper, 1994): this level of detail is produced in the latter stages of the development process. For example, the complement, length and underwater hull form of a ship are defined prior to the diameter of bolts, length of weld runs or positions of pipes. Throughout the design process parameters are progressively set, constraining the design of an engineering artefact. As such, when an engineering artefact transitions between different stages, enters production or is considered to be complete requires a level of certainty that the parameters that are defined are not going to change. An engineering change therefore refers to the event where a structural parameter that is generally accepted to be its final development state, is modified. This general acceptance may well be provided through the provision of detailed drawings, but equally could be a documented or widely accepted parameter that constrains the design of the artefact

Summarising the definitional constraints that are described in relation to definitions of engineering change, one insight can be offered:

1. Engineering changes are constrained to cases where a structural parameter that was generally accepted to be its final development state, is modified.

2.2.3 Engineering change definition

Based on the review of definitions for the term engineering change, it is evident that a single definition has yet to be agreed upon. As such, in literature the term engineering change is presented and defined in the context of subtly different cases. Nevertheless, reviewing these different definitions a number of insights into the nature of engineering change have been identified and presented based on the commonalities between these. Synthesising these insights, this thesis adheres to the following definition for engineering change:

> **A modification to any aspect of an artefact's structure that had been set during its current development project.**

This definition differentiates from previous definitions in a number of ways. Firstly, it stipulates that an engineering change must affect an artefact's structure. Changes to an artefact's behaviour or functional parameters may be referred to as an engineering change only if they result in the modification to the structure of the artefact. Secondly, the use of the phrase [any aspect] that had been *set* opens up the definition to additional lifecycle stages as the setting of certain structural aspects permeates the product lifecycle. For example, in the example of car design, the length of the chassis will be set early in the product lifecycle. As such, any change once this has been set will be referred to as an engineering change. Finally, this definition constrains engineering change to a modification within the current development project. This is in recognition that during a product development cycle, in which a previous design was used as a basis for the future design, aspects will have been set in the previous development project. However, in the current development project the same structural aspect may well be known to be subject to change. For example, the length of the chassis of a car will have been set in a previous project, yet may well be subject to change in the current project. As such, when the project commences, any change to this will not be an engineering change until the length of the chassis has been set within the current development project.

2.3 Engineering change management

Huang et al. (2001) reported that engineering changes during the development of an engineering artefact are inevitable. Indeed, a range of research projects have sought to quantify the number of changes that can occur throughout a product's development cycle (Bhuiyan, Gatard et al. 2006, Sudin and Ahmed 2009). In parallel, research has shown that changes later in the development cycle or during the service stage, are more expensive than those that occur earlier, with Kidd and Thompson (2000) suggesting it could be as much as ten times more expensive to make an alteration in a later stage than in the present. Given this added expense it could be considered that engineering changes should be prioritised to be completed during the early stages of development. However, a recent case study in an engineering firm presented by Bhuiyan et al. (2006) acted as a reminder that the number of engineering changes can still peak during the latter stages. Based on this knowledge, it is not difficult to accept McIntosh’s (1995) statement that engineering changes can constitute as much as 70 – 80% of the final cost of a product.

Whilst engineering changes bear a finanical cost, this monetry impact is not the only effect associated with this phenomenon. In another case study of engineering change in a manufacturing organisation, Hegde et al. (1992) found that for each engineering change that was raised a single part would take an additional 22 days to proceed through the production system. Likewise, Terwiesch and Loch (1999) reported that it is not uncommon for the processing and implementation of engineering changes to require between a third and half the total engineering capacity on a project. Engineering changes also have a distinct impact on the efficiency of a development project. Supporting this statement, Blackburn (1992) suggested that in airframe manufacturing, the value adding periods associated with the processing of engineering changes can be as low as 8.5%. Coupling this knowledge with research cited by Wasmer et al. (2011), reporting that in 2005 within just three engineering organisations (Ford, GM and DaimlerChrysler) around 350,000 engineering changes were cumulatively recorded at an average cost of $50,000, the value of the inefficiencies associated with engineering changes can be considerable.

Given the associated costs, delays and inefficiencies that can be caused, it could be assumed that engineering changes are detrimental to any engineering project. However, offering an opposing view, Wright (1997) suggests that whilst the significant impacts associated with engineering changes cannot be ignored, they can also represent a source of opportunity. Describing that whilst engineering changes can be viewed with distain by manufacturing, by inventory control as being costly and by production control as being confusing, the marketing function views the process as a mechanism for staying competitive. This intriguing dichotomy highlights the duality of opinion on engineering change, with the mitigation of these negative consequences representing a core driver in engineering change research.

To mitigate these negative consequences, a number of engineering change management strategies have been reported. With the aim of decreasing the difficulty of implementing engineering changes, Fricke and Schulz (2005) outline that engineered artefacts should incorporate changeability into their system architecture. As such, when a change is required to an engineered artefact, the number of hours of work that is required to implement this change could be reduced. Further, work in the systems engineering domain has outlined that the cost to extract defects from an engineered artefact, increases significantly as an engineering project moves through the product lifecycle (Kidd and Thompson 2000). As such, to combat this, systems engineering theory advocates trade space exploration of different options at the start of the engineering project to reduce the number of engineering changes that are required later within the product lifecycle (INCOSE Systems Engineering Handbook, v.3.2.2).

Whilst a number of strategies exist for the management of engineering change, the implementation of a recognised engineering change management process is reported as being very common in industry. Indeed, in a recent survey of the UK's manufacturing industry, over 90% of the 150 organisations that responded reported that they formally managed engineering changes (Huang and Mak 1999). Reflecting this, in literature, the process for the management of engineering change has received increasing research attention with a number of authors offering innovative methods for this (Flanagan, Eckert et al. 2003, Clarkson, Simons et al. 2004). Nevertheless, as engineering change is considered to be an inevitable phenomenon (Huang, Yee et al. 2001) in the development of an engineering artefact, so a process for managing this phenomenon is also considered to be required. Based on this, the following section presents current research on the process that drives the management of engineering change leading towards a taxonomy of the activities that compose the engineering change management process.

2.3.1 Engineering change management process overview

The engineering change management process has been reported to be a process that is often referred to but seldom defined (Jarratt, Eckert et al. 2011). Nevertheless, an argument has been proposed that the engineering change management process is similar to a small scale, highly constrained design process or project (Leech and Turner, 1985). In another paper, this process has been described as the process of making engineering changes to a product in a planned or systematic fashion (Rouibah and Caskey 2003). As such, an engineering change management process can be represented as a sequence of activities (Chen, Shir et al. 2002). Given that the input to the process is generally a requirement to improve some aspect of an engineering artefact, precipitating as the motivation to change (Eckert et al., 2006) and results in a modification to the structure of an engineering artefact that reflects this improvement, an appropriate description can be offered. As such, the engineering change management process is referred to within this thesis as:

> **A series of interrelated activities that progress from the identification of a problem or opportunity with an engineered artefact to an implemented solution that modifies any aspect of an artefact's structure that had been set during its current development project.**

The engineering change management process has been reported as to vary across different organisations (Pikosz and Malmqvist 1998) and different types of product development project (Tavčar and Duhovnik 2005). It has been reported as being a complex process, handling various types of knowledge and requiring collaboration amongst distributed engineers (Lee, Ahn et al. 2006). Mirroring this, current literature presents a range of engineering change management processes that have subtle variations. Based on the activities that are described in nine of these processes, a categorisation of the activities is presented in Table 2. Grouping similar activities together, the different engineering change management processes have emerged to consist of distinct phases, each containing a number of activities. As such, using this phased model of engineering change management processes, a structure is presented through which different engineering change management processes can be discussed.

Table 2 - The various phases of the engineering change process

Authors	Engineering change process phases					
(Hwang, Mun et al. 2009)	Identification problem	Alternative solutions	Definition of changes	-	Realisation of changes; roll-out in production	-
(Eckert, de Weck et al. 2009)	Detection of the need of a change	-	Pre-evaluation of the change; Technical and organisational planning of the change; Evaluation of a change	Decision making on this change	Realisation of the change	-
(Motawa, Anumba et al. 2007)	Identify	-	Evaluate; propagation	Approval	-	-
(Lee, Ahn et al. 2006)	Detecting problems; discussing problems	Raising engineering change request	Analyse engineering change request; investigate other effects; cost analysis	Engineering approval	-	Validate new data
(Tavčar and Duhovnik 2005)	-	Idea – change request	Change preparation	Change approval	Implementation in production; change of documentation	-
(Jarratt, Eckert et al. 2004)	Identify the need for a change	-	Evaluate the possible impacts of the change	Approve the change	Implement the change	Review the change
(Rouibah and Caskey 2003)	-	Definition of the design change required	Identification of the parameters to be changed	-	Change control of the parameter	Audit of parameters affected by this change; Recording the change for historical reference
(Peng and Trappey 1998)	-	Engineering change request	Evaluated by departments; test and record;	-	Engineering change action; engineering data updating	-
(Maull, Hughes et al. 1992)	-	Filter proposal; Design investigation	Appraise design	Authorise change	Execute change	-
Synthesised classification	Identification	Generation	Prediction	Approval	Implementation	Post-change review

Synthesising the various engineering change management processes, purports a six phase classification: identification, generation, prediction, approval, implementation and post-change review. Briefly, in the identification phase the inadequacy in the definition of an engineering artefact is established, in the generation stage a new solution that overcomes this inadequacy is developed, in the prediction stage the probable effects of implementing the new solution are forecast, in the approval stage a decision is taken over whether to implement the new solution or not before the new solution is implemented and the structure of the engineering artefact modified before the solution is then reviewed. However, interpreting the description of the engineering management process as a process of making engineering changes to a product in a planned or systematic manner (Rouibah and Caskey

2003), the end point of the process seems to be the executing or implementing of an engineering change. Therefore, whilst the post-change review phase exists in three of reviewed engineering change management processes (Rouibah and Caskey 2003, Jarratt, Eckert et al. 2004, Lee, Ahn et al. 2006), within this thesis it is not considered to be a core phase of the engineering change management process per se. This is reflected by Huang and Mak's (1999) survey in which they found that auditing and reviewing activities were only enacted by approximately one third of all corresponding companies. Likewise, Jarratt et al. (2011) reported that reviewing is not enacted by all companies during engineering change management after the change has been implemented. As such, whilst this activity may be enacted in certain circumstances, this is not considered to be a core phase of the engineering change management process per se. On this basis, the engineering change management process is considered to consist of five fundamental phases: identification, generation, prediction, approval and implementation.

The relationships between the phases in the nine reviewed engineering change management processes have been seen to vary. Some suggest a sequential relationship (Peng and Trappey 1998, Jarratt, Eckert et al. 2004, Tavčar and Duhovnik 2005, Hwang, Mun et al. 2009) with the output of each phase subsequently representing the input to the following phase in a consecutive manner. In comparison, the others (Maull, Hughes et al. 1992, Rouibah and Caskey 2003, Lee, Ahn et al. 2006, Motawa, Anumba et al. 2007, Eckert, de Weck et al. 2009, Jarratt, Eckert et al. 2011) suggest that feedback relationships can exist between the phases in which the outputs from a single phase may be used as the input for a phase that has already occurred. For example, if a proposed solution that has been generated is rejected in the approval phase, then rather than the process stopping, this can act as the stimulus for another new solution to be generated and subsequently processed. Summarising the relationships offered by the authors cited previously in this paragraph, Figure 3 demonstrates the possible relationships between the phases. In this figure the solid lines represent sequential relationships whilst the dashed lines represent feedback relationships.

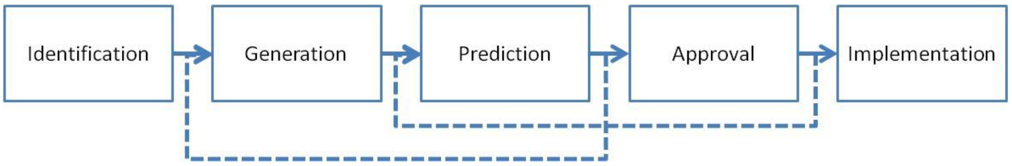


Figure 3 - Relationships between stages of the engineering change management process

2.3.2 Engineering change management process activities

Composing the synthesised phases of the engineering change management process is a number of associated activities. Huang and Mak (1999) reported fourteen such activities that embodied the engineering change management process prior to executing a survey to establish how frequently these activities were performed within industrial engineering change management processes. These activities were: identify change opportunities; prepare engineering change proposals; receive engineering change application; raise engineering change proposal; filter change application (eliminate duplications, etc.); submit engineering change requests; receive/record/ update keep track of change request; work out solution alternatives and choose one of them; analyse/evaluate the effects (costs and benefits) of the change; prioritise/classify changes; approve/authorise change package/request; determine the effectivity date; notify all parties concerned/update their files, and audit/review if the change has achieved its objective. However, through their proceeding survey, a number of respondents commented that these activities had over-emphasised the administrative activities, and did not pay sufficient attention to technical activities associated with the identification and implementation of engineering changes. The necessity to establish these technical activities is described in a later publication from Huang et al. (2003) which detailed the results of a similar survey with engineering change management in manufacturing organisations based in Hong Kong. In this publication Huang et al. (2003) described that the majority of companies were “quite unsatisfied” with the analytical activities for establishing the effects associated with implementing engineering changes, leading to the conclusion that it was necessity to develop methodologies and/or techniques for these technical activities so that the engineering change management process could be improved.

To establish what is involved with each of these phases a review of the associated activities is therefore required. From Table 2 it is clear that a number of activities exist within the reviewed literature. However, without going into the detail of the descriptions associated with these activities it is unclear whether the terminology used by different authors is consistent for the reported activities. As such, the following section offers a synthesis of the activities that compose the engineering change management process, presenting the fundamental activities that are described in the reviewed processes.

2.3.2.1 Identification

From the various engineering change management processes reviewed, the first phase that has been synthesised is that of identification. Huang et al. (2003) consider this phase as being principally concerned with establishing the needs for an engineering change, and in particular establishing why the engineering change is required. In a survey of the UK manufacturing industry Huang and Mak (1999) found that almost 70% of the businesses identify opportunities to change. Within this phase, two fundamental activities have been identified: realising and documenting.

Realising

Whilst the terminology used varied, the act of realising was described as being part of engineering change management process by five authors (Jarratt, Eckert et al. 2006, Lee, Ahn et al. 2006, Motawa, Anumba et al. 2007, Eckert, de Weck et al. 2009, Hwang, Mun et al. 2009). Of these terms, Hwang et al. (2009), Motawa et al. (2007) and Jarratt et al. (2004) all describe the activity as identification. Hwang et al. (2009) suggest the identification of a problem, whilst Jarratt et al. (2004) suggest the identification is of the need to change. Further, Eckert et al. (2009) presents that the detection is of a need to change whilst Lee et al. (2006) report that the detection is of a problem. However, currently no definitions for the terms detection or identification are proposed and therefore the process by which problems are detected or identified is unclear. Nevertheless, Lee et al. (2006) proceed to describe that it is through discussion that engineers and team members realise whether an engineering change is necessary or not.

Documenting

The act of documenting is evident within the identification phase of the engineering change management process in papers presented by Jarratt et al. (2011) and Lee et al. (2006). Jarratt et al. (2011) outlines that most companies have standard electronic or paper based forms that must be completed to outline the reason why the engineering change is necessary. Lee et al. (2006) refers to this form as an engineering change request, again reporting that this must contain the reason for initiating an engineering change. Following the documentation of the reason why an engineering change is required, Jarratt et al. (2011) reports that this document is forwarded to an engineering change administrator who then enters this information into an engineering database.

2.3.2.2 Generation

The second synthesised phase of the engineering change management process is that of generation. Lee et al. (2006) consider generation, in an engineering change context, as the preparation of alternative solutions, where these solutions satisfy the need for the change. In a survey of UK manufacturing industries Huang and Mak (1999) reported that approximately 65% of UK manufacturing industries work out a number of solution alternatives and choose between these as core activities during the engineering change management processes. Within this phase, three fundamental activities have been identified: solution development, documenting and selecting.

Solution development

Maull et al. (1992) describes that following the identification of the need to change, the development of a design to provide a solution to overcome the definitional inadequacy that contextualises the need to change is required. Hwang et al. (2009) and Jarratt et al. (2011) report that multiple different solutions may be developed for a single change need; however a single solution is the norm. Further, Eckert et al. (2004) presents a case where different parts of the solution are developed by different engineering teams which are brought together to generate a holistic solution.

Documenting

The act of documenting the solution that has been developed is evident in papers by (Peng and Trappey 1998, Rouibah and Caskey 2003, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006). Lee et al. (2006) state that following the decision to initiate an engineering change, a form that contains information on the product and components that need to be changed and a textual description of the developed solution is created. Tavčar and Duhovnik (2005) state that it is the idea for overcoming the need to change that should be documented into an engineering change proposal.

Selecting

The act of selecting is only explicitly reported in the process presented by Maull et al. (1992); however, the activity is evident in papers by both Hwang et al. (2009) and Jarratt et al. (2011). In this process, Maull et al. (1992) considers that the solution that overcomes the need to change is generated externally. In such a case, the first activity that is reported is the filtering of engineering change proposals to remove duplicated and uneconomic changes. Maull et al. (1992) proceeds to describe that an engineering change proposal delivers an outline of the new solution. As such, in this case the act of selecting refers to the application of criteria to a specific solution to determine whether the solution is appropriate or not. This is enacted prior to the prediction or approval phases and acts as a less formal recommendation on whether to proceed with a specific solution, or not.

Supporting the existence of the act of selecting within the engineering change management process, Hwang et al. (2009) and Jarratt et al. (2011) report that instead of a single solution multiple solutions are sometimes generated. However, Jarratt et al. (2011) reports that typically only a single solution is developed, citing reasons such as time pressures, to rationalise this. Nevertheless, as only a single solution can be instantiated, a selection process for determining which solution to proceed with is evident.

2.3.2.3 Prediction

Fuelled by the ability for an engineering change to propagate and cause knock on effects to associated parts and components, the prediction phase is concerned with the forecasting of these effects (Eckert, Keller et al. 2006). With the structure of the engineering artefact being central to the engineering change management process, the prediction phase has been seen to focus predominantly on components within the design e.g. (Clarkson, Simons et al. 2004, Jarratt, Eckert et al. 2004). However, Oduguwa et al. (2006) suggest that the prediction phase considers two separate impact assessments: establishing the effect of changing an individual requirement on the other requirements and a cost analysis for estimating the incurred cost of changing a requirements. As such, during the prediction stage all documents that are affected as a result of an engineering change are established (Pikosz and Malmqvist 1998). Jarratt et al. (2006) consider the prediction phase of the engineering change management process as the riskiest whilst Ariyo et al. (2010) suggest that being able to predict the knock-on effects of change accurately, consistently and comprehensively would be of significant benefit to a business. Within this phase, four fundamental activities have been identified: analysing, composing, planning and testing.

Analysing

The act of analysing is a key theme in engineering change literature and is evident in the processes under a number of different terms: appraise (Maull, Hughes et al. 1992), analyse (Lee, Ahn et al. 2006), evaluate (Peng and Trappey 1998, Jarratt, Eckert et al. 2004, Motawa, Anumba et al. 2007, Eckert, de Weck et al. 2009), identification (Rouibah and

Caskey 2003), investigate (Lee, Ahn et al. 2006) and propagate (Motawa, Anumba et al. 2007). Peng and Trappey (1998) reported that the evaluation process consisted of specific analyses from different departments, providing an example of an engineer checking how the changes affect production processes, tooling, material handling, etc. Similarly, Jarratt et al. (2004) described evaluation as establishing the possible impacts on both the product and the development process. In addition, Motawa et al. (2007) define the activity of evaluation as the assessment of the implications based on both tangible and intangible criteria, and quantitative and qualitative data, leading to the optimum selection of change options. Throughout the range of activities, the theme of forecasting the effects associated with the implementation of the new design can be elicited, with Jarratt et al. (2011) providing three examples of which factors should be assessed: the impact upon design and production schedules; how relationships with suppliers might be affected, and will a budget overrun occur. Indeed the theme of analysis is mirrored across a number of other activities: analyse (Lee, Ahn et al. 2006), identify (Rouibah and Caskey 2003) and investigate (Lee, Ahn et al. 2006). Furthermore, analysing is evident in the terms propagate (Motawa, Anumba et al. 2007), described as the establishing of the impacts of an engineering change, appraise (Maull, Hughes et al. 1992), described as the act of establishing the feasibility, cost and possible embodiment points are established and prepare (Tavčar and Duhovnik 2005), described as the enactment of an economic assessment of the change along with stock data of components.

Composing

The act of composing is evident in papers presented by Hwang et al. (2009), Jarratt et al. (2011) and Peng and Trappey (1998). Hwang et al. (2009) describes that all the associated changes should be collated to provide a comprehensive view of the generated solution. This is subsequently used to communicate the intentions of the engineering change. Likewise, Peng and Trappey (1998) report that the findings from the act of analysis can be in different forms and should be recorded to provide an overall view of the impact of implementing the engineering change. Jarratt et al. (2011) describes that this should contain the components or systems that are likely to be affected by implementing the new solution and should be collated into a single information source.

Planning

Given the range of factors that can be affected as a result of an engineering change, planning for the implementation of the engineering change is evident in the engineering change management process presented by Eckert et al. (2009). In this process the act of planning is reported to cover both technical and organisational considerations. As such, rather than only analysing the effects, during this act, plans are developed to enact these changes. Eckert et al. (2004) report on a case study in which the chief engineer was responsible for planning, assigning appropriate deadlines and scheduling the changes at a high level before this was repeated in detail by the individuals responsible for the development of a potential solution.

Testing

Adding a layer of verification to the analysis Peng and Trappey (1998) propose that prototyping of the change should be done. During the test activity, the modification is executed to establish whether the engineering artefact behaves as expected. In the context of serial production, Tavčar and Duhovnik (2005) report that prototype tests should be executed prior to submission for approval; however, in the same paper the act of testing is not evident in engineering change management processes in individual production.

2.3.2.4 Approval

Peng and Trappey (1998) consider approval in an engineering change context as a confirmation that a change can be made upon the product data. As such it can be considered to be an essential activity in the engineering change management process (Rouibah and Caskey 2003). Reflecting this in a study of UK manufacturing industries, Huang and Mak (1999) suggested that approximately 85% of businesses formally approve engineering changes, representing the second most common activity involved in the engineering change management process. Within this phase, only one fundamental activity has been identified: authorising.

Authorising

The act of authorisation is prior to implementing an engineering change and is evident in a range of papers (Maull, Hughes et al. 1992, Jarratt, Eckert et al. 2004, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006, Motawa, Anumba et al. 2007, Eckert, de Weck et al. 2009). Lee et al. (2006) states that the authorising is enacted to approve any changes in the unit cost of a part and to check for possible errors and inconsistencies in the proposed solution. Tavčar and Duhovnik (2005) also considers that the activity of authorising is enacted to validate the implementation of a specific solution. Jarratt et al. (2004) reports that this authorisation is required before the solution can be implemented, whilst Maull et al. (1992) report that to authorise a change all the associated information needs to be collated and evaluated, linking this activity to the output from the prediction phase.

This authority is also presented as being granted by different stakeholders. Motawa et al. (2007) states that authorising is executed by a customer to make a decision on whether to implement a change option or not. In addition, Lee et al. (2006) states that authorising is enacted simultaneously by the cost management department and the technology management department. Further, in a publication by Jarratt et al. (2011) the approval authority is referred to as a form of engineering change board or committee. Jarratt et al. (2011) proceed to outline that the engineering change board should contain senior to middle ranking staff from key functions, such as: product design, manufacture, marketing, supply, quality assurance, finance, product support. Given the different stakeholders that are cited, the act of authorising can be presented as being enacted by multiple different stakeholders before the appropriate authorisation to implement is granted.

2.3.2.5 Implementation

The implementation phase of the engineering change management process is primarily concerned with the realising of a proposed change (Aurich and Rößing 2007). Maull et al. (1992) consider implementation as the final activity in this process, where the goal of implementation is to update the product whilst maintaining delivery and without incurring downtime. Whilst the previous phases of the engineering change management process have been concerned with preparing, the implementation phase represents the instantiation of a change. Within this phase, two fundamental activities have been identified: instantiating and ensuring.

Instantiating

The enactment of an engineering change is evident in six of the reviewed processes (Maull, Hughes et al. 1992, Peng and Trappey 1998, Jarratt, Eckert et al. 2004, Tavčar and Duhovnik 2005, Eckert, de Weck et al. 2009, Hwang, Mun et al. 2009). Throughout the previous stages, whilst work has been done, it is not until this activity is reached that any actual modifications are instantiated. Hwang et al. (2009) refers to this act under the terms realisation and roll out, reporting that the modification is not only instantiated into the engineering artefact but the production processes are updated. Tavčar and Duhovnik (2005) take a similar stance, using the term implementation to reflect the modifications that are required to the production processes to facilitate the modifications to the engineering artefact. In addition, the instantiation of the changes upon the associated documentation are also described in the processes presented by Tavčar and Duhovnik (2005) and Peng and Trappey (1998). On the other hand, Maull et al. (1992) uses the term execute to describe the modifications to the final drawings, part registers etc. prior to the release to the affected areas. Given these descriptions, it is evident that instantiation of an engineering change to the structure of an engineering artefact can involve the modification to a significant number of information sources and knowledge associated with the engineering artefact. Given the impacts associated with an engineering change, both Jarratt et al. (2011) and Bhuiyan et al. (2004) report that the instantiation of engineering changes can either occur immediately after approval or be phased in.

Ensuring

In addition to instantiation, Rouibah and Caskey (2003) describe that control is also part of the implementation phase. In their description, Rouibah and Caskey (2003) define the control activity as referring to ensuring that the change is being properly implemented. Given the significant possibilities of components, documentation, drawings, etc. that could change as a result of an engineering change (as described in section 2.1.2), the act of ensuring seeks to guarantee that all modifications are instantiated into each of these data sources as needed. The act of ensuring is cited by Wright (1997) as a major problem that is frequently associated with engineering change. In the paper presented by Wright (1997), this problem is caused by a lack of ensuring that only the up to date documentation is available to manufacturing departments. In other papers (e.g. Fowler 1996) and industry standards (e.g. BS 15288:2002), this activity is referred to as configuration management and represents a significant field of research in its own right.

2.3.3 Activities associated with the engineering change management process

Within the various phases of the engineering change management process a range of activities have been identified. These activities have undergone synthesis to establish common traits within these terms. As such, within the five phases of the engineering change management process, twelve distinct activities have been identified. An overview of these activities is provided in Table 8, detailing the existence of these activities within the nine processes reviewed to establish the five phase model of the engineering change management process.

Table 3 –Activities associated with the engineering change management process

Phase	Activity	Activity evident in engineering change management process									Total number of processes that the activity is evident in
		(Maull, Hughes et al. 1992)	(Peng and Trappey 1998)	(Rouibah and Caskey 2003)	(Jarratt, Eckert et al. 2004)	(Tavčar and Duhovnik 2005)	(Lee, Ahn et al. 2006)	(Motawa, Anumba et al. 2007)	(Eckert, de Weck et al. 2009)	(Hwang, Mun et al. 2009)	
Identification	**Documenting**						✓				**1**
	Realising				✓		✓	✓	✓	✓	**5**
Generation	**Documenting**		✓	✓		✓	✓				**4**
	Solution development	✓								✓	**2**
	Selecting	✓									**1**
Prediction	**Analysing**	✓	✓	✓	✓	✓	✓	✓	✓		**8**
	Composing		✓							✓	**2**
	Planning								✓		**1**
	Testing		✓								**1**
Approval	**Authorising**	✓			✓	✓	✓	✓	✓		**6**
Implementation	**Ensuring**			✓							**1**
	Instantiating	✓	✓		✓	✓			✓	✓	**6**

2.4 Nature of the products reported on in this review

Based on the review presented in the previous sections it is apparent that the activities that are reported to compose the engineering change management process and the definitions of engineering change vary within different publications. To explore these differences, a review of the nature of the products that contribute to the definitions and processes has been conducted and is presented in the following section. To focus this review, five categories have been used to decompose the nature of the products upon which the research is based: product complexity; degree of customisation; production quantity and product level (see Table 4). For clarity, the product complexity covers the degree to which the product contains interconnected parts, dependencies and interfaces that require simultaneous development by teams of engineers. The degree of customisation covers the degree to which the product varies from the standard design. Production quantity covers the number of products produced from a single design. Finally, the product level covers the degree of newness as defined by avbi and Duhovnik (1995), covering original, innovative, variational and adaptive. In addition, the type of product or project that forms the context of the paper is presented to highlight the context in which the paper has been developed. For clarity, if a number of products are presented in the paper, the one upon which the process or definition for engineering change that has been referenced is considered.

Table 4 – The nature of the products focussed on in the cited papers

Author	Product / project description	Complexity	Degree of customisation	Production quantity	Product level
(Harhalakis 1986)	Made to order, specially engineered large size compressors and pumps	Medium	High	Low	Variational
(Maull, Hughes et al. 1992)	An electronic goods manufacturer and a consumer electronics product manufacturer	Low	Low	High	Variational
(Wright 1997)	-	-	-	-	-
(Peng and Trappey 1998)	Process presented and applied to the example of the design of a pen	Low	Low	High	Adaptive
(Huang et al., 1998, 1999, 2001, 2003)	Manufacturing organisations	-	-	-	-
(Terwiesch and Loch 1999)	Development of a climate control system for a new vehicle	Medium	Low	High	Variational
(Barzizza, Caridi et al. 2001)	Made to order, information technology firm	-	-	-	-
(Rouibah and Caskey 2003)	Applied to the development of a car in which the development required more than one company	High	Medium	High	Variational
(Jarratt, Eckert et al. 2004)	Development of a diesel engine	Medium	Low	High	Adaptive
(Tavčar and Duhovnik 2005)	Low complexity products focussing on differences between individual, serial and modular production	Low	Low	High	Variational
(Lee, Ahn et al. 2006)	Major Korean automobile company working on a new product development project	High	Medium	High	Variational
(Motawa, Anumba et al. 2007)	Presented in terms of all construction projects	High	High	Low	Innovative
(Habhouba, Desrochers et al. 2007)	Dimensional change in a specific component within the aerospace industry	Low	Low	High	Adaptive
(Eckert, de Weck et al. 2009)	German automobile company	-	-	-	-
(Hwang, Mun et al. 2009)	The integration of component parts from distributed component manufacturers	Low	Low	High	Adaptive
(Kocar and Akgunduz 2010)	-	-	-	-	-

Decomposing the papers cited in the previous sections, it is evident that the nature of the products that have formed the focus of the development of both the definitions for engineering change and the activities that compose the process for the management of these changes are different. Given this range, the variation in process activities and definitions of engineering change that are reported in the academic texts could be justified. As such, future research that seeks to extend beyond single cases should ensure that the nature of the products that form the context of the cases is consistent across each. For clarity, as defined in section 1.1, to mitigate the effects of different types of engineering artefact upon the research reported on in this thesis, the scope of this study is constrained to:

> **Complex, low quantity, highly customised design-to-order, physical engineering artefacts that represent an innovative level of newness**

2.5 Overview of reviewed papers

Within this chapter, a range of papers that have contributed to knowledge in the field of engineering change management have been reviewed. Forming the bulk of this review were papers that offered definitions of engineering change or processes for the management of engineering change. However, the presented definitions and processes were not always the main contribution contained within the papers. As such, in the following summary table, an overview of the content of the papers is presented along with the methodology used by the authors and the type of contribution that is offered. This can be found in Table 5.

Table 5 - Methodology of reviewed papers

Author	Paper overview	Methodology adopted	Contribution type
(Harhalakis 1986)	An approach to engineering change management within an existing material resource planning process	Not reported	Prescriptive
(Maull, Hughes et al. 1992)	Establishing the influence that engineering changes have on the bill of materials	Process development and test through case study	Prescriptive
(Wright 1997)	A summary of the current state of the art in engineering change management research	Literature review	Descriptive
(Peng and Trappey 1998)	A STEP based approach to engineering change and engineering data management	Process development and theoretical implementation	Prescriptive
(Huang et al., 1998, 1999, 2001, 2003)	An overview of current industrial engineering change management practice	Survey findings and insight into potential process developments	Descriptive
(Terwiesch and Loch 1999)	Guidelines for increasing the speed of the engineering change management process	Case study	Prescriptive
(Barzizza, Caridi et al. 2001)	Means to decide when and at what cost to implement an engineering change	Process development and test through case study	Prescriptive
(Rouibah and Caskey 2003)	Process for multi-company engineering change management	Process development and test through case study	Prescriptive
(Jarratt, Eckert et al. 2004)	A model that highlights the relationships between components in an engineered product and risk of change propagating between these	Process development and test through case study	Prescriptive
(Tavčar and Duhovnik 2005)	Optimisation of engineering change management for individual and mass production	Process development and test through case study	Prescriptive
(Lee, Ahn et al. 2006)	A process for knowledge management and collaboration in engineering change management	Process development and test through case study	Prescriptive
(Motawa, Anumba et al. 2007)	Impact prediction system that links project characteristics, change causes and effects	Process development and theoretical implementation	Prescriptive
(Habhouba, Desrochers et al. 2007)	A method for supporting decision making when considering whether to implement a solution or not	Process development and test through case study	Prescriptive
(Eckert, de Weck et al. 2009)	A comparative analysis of causes, sources and approaches to engineering change management in industry	Workshops / presentations / group discussions	Descriptive
(Hwang, Mun et al. 2009)	Method for rapid engineering change propagation between companies	Process development and theoretical implementation	Prescriptive
(Kocar and Akgunduz 2010)	Development of a collaborative design environment for improving engineering change management	Process development and theoretical implementation	Prescriptive

From the categorisation of the papers presented in Table 5, it is evident that a range of contributions have been offered. These are generally based upon process development type activities in which the author offers a new approach to some aspect of engineering change management. This is then either tested through a case study, using an industrial case, or through a theoretical implementation in a hypothetical engineering case. This approach provides a prescriptive insight into how engineering changes should be managed, outlining the benefits of implementing the new approach. In addition, another smaller number of contributions are offered that provide an insight into the nature of engineering change management. Offering descriptive insights into engineering change management practice, these papers are based upon a variety of research techniques: case studies, workshops, surveys, etc. Instead of offering an improved means of managing engineering changes, these papers provide knowledge of industrial engineering change management practice.

2.6 Discussion

Reviewing current literature, it is evident that processes for the management of engineering change have formed the focus of considerable research effort. Based on the reviewed processes, it can be reported that engineering change management processes consist of a number of activities. Synthesising these activities, a generic five phase model of the engineering change management process has been presented that composes twelve distinct activities.

Composing these five phases, twelve activities have been identified. Of the twelve activities, none were found to have been unanimously represented in any of the nine reviewed engineering change management processes (as demonstrated in Table 8). Further, in some instances only a minority of the reviewed processes provided evidence for the existence of activities that were described as crucial by other authors in the field (e.g. solution development). Given this paradox, it can be concluded that a single generic engineering change management process cannot be truly representative of all engineering change management processes that exist. Therefore, the engineering change management process must be influenced by factors that drive the enactment of activities in certain instances and not in others.

It has been presented above that the nature of the products can influence the process activities and definition of engineering change. As such, care must be taken to maintain the nature of the product when conducting research within this domain. Furthermore, insights into the causes of differences in engineering change management processes have been offered by two authors (Pikosz and Malmqvist 1998, Tavčar and Duhovnik 2005). In the respective papers, Pikosz and Malmqvist (1998) reported that variations can be caused by organisational, market and product issues, whilst Tavčar and Duhovnik (2005) reported that the engineering change management process can be effected by whether a product was to be mass or individually produced.

However, little is known of what other influencers exist to explain why variations are found in the processes for managing engineering change. Of potential influencers, Rouibah and Caskey (2003) offer a statement that engineering change management during the detailed design and production stages is often more formal. Given this observation, it can be concluded that the product lifecycle also has an influence upon the engineering change management process. This is given further emphasis by Jarratt et al. (2011) through an statement that engineering change management activity varies significantly depending on the stage of the lifecycle an engineering artefact is currently within; however, this statement is neither cited nor justified. As such, no research has been found to demonstrate whether the activities that compose the engineering change management process are enacted at the different stages of the product lifecycle or not. In addition, no research been found that examines other characteristics of the engineering change management process that vary within the product lifecycle. In summary, the activities that compose the engineering change management process within different stages of the product lifecycle and the characteristics of this process that vary within these stages are not currently known.

Further, in section 2.2.3 a strong relationship between engineering change and the engineering artefact that dictates the context for the engineering change has been reported in a number of the definitions of engineering change e.g. (Wright 1997, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006). Given the necessity for an engineering change to modify the structure of an engineering artefact and reflecting upon the knowledge that there has been a long recognition that an existing or putative engineering artefact can be described based upon the type of knowledge that can be associated with its design (Qian and Gero 1996), a link between engineering change and artefact knowledge is evident. With Lee et al. (2006) purporting the knowledge intensiveness associated with the management of engineering change, a further relationship between artefact knowledge and the engineering change management process is also evident. However, to date no research has been found to focus on formalising this relationship and as such the relationship between artefact knowledge and the engineering change is currently unclear.

2.7 Chapter summary

This chapter has outlined a range of published work in the field of engineering change management focussing on two topics: defining engineering change and establishing the activities associated with the engineering change management process. Reporting on a review of definitions for engineering change, two commonalities were identified. First it was identified that the definitions were based upon descriptions of what that if changes can be referred to as an engineering change. Second, that constraints were placed upon definitions of engineering changes such that a distinction between engineering change and other product development activities could be established. As such, a definition of engineering change that is adhered to within this thesis has been presented that is based upon these insights. Following this, a review of literature on the engineering change management process was presented. Based on nine published engineering change management processes, five fundamental phases were synthesised: identification, generation, prediction, approval and implementation. Within these phases twelve distinct activities were established.

Citing the lack of unanimous existence of these twelve activities within the reviewed engineering change management processes, it was established that the engineering change management process could be influenced by the organisation, market, product and production quantity. Further the stage of the product lifecycle has also been discussed as having an influence on the engineering change management process. However, it was noted that to date no research had been found that demonstrated whether the activities that compose the engineering change management process are the same at different stages of the product lifecycle or not. As such, a knowledge gap was reported in regard to what activities are enacted during the engineering change management process at different stages of the product lifecycle. In addition, it was reported that is currently not known how artefact knowledge relates to the engineering change management process.

Building on the five phase model of the engineering change management process presented in section 2.3.3, the following chapter proceeds to explore the relationship between artefact knowledge and the activities that compose the engineering change management process.

Chapter 3 - ARTEFACT KNOWLEDGE AND THE ENGINEERING CHANGE MANAGEMENT PROCESS

In the previous chapter, the engineering change management process has been demonstrated to be composed of five fundamental phases. Within these five phases, twelve distinct activities have been reported and discussed. Focussing on the key relationship between the engineering change management process and the engineering artefact that forms the context of the engineering change, a recognised taxonomy, hereafter referred to as artefact knowledge, is used to formalise this relationship. As such, the intention of this chapter is to present a model that demonstrates the relationship between artefact knowledge and the activities that compose the engineering change management process, based on a review of current literature. To facilitate this, an overview of literature that discusses artefact knowledge is provided in section 3.1. This includes a presentation of recent work that contributes to definitions for a decomposition of artefact knowledge in terms of function, behaviour and structure. It then proceeds to discuss the existence of these knowledge types in different forms, culminating in the definition of seven artefact knowledge types. Based on these definitions, current literature that provides an insight into the relationship between artefact knowledge and the engineering change management process is then discussed, prior to the presentation of a model of this relationship at the end of section 3.2. This model is then discussed in the section 3.3, before the chapter is summarised in section 3.4.

3.1 Artefact knowledge

Qian and Gero (1996) purport that there has been a long recognition that an existing or putative engineering artefact can be described based upon the type of knowledge that can be associated with its design. Gero (1990) referred to these using the terms function, behaviour and structure, with each of these representing a specific type of knowledge. These terms have subsequently become almost ubiquitous within engineering design literature, if not always explicitly described. However, they have also been a considerable source of debate within the design community. In particular, Dorst and Vermaas (2005) criticised these terms for their definitional inconsistency and ambiguity. This was also found by Umeda et al. (1996) who wrote: “There is no clear and uniform definition of *function* because function is an intuitive concept depending on the designer’s intention.” To stride towards an understanding of these terms and present the consistencies, definitions that have been proposed by nine authors have been collected and are presented in Table 6.

Table 6 - Definitions for artefact knowledge elements

Author	Function	Behaviour	Structure
(Hybs and Gero 1992)	Purpose of the product or artefact.	Effect of interaction of an artefact with its environment.	Configuration, arrangement, organization and form of product's constituents and their relationships.
(Umeda, Ishii et al. 1996)	A description of behaviour abstracted by human through recognition of the behaviour in order to utilize the behaviour.	Sequential state transitions along time, assuming that physical phenomena determine behaviour of an entity.	-
(Qian and Gero 1996)	Labels representing the purposes of an artefact.	Behaviour is one of the ways by which the meaning of the structure is inferred by a designer or user.	The structure specifies what elements the design is composed of, what the attributes of the elements are, and how they are related.
(Rosenman and Gero 1998)	The results of the artefact's behaviours.	The artefact's actions or processes in given circumstances of the natural environment.	The elements of the artefact, the material arrangement of these elements and their connectivity.
(Gero and Kannengiesser 2004)	The purposes of the design being designed, i.e., its teleology.	Attributes derivable from structure or expected of structure.	The elements of an artefact and their relationships.
(Vermaas and Dorst 2007)	Those physical dispositions of an artefact that contribute to the purposes for which the artefact is designed.	The physical dispositions of the artefact.	The materials of the artefact, the dimensions and geometry of these materials, and their topological relationships.
(Wang, Duffy et al. 2007)	The intention, purpose or duty of the artefact.	Behaviour describes what the artefact does and how it achieves its functions.	Derived from the artefact's components and their physical relationships, structure describes distinctive attributes that identify the artefact and their interactions.
(Goel, Rugaber et al. 2009)	A schema that specifies its preconditions and post conditions.	A sequence of states and transitions between these.	Components, the substances contained in the component, and connections between components.
(Galle 2009)	Serving given purposes: a set of physical dispositions such that any material construct having them can be used in a way that contributes to the purposes.	Of a structure: the set of physical dispositions, which any material construct embodying that structure has.	A triple (R, M, f) where R is a finite set of regions of 3d Euclidean space (defined in a given coordinate system), M is a finite set of materials, and f is a total function from R to M.

Whilst there may not be a unanimously accepted set of definitions for the terms function, behaviour and structure, a review of the various definitions enables common themes to be elicited. These common themes form the basis of the discussion contained in sections 3.1.1, 3.1.2 and 3.1.3. In addition, the existence of function, behaviour and structure in different ontological states is covered in section 3.1.4 before the section is summarised in section 3.1.5.

3.1.1 Function

A number of definitions for the term function suggest some form of antecedence to artefact development, describing the presupposed artefact’s purpose (Hybs and Gero 1992, Qian and Gero 1996, Gero and Kannengiesser 2004, Wang, Duffy et al. 2007). As such, the function can be considered to be the intention of the engineering artefact (Deng, Tor et al. 1999), expressing the state or series of states that the engineering artefact requires to achieve (Chandrasekaran 1990). Essentially, meeting the functions forms the primary reason for designing an artefact (Chandrasekaran and Josephson 2000, Ullman 2002). However, these descriptions seem to ignore the sometimes unintentional emergence of design functions. For example, a nut can be opened with a nut cracker equally as effectively as if using a stone. In such an instance, the artefact exists prior to definition of a function and so the functional presupposition to design development is not accurate (Galle 2009). The definition of function by Rosenman and Gero (1998) reflects this, referring to the function as an output of the design process rather than an input.

A definition of function that purports a singular sequential relationship, as either an input or output of a structural or behavioural manifestation has been recognised as being not truly representative in some of the more recent contributions (Vermaas and Dorst 2007, Galle 2009, Goel, Rugaber et al. 2009). As such, these contributions combine both the intended purpose of the artefact and the other possible uses of the artefact. Therefore, within this thesis the function of an artefact has been taken to refer to both the purpose of the artefact (design intent) as well as the possible uses of that artefact could have that do not necessarily form the purpose of the artefact (design usage).

3.1.2 Behaviour

The first item of note when reviewing the literature that defines behaviour is the curious coupling with structural and functional knowledge definitions. In their descriptions, six authors (Hybs and Gero 1992, Qian and Gero 1996, Rosenman and Gero 1998, Gero and Kannengiesser 2004, Wang, Duffy et al. 2007, Galle 2009) consider behaviour to be a result of the structure of an artefact. As such, behaviour can be considered to be constrained and dictated by the structure. On the other hand, behaviour is also considered to be coupled with the function (Gorti, Gupta et al. 1997, Wang, Duffy et al. 2007), describing how an artefact achieves its function. Therefore, behaviour can also be considered to be a means of description of how the function of the artefact is met.

Another theme in literature that defines the term behaviour is that of different states. Umeda et al. (1996) discus behaviour as state transitions that occur through time, whilst Goel et al. (2009) considers behaviour to describe a series of states and the transitions between these states. As such, the dynamic nature of behaviour can be considered (Takeda, Yoshioka et al. 1996, Deng, Tor et al. 1999) leading to the conclusion that the behaviour of an artefact can vary over time and can be influenced by the environment in which it exists (Hybs and Gero 1992). Based on these themes, the behaviour of an engineering artefact is taken in this thesis to be a representation of how an artefacts function is or is to be met. This behaviour is then subsequently embodied through the structure of an engineering artefact.

3.1.3 Structure

The definitions for the structure of an artefact seem to share greater commonality than the other knowledge type classifications. The descriptions are dominated with physical items: components (Wang, Duffy et al. 2007, Goel, Rugaber et al. 2009), elements (Qian and Gero 1996, Rosenman and Gero 1998, Gero and Kannengiesser 2004), materials (Rosenman and Gero 1998, Vermaas and Dorst 2007, Galle 2009), and relationships between these items (Hybs and Gero 1992, Qian and Gero 1996, Rosenman and Gero 1998, Gero and Kannengiesser 2004, Vermaas and Dorst 2007, Wang, Duffy et al. 2007, Goel, Rugaber et al. 2009). This suggests that the structure is decomposable into constituent parts and sub-systems. The emergent properties of this composed view of an artefact plays an important role in forming and constraining behaviours (Wang 2008). As such, a structure is considered to be a finite set of element variables linked by fundamental relationships (Galle 2009) that are decomposable and constrain artefact behaviour (Wang 2008).

From literature it is possible to represent structural knowledge based on two considerations: design parameters and design configuration (Rouibah and Caskey 2003). In this context design parameters consist of three elements: geometry, materials and dimensions (Vermaas and Dorst 2007). These can be discussed based on either specific components within the artefact or the entire artefact itself. In addition, the design configuration describes the topological relationships between the components within the artefact.

3.1.4 Artefact knowledge spaces

The activity of designing represents a process during which designers make changes to the environment (Gero and Kannengiesser 2004). Through observing the effects of these changes, decisions are then made on whether new actions need to be executed. As this observation acts to inform the decision making process for the designer, how the designer perceives the effects of their actions acts to alter their opinions (Gero and Kannengiesser 2004). Gero (1990) first suggested that the way by which artefact knowledge is viewed can result in different instances of the same type of knowledge to be considered. These "views", herein referred to as artefact knowledge spaces, help to rationalise the various perspectives that exist within a design context.

Focusing initially on behavioural knowledge, Gero (1990) first considered that behaviour can exist in two forms: one that is directly derivable from the structure and the other that provides the syntax by which the function semantics can be achieved. In a later publication, Gero and Kannengiesser (2004) extended the concept of artefact knowledge spaces by proposing that the structure and function can also exist in more than one form. Considering the different perspectives three artefact knowledge spaces were suggested: external, interpreted and expected. The external artefact knowledge space was defined as "...the world that is composed of representations outside the designer or design agent"; the interpreted artefact knowledge space was defined as "...the world that is built up inside the designer or design agent in terms of sensory experiences, percepts and concepts. It is the internal, interpreted representation of that part of the external world that the designer interacts with", and the expected artefact knowledge space was defined as "...the world that the imagined actions of the designer or design agent will produce. It is the environment in which the effects of actions are predicted according to current goals and interpretations of the current state of the world" (Gero and Kannengiesser 2004).

Building upon the artefact knowledge spaces as offered by Gero and Kannengiesser (2004), Wang et al. (2007) proposes relationships between these phases. Wang et al. (2007) state that in the expected knowledge space, mental constructions of what the artefact is meant to achieve, how it is meant to achieve it and what the form the artefact requires to achieve can exist. Following this, through a process of instantiation the mental constructs are embodied into physical representations (for example, in a set of drawings) within the instantiated artefact domain (referred to by Gero and Kannengiesser (2004) as the external knowledge space). From these representations physical dispositions can be established and evaluated against what was originally expected to establish conformity. Furthermore, from these representations meta-physical dispositions considered to exist in certain working conditions can be interpreted by the designers (for example usability) that can themselves be evaluated against which was expected. These relationships are presented in Figure 4.

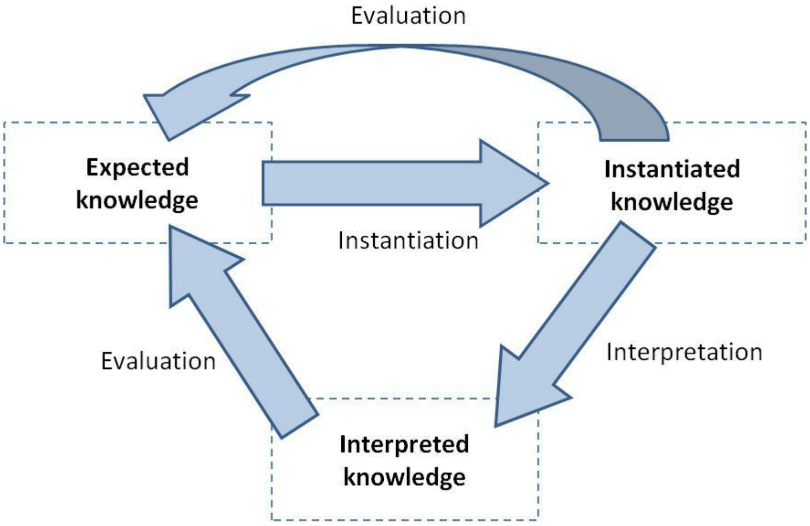


Figure 4 - Relationship between artefact knowledge spaces

The existence of each type of artefact knowledge within each of the artefact knowledge spaces has been set out by both Gero and Kannengiesser (2004) and Wang et al. (2007). Through considering the existence of artefact knowledge in the three artefact knowledge spaces, Wang et al. (2007) suggested that not all types of knowledge can exist in all of the artefact knowledge spaces. Specifically, the structure could not exist within the interpreted knowledge space and the function could not exist in the external knowledge space.

Given the above discussion, artefact knowledge is composed of three fundamental types: function, behaviour and structure. Further, that three artefact knowledge spaces exist: expected, interpreted and instantiated. Considering the existence of the fundamental types of artefact knowledge in the various artefact knowledge spaces suggests that not all of these types can be accurately demonstrated within these phases (Wang, Duffy et al. 2007). As such, recent literature on artefact knowledge informs that there are seven types of artefact knowledge that can be considered: expected function, expected behaviour, expected structure, instantiated behaviour, instantiated structure, interpreted behaviour and interpreted function (Wang, Duffy et al. 2007). Further that links between the knowledge domains demonstrates a process flow that Wang et al. (2007) present as a post positivist view (or p-FBS model) of the design process (see Figure 5).

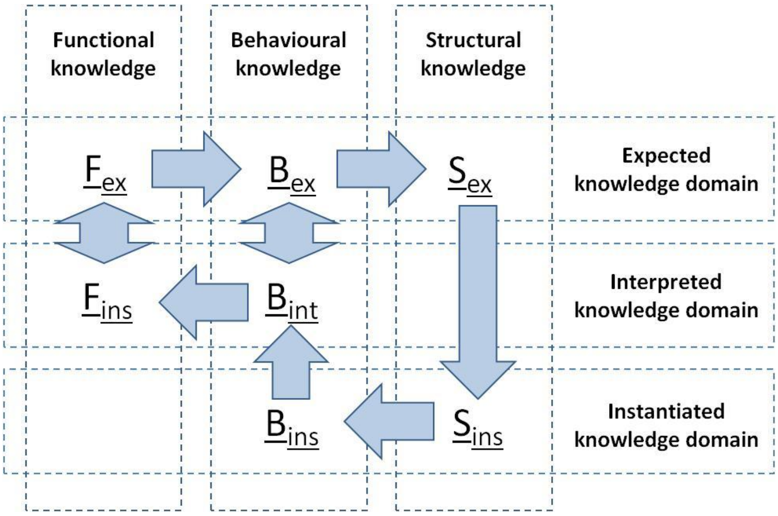


Figure 5 - The p-FBS model adapted from Wang et al. (2007)

A description of these artefact knowledge types are provided below and is supplemented with an example of these different types, based on the example of a pen:

- **Expected function**

The expected function stems from the design requirements, containing specifications, descriptions of constraints and customer / designers' intentions (Wang, Duffy et al. 2007). Representing the purpose of the engineering artefact, the expected function describes what the artefact is meant to do or achieve. Referred to as design intent by Ganeshan et al. (1994), the expected function forms the basis for a range of technical design decisions.

Example: *To create a visible mark on a piece of paper.*

- **Expected behaviour**

The expected behaviour represents the attributes that are expected from the artefact's structure (Wang, Duffy et al. 2007). Acting as the link between the expected function and expected structure, the expected behaviour describes the attributes that are required from the artefact's structure to achieve the expected function.

Example: *Through the application of ink via a hand manipulated device at a rate of 1 ml / 100 m.*

- **Expected structure**

The expected structure represents the designers’ expectations of the items which embody the design and the relationships between these items (Wang, Duffy et al. 2007). As such the expected structure describes design decisions (Ganeshan, Garrett et al. 1994) in reference to geometrical, dimensional and material parameters and design configuration (Rouibah and Caskey 2003) that the artefact is expected to embody.

Example: *The outer shaft and ink holder that are to be made of plastic and a nib and ball made of metal.*

- **Instantiated structure**

The instantiated structure represents the physical items and relationships between those items that compose the artefact at a particular and specified point during the design process (Wang, Duffy et al. 2007). As such, instantiated structure describes the geometrical, dimensional and material parameters and design configuration that the artefact embodies.

Example: *The ball measuring 1mm in diameter is encased within the nib of the pen and the diameter of the outer shaft is 25mm.*

- **Instantiated behaviour**

The instantiated behaviour represents the attributes derived directly from the structure of the artefact upon which design development is currently proceeding. Also referred to as the behaviour of the structure (Gero 1990), the instantiated behaviour refers to the attributes that are objectively exhibited by the artefact.

Example: *The device delivers a flow rate of 1.1 ml / 100 m.*

- **Interpreted behaviour**

The interpreted behaviour represents the attributes that are observed or considered to be observable by designers within specific working environments. The interpreted behaviour is an explanation or analysis of an artefact according what the designer expects (Wang, Duffy et al. 2007). As such, the interpreted behaviour represents the attributes that are subjectively interpreted by the designer based on the instantiated structure and instantiated behaviour.

Example: *The diameter of the outer shaft leads to difficulties in gripping, curtailing prolonged usage.*

- **Interpreted function**

The interpreted function is derived from the interpreted behaviour of the artefact (Wang, Duffy et al. 2007). As such, the interpreted function represents the ways by which the artefact can be used and what the artefact can do.

Example: *Creates a visible mark on a surface.*

3.1.5 Parallels with systems engineering

Reviewing the different definitions for the types of artefact knowledge presented in the previous section, a strong correlation between these types and nomenclature from the field of systems engineering has emerged. Within the following section, an exploration of the relationship between artefact knowledge and systems engineering nomenclature is presented.

Within the field of systems engineering, the requirements that guide the design and development of an engineered artefact have been categorised. These depend on the type of requirement that they place upon the engineered artefact. Reviewing literature results in a range of different categories; however, two main types of requirements are most commonly cited: functional and non-functional requirements. In the simplest terms, functional requirements describe what the system being designed should do (Otto and Wood 2001, Bagchi 2005), be or perform (Jacobsen, Sigurjónsson et al. 1991). Otto and Wood (2001) state that functional requirements should be defined in the most generic terms possible, and be stated, initially, in solution neutral terms. This is reflected by Jacobsen et al. (1991) who report that functional requirements are to be expressed as pairs of a transitive verb and a noun. Conversely, while functional requirements outline what the system should do, non-functional requirements prescribe quality factors such as performance, quality, accuracy, reliability, robustness, etc. (Bagchi 2005). Citing a report hosted by the University of Geneva, Switzerland, Bagchi (2005) describes that non-functional requirements are based on various constraints or attributes of the tasks specified by the functional requirements. This is reinforced by Lubars et al. (1993), reporting that performance requirements often interact with functional requirements. As such, a clear link between functional and non-functional requirements is evident.

Linking the types requirements described above, a clear relationship to artefact knowledge is evident. Of these, it is apparent that functional requirements and functional knowledge share significant similarities. In particular, the functional requirements outline what the artefact being designed should do, drawing parallels with expected function. Likewise, parallels can be drawn between non-functional requirements and behavioural knowledge. Again, as non-functional requirements prescribe qualities that are required of the artefact, a link is evident with expected behavioural knowledge.

Systems engineering texts inform that following the definition of the functional and non-functional requirements, an architectural design process should be conducted (BS 15288:2002). This process produces an architectural solution that is defined in terms of the requirements for each architectural element from which the artefact is to be configured. As such, for each of the artefact’s architectural elements, an explicit relationship with the functional and non-functional requirements is required to be produced (INCOSE, Systems Engineering Handbook, October 2011, version 3.2.2). This then defines how the artefact should be structured, closely reflecting the expected structural artefact knowledge type.

Once the functional requirements, non-functional requirements and architectural solution have been outlined, the implementation process commences, within which the engineered artefact is designed (INCOSE, Systems Engineering Handbook, October 2011, version 3.2.2). Through this process, the engineered artefact is instantiated, culminating in the creation of drawings, sketches, 3D CAD models and other representations of the artefact. During this process, design literature informs that an individual may possess knowledge of the current form of the engineered artefact, terming knowledge that relates to the physical items or relationships between those items as instantiated structural knowledge (Wang et al., 2007). As such, a relationship between the current design of the artefact and instantiated structural knowledge is apparent.

Systems engineering also places an emphasis on ensuring that reference is made back to the requirements throughout the design process, to ensure that the artefact satisfies these requirements (INCOSE, Systems Engineering Handbook, October 2011, version 3.2.2). Assessing the current and potential future states of the artefact against the functional and non-functional requirements, the performance of the artefact can be assessed to determine whether or not the engineered artefact satisfies its requirements. Assessing the artefact in terms of whether it complies with its non-functional requirements requires both knowledge of the performance of the artefact and the requirements against which to assess the artefact.

Design literature terms this type of knowledge as behavioural knowledge and states that it can exist in instantiated and interpreted forms (Wang et al., 2007). Furthermore, to ensure that the artefact meets its design intent, knowledge of the performance of the artefact and its functional requirements is required. This is defined as functional knowledge in design literature, with the act of evaluation being executed to determine whether the interpreted function meets the expected function (Wang et al., 2007).

To summarise, it is evident that whilst the terminology is different, significant similarities exist between the models of artefact development presented within the fields of design knowledge and systems engineering. As an explicit comparison of some key terminology in this field, Table 7 is presented. From this, a comparison between the terminology used in design and systems engineering literature is evident. As such, whilst this thesis adopts the terminology from the field of design theory, comparisons with systems engineering literature can also be taken.

Table 7 - Comparison between terminology in design and systems engineering literature

Design literature	Systems engineering literature
Expected function	Functional requirements
Expected behaviour	Non-functional requirements
Expected structure	Architectural design
Instantiated structure	Artefact design
Instantiated behaviour	Non-functional performance
Interpreted behaviour	Non-functional performance
Interpreted function	Functional performance

3.1.6 Summary

Based on a review of current literature, it has been established that an engineering artefact can be discussed based upon different types of knowledge associated with that artefact. To this end, artefact knowledge, composing, function, behaviour and structure has been discussed by a number of authors, presenting similar, yet subtly different definitions. Synthesising these contributions, definitions for function, behaviour and structure have been offered in section 3.1.1, 3.1.2 and 3.1.3 respectively and are adhered to throughout the remainder of this thesis. Further, in sections 3.1.4 and 3.1.5, artefact knowledge has been discussed as existing in different forms. Presenting three artefact knowledge spaces (expected, instantiated and interpreted), Wang et al. (2007) has argued that not all fundamental types of artefact knowledge exist within these spaces. As such, seven forms of artefact knowledge have been established: expected function, expected behaviour, expected structure, instantiated structure, instantiated behaviour, interpreted behaviour and interpreted function.

3.2 Artefact knowledge usage and creation

Based on the review of definitions for engineering change as presented in chapter 2, a strong link between the definitions of engineering change and the engineering artefact that dictates the context for the engineering change has been reported. Further, given the knowledge intensiveness that is associated with the management of engineering change (Lee et al., 2006), a relationship between artefact knowledge and the engineering change management process is evident. In the following section, through a review of literature, this relationship is explored. To achieve this, in section 3.2.1 the types of artefact knowledge that are used and created through the enactment of the activities that compose the engineering change management process are presented based upon engineering change management process literature. In addition, in section 3.2.2 artefact knowledge usage and creation is discussed, based upon engineering change support system literature. Finally, in section 3.2.4., a model that encompasses artefact knowledge usage and creation based on both engineering change management process literature and engineering change support system literature is presented.

3.2.1 Artefact knowledge existence within engineering change management process literature

Activity theory informs that activities are, “endlessly multifaceted, mobile, and rich in variations of content and form” m, Miettinen et al. 1999). From a design perspective, Sim and Duffy (2003) define an activity as a rational action taken by an agent to achieve a knowledge change of the design and/or its associated process. In such an instance, activities can be discussed based on the difference between the knowledge prior to the activity and that which exists after the activity has been enacted (Sim and Duffy 2003). Given the similarities between the engineering change management process and design process, as indicated by Leech and Turner (1985), an engineering change activity could also be discussed based on the knowledge that is used to enact the activity and the knowledge that is created as a result of the activity.

Considering the types of artefact knowledge that have been presented in section 3.1.4, the following section reports on how artefact knowledge is used and created with the engineering change management process. Based on a review of literature that describes the engineering change management process, an initial insight into this relationship is offered. In the following sections, the types of knowledge that are discussed as the inputs to and the outputs from the activities that compose this process are presented with an emphasis being placed on instances where artefact knowledge has been reported as being used or created. Progressing through each of the five phases of the engineering change management process in turn, the relationship between artefact knowledge and engineering change management process is discussed culminating in the presentation of a model of this relationship in section 3.2.2.6.

3.2.1.1 Identification

- As described in the previous chapter, the identification phase is composed of two activities: realising and documenting.

Four authors were found to present the act of realising as an activity within the identification phase. Of this act, Hwang et al. (2009) and Lee et al. (2006) report that the output is the detection of a problem. Similarly, Jarratt et al. (2004) and Eckert et al. (2009) describe the output to be the detection of a need to change. However, given the nature of the terms “problem” and “need to change” are not discussed further, leaving the reader to question what constitutes a problem or a need to change. Similarly, Eckert et al. (2004) reports that changes can either be realised through errors in the design process as emergent changes or initiated from an outside source, but also does not define exactly what is required to realise that a change is required. Given this limited quantity of information a clear picture of what types of artefact knowledge are used and created through the enactment of realising cannot be provided. As such, it is not possible to couple artefact knowledge with the act of realising based on current literature.

The act of documenting during the identification phase is reported in papers presented by Jarratt et al. (2011) and Lee et al. (2006). Jarratt et al. (2011) outlines that most companies have standard electronic or paper based forms that must be completed to outline the reason why the engineering change is necessary: a form referred to by Lee et al. (2006) as an engineering change request. Whilst Jarratt et al. (2011) outlines a number of administrational statements that are required to be contained within this engineering change request, a description of which systems or components that are likely to be affected is also required. Given that to document which components or systems are likely to change requires instantiated structural knowledge, the act of documenting during the identification phase can be said to use instantiated structural knowledge.

3.2.1.2 Generation

- Based on a review of literature, the generation phase has been demonstrated to be composed of three activities: solution development, documenting and selecting.

Solution development is evident in only two of the reviewed processes, presented by Maull et al. (1992) and Hwang et al. (2009). Whilst Hwang et al. (2009) does not provide any discussion on this act, Maull et al. (1992) describes this as the development of a design to provide a solution to the specific problem. Whilst to satisfy the definition of engineering change as presented by a number of authors, e.g. (Wright 1997, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006), it can be assumed that this solution must be evident in a modified structure, this is not actually reported. As such, based on literature it is not clear whether structural knowledge is used or created during the act of solution development. Neither is it clear whether other types of artefact knowledge are used or created during the enactment of this activity.

The act of documenting is evident in the engineering change management processes presented by four authors Peng and Trappey (1998), Rouibah and Caskey (2003), Tavčar and Duhovnik (2005) and Lee et al. (2006). However, of these four authors, only Lee et al. (2006) describes that a document, referred to by Tavčar and Duhovnik (2005) and Peng and Trappey (1998) as an engineering change request, contains information on the product and components that need to be changed. Whilst the nature of this information is not further described, given the information being related to the configuration of the engineering artefact in the state that needs to be changed, the use of instantiated structural knowledge is evident in the act of documenting.

Selecting is evident only in the process presented by Maull et al. (1992). Whilst Maull et al. (1992) cite financial knowledge and knowledge of similar design solutions as a mechanism for choosing which of the solutions to consider, what types of artefact knowledge are used and created during the enactment of these activities is not discussed. As such, the types of artefact knowledge that are used and created through the act of selecting are not evident.

3.2.1.3 Prediction

- The prediction phase has been demonstrated to be composed of four activities: analysing, composing, planning and testing.

The act of analysing is frequently presented as an activity in published engineering change management processes. For this activity, a number of types of knowledge are cited as being created. Peng and Trappey (1992) reported an example of an engineer establishing how the proposed change affects production processes, tooling, material handling, etc. Similarly, Jarratt et al. (2004) reported that the possible impacts on both the product and the development process are established as a result of this act. In addition, Maull et al. (1992) reports that as a result of the act of analysis, the feasibility, cost and possible embodiment points are established with an economic assessment of a change also being reported by Tavčar and Duhovnik (2005) as an output of this act. Further, as an input to the act of analysing Motawa et al. (2007) suggests that both tangible and intangible, as well as quantitative and qualitative criteria are used. However, whilst a number of different types of knowledge have been presented as being used and created through the act of analysing, it has not been possible to infer what types of artefact knowledge are used and created and hence no relationships can be reported.

The act of composing has been reported in literature presented by Hwang et al. (2009), Jarratt et al. (2011) and Peng and Trappey (1998). Hwang et al. (2009) and Peng and Trappey (1998) describe the aim of composing as the pulling together the different analyses into a single, documented information source. However, the content of these different analyses is not discussed. In a more recent publication, Jarratt et al. (2011) describes that this the act of composing should pull together the components or systems that are likely to be affected. In such an instance, knowledge of the structure of the existing engineering artefact is evident. Therefore, the act of composing uses expected structural knowledge.

The act of planning is only evident in the engineering change management process as presented by Eckert et al. (2009). In this process, planning is reported to use both technical and organisational inputs. However, as no further description is provided about the nature of these inputs, the types of artefact knowledge used cannot be reliably presented.

The act of testing is also only evident in the process presented by Peng and Trappey (1998). During a test activity, the new solution is trialled to establish whether the artefact behaves as expected. As such, the input to act of testing is expected behavioural knowledge with the output being instantiated behavioural knowledge. Therefore, a relationship between artefact knowledge and the act of testing is evident.

3.2.1.4 Approval

- The approval phase has been demonstrated to be composed of only one activity: authorising.

The authorising of an engineering change is evident in six of the reviewed processes (Maull, Hughes et al. 1992, Jarratt, Eckert et al. 2004, Tavčar and Duhovnik 2005, Lee, Ahn et al. 2006, Motawa, Anumba et al. 2007, Eckert, de Weck et al. 2009). In these processes, the act of authorising is described as a key stage in the process, with the output being a decision on whether to implement a change or not (Motawa, Anumba et al. 2007). However, whilst this process is desribed in six of the reviewed processes, the knowledge that is required to take the decision on whether to implement an engineering change or not has only been reported by Maull et al. (1992). In this process, Maull et al. (1992) state that all the associated information needs to be collated and evaluated, contributing to the basis upon which the decision is made. However, the nature of this information is not presented in such a way as to offer an insight into the usage or creation of artefact knowledge through the act of authorising. Therefore, no description of this relationship can be offered.

3.2.1.5 Implementation

- The implementation phase has been demonstrated to be composed of two activities: instantiating and ensuring.

Through the descriptions and insights into the act of instantiation presented in six of the reviewed processes (Maull, Hughes et al. 1992, Peng and Trappey 1998, Jarratt, Eckert et al. 2004, Tavčar and Duhovnik 2005, Eckert, de Weck et al. 2009, Hwang, Mun et al. 2009) relationships between artefact knowledge and the engineering change management process have been identified. Hwang et al. (2009) describes this activity as the instantiation of changes to the engineering artefact. Further, Tavčar and Duhovnik (2005) discuss this act in terms of the modifications that are required to be made to the production processes to facilitate the modifications to the engineering artefact. Maull et al. (1992) also contributes describing that modifications to the final drawings, part registers etc. prior to the release to the affected areas are enacted. Finally, Tavčar and Duhovnik (2005) and Peng and Trappey (1998) report that the instantiation encompasses modifications to the associated documentation as well. Based on these insights, it is evident that through the act of instantiation, expected structural knowledge of the changes that are needed to be made and instantiated structural knowledge of the artefact itself are used. Through the act of instantiating, the instantiated structure is subsequently modified to meet the expected structure. As such, the act of instantiation uses expected structural knowledge in terms of what the new solution should be and instantiated knowledge in terms of the existing product structure. As a result of instantiation, a new instantiated structure is created that differs from the previous instantiated structure. Therefore, the act of instantiating uses both expected and instantiated structural knowledge and creates structural knowledge as well.

Ensuring is defined by Rouibah and Caskey (2003) as the activity associated with assuring that an engineering change is being properly implemented. Of this activity, Jarratt et al. (2011) reports this as including the updating of all associated information. However, no further discussion is presented on what information is required to be completed, nor what types of knowledge are used or created through the enactment of this activity. As such, the relationship between the artefact knowledge and the act of ensuring is currently unknown.

3.2.1.6 Summary

Based on a review of engineering change management process literature, artefact knowledge has been demonstrated to relate to the activities that compose the engineering change management process. However, whilst artefact knowledge is evident within engineering change management process literature, literature that discusses the relationship between artefact knowledge and the activities that compose engineering change management process is scarce. By comparison, descriptions of the activities that compose the engineering change management process are more abundant; however, only a few of these extend to describe the inputs to and outputs of these activities. Of these, fewer still focus on the engineering artefact, contributing to a limited insight into the relationship between artefact knowledge and the engineering change management process. Nevertheless, a model of artefact knowledge usage and creation during the enactment of the activities that compose the engineering change management process can be presented (see Table 8). From this model it can be seen that eight relationships between artefact knowledge and activities that compose the engineering change management process exist. Of these, six relationships are based upon the usage of artefact knowledge and two are based on artefact knowledge creation.

Table 8 – The relationship between artefact knowledge and the engineering change management process based on engineering change management process literature

Artefact knowledge usage							Activity	Artefact knowledge creation						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
							Identification phase							
			X				Documenting							
							Realising							
							Generation phase							
			X				Documenting							
							Solution development							
							Selecting							
							Prediction phase							
							Analysing							
			X				Composing							
							Planning							
	X						Testing					X		
							Approval phase							
							Authorising							
							Implementation phase							
							Ensuring							
		X	X				Instantiating				X			

3.2.2 Artefact knowledge existence within engineering change support system literature

Whilst section 3.1 has focussed on reporting literature that discusses the engineering change management process, another branch of engineering change literature also contributes to formalising the relationship between artefact knowledge and the engineering change management process: engineering change support system literature. Engineering change support system development represents a distinct branch of the engineering change research field. Benefitting from increased research attention over the past decade, a range of supporting solutions to engineering change problems have been published. Fundamentally, engineering change support systems are prescriptive tools or frameworks that facilitate the enactment of specific activities within the engineering change management process and can be broken down into two main types: impact analysis systems and automatic instantiation systems. To achieve this facilitation, engineering change support systems use and create knowledge in a number of forms.

Applying the artefact knowledge taxonomy, presented in section 3.1, to these systems and establishing the activities that these systems have been developed to contribute towards, a further insight into the relationship between the engineering change management process and artefact knowledge is presented. To achieve this additional insight, a total of thirteen published engineering change support systems are discussed: nine of which are impact analysis systems and four of which automatic instantiation systems. Given that impact analysis systems contribute to the act of analysis within the prediction phase and automatic instantiation systems contribute to the act of instantiation within the implementation phase, based on the types of artefact knowledge that they use and create, a second insight into the relationship between artefact knowledge and the engineering change management process can be offered. As such, this section discusses the types of artefact knowledge that are used and created by these systems, culminating in the presentation of a model of artefact and engineering change management process relationships based on engineering change support system literature.

3.2.2.1 Impact analysis systems

Impact analysis systems form the bulk of engineering change support systems reported in literature. By providing supporting systems, the impact associated with implementing an engineering change can be more readily forecast at the time that the change is proposed than is possible with traditional impact analysis methods (Eckert, Keller et al. 2006). As such, increases in the efficiency of analysis activities have been cited (Clarkson, et al. 2004). Applying similar but subtly different techniques, these systems enable the user to quickly analyse the impact of implementing a proposed change without the need of traditional time consuming analysis activities enacted by a range of individuals associated with the development of the engineering artefact. However, to facilitate this reduction in the time requires considerable input during the setting up of these systems, e.g. (Clarkson et al., 2004).

Of the thirteen reviewed engineering change support systems, nine of these systems were found to be impact analysis systems (Flanagan, Eckert et al. 2003, Rouibah and Caskey 2003, Clarkson, Simons et al. 2004, Jarratt, Eckert et al. 2004, Oduguwa, Roy et al. 2006, Tang, Xu et al. 2008, Xue, Cheing et al. 2008, Koh and Clarkson 2009, Reddi and Moon 2009). These systems were found to exist in isolation of other tools used in the development process (e.g. computer aided drawing packages), relying on the input from a number of individuals who had knowledge of the structure of the engineering artefact. In general, they provided a formalised means for capturing the structure of an engineering artefact, highlighting structural interfaces between parts within the engineering artefact. To achieve this, six of the systems used design structure matrices, presenting the different parts that compose the engineering artefact in the columns on the left hand side and mirroring this information on the first row as well (Rouibah and Caskey 2003, Clarkson, Simons et al. 2004, Jarratt, Eckert et al. 2004, Tang, Xu et al. 2008, Xue, Cheing et al. 2008, Reddi and Moon 2009). The structural interfaces within the engineering artefact were then represented by a cross in the corresponding box between these parts, indicating that there is some form of relationship between these. This built up a simple view of the parts that compose the engineering artefact and the interrelationships between those parts. As such, when a change to an engineering artefact was being analysed and considered, the parts that may change as a result can be quickly established.

To build up the view of the structure of the artefact that these systems are based upon requires the input from different individuals (Clarkson, Simons et al. 2004). Fundamentally, as these engineering change support systems are built up from knowledge of the parts that compose the engineering artefact and the relationships between those parts, instantiated structural knowledge is used to prepare these models. Once populated, these systems offer the user with an overview of what parts are expected to change following the modification to an initiating part within the engineering artefact. As such, these systems require both instantiated structural knowledge for the initial population of the framework and expected structural knowledge in terms of which is the initiating part. As a result, the other parts that are expected to be impacted as a result of a change to initiating part can be established. To this end, these systems use both instantiated and expected structural knowledge and create expected structural knowledge (see Figure 6).

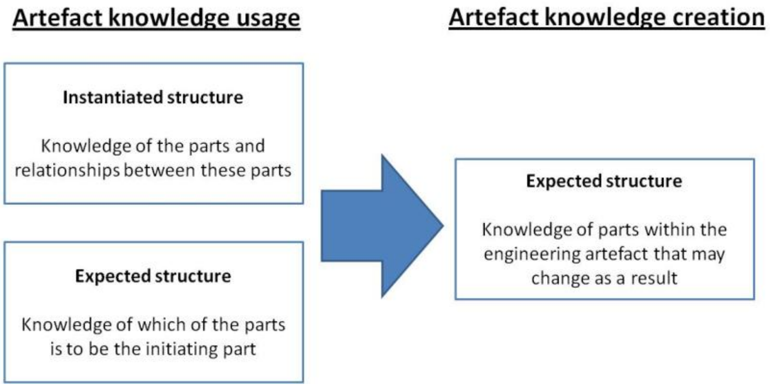


Figure 6 – Structural impact analysis systems

Whilst these six systems focus solely on structural knowledge, two further systems provide an extension to the functionality offered (Flanagan, Eckert et al. 2003, Oduguwa, Roy et al. 2006). As previously, the framework for these systems is a design structure matrix, presenting a view of the structure of an engineering artefact. However, in these systems both the relationship between the structure of the engineering artefact and the function of parts that compose the engineering artefact is presented. Including the purpose of the parts within the same framework then enables the user not just to establish which parts may be impacted by the engineering change, but what functions could be impacted as well. Again, to populate this system requires instantiated structural knowledge and expected structural knowledge, but for these engineering change support systems, expected functional knowledge in terms of what the engineering artefact is meant to achieve is required as well. As a result of using these systems the effects upon other parts and components within the engineering artefact can be established. Furthermore, based on the new structure, an interpretation of whether the new structure will meet the expected function is facilitated. As a result, interpreted functional knowledge is created. Therefore, these systems can be said to use both expected functional and instantiated structural knowledge and create both expected structural and interpreted functional knowledge (see Figure 7).

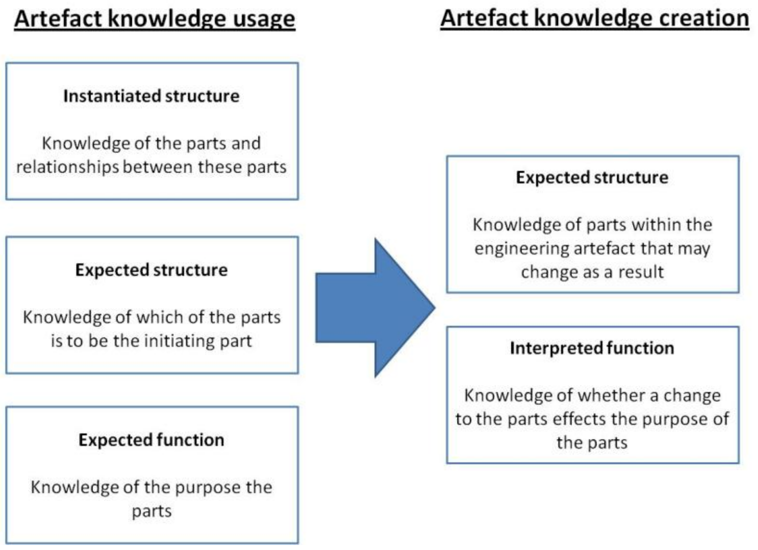


Figure 7 - Functional and structural impact analysis systems

Finally, Koh and Clarkson (2009) present an extension to the impact analysis systems that consider only structural knowledge, incorporating behavioural knowledge into the impact assessment. Based on a view of the structure of the engineering artefact through the use of a design structure matrix, this system facilitates the consideration of the impact that changing a design feature has upon the product attributes. In this context, a design feature is a design parameter that is being considered to be changed (e.g. reduced fan blade height in an aero engine) whilst a product attribute refers to behavioural characteristics associated with the engineering artefact (e.g. weight, noise, power). Representing the structure through the use of a design structure matrix has already been discussed as using both instantiated and expected structural knowledge. However, in this instance the usage of expected structural knowledge is not used to inform which of the parts is to be the initiating part, instead being used to detail what parameters are to be changed. In addition, expected behavioural knowledge is used to detail the required attributes and to link the required attributes to the design parameters. As a result of using this system, an engineering change practitioner can then assess whether a modification to a design parameter will result in a modification to a specific part (expected structural knowledge) in addition to whether it affects the required attributes (interpreted behavioural knowledge). For example, the system could provide the user with an insight into whether a reduced fan blade height has an impact upon the power of the engine and the other components within the engine. As such, this system uses instantiated structural, expected structural and expected behavioural knowledge and creates expected structural and interpreted behavioural knowledge (see Figure 8).

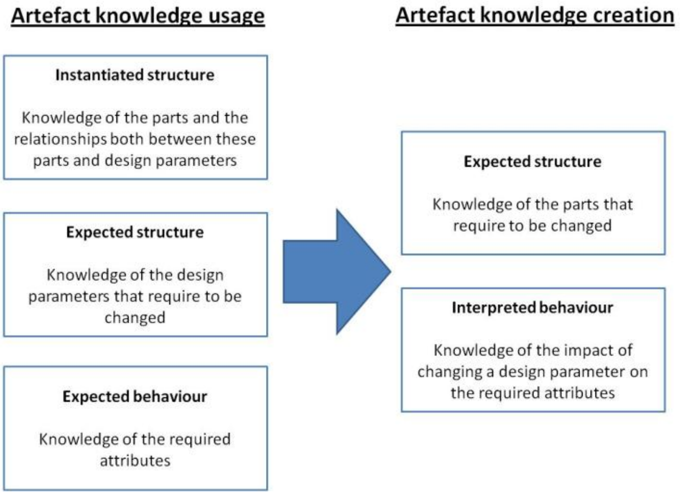


Figure 8 - Behavioural and structural impact analysis systems

3.2.2.2 Automatic instantiation systems

Automatic instantiation systems contribute to increasing the efficiency of the engineering change management process by offering mechanisms for automatically updating parts within the engineering artefact that are affected as a result of the engineering change. This is achieved through the use of computer aided drawing packages and computational algorithms that act to model not just the parts that compose and engineering artefact, but the relationships between these parts as well. Cross referencing the aim of these systems against the definitions of the activities that compose the engineering change management process, these systems contribute to the act of instantiation.

Of the fifteen reviewed engineering change support systems, four automatic instantiation systems were identified (Peng and Trappey 1998, You and Yeh 2002, Do, Choi et al. 2007, Hwang, Mun et al. 2009). These systems are typically based around computational algorithms run in tandem with computer aided drawing packages. Utilising the parts of the engineering artefact in a computer model, the individual is asked to define the relationships that exist between these parts, generated from a list of possible relationships. This definition then provides a mathematical representation about the interdependencies between the parts within the engineering artefact such that when one part changes, the change can be propagated to the new part through the defined relationship. For example, if the size of the bolt was increased from a M6 to an M8, the hole in which the bolt was placed would automatically be updated in through the use of automatic instantiation systems.

Whilst the benefits of automatic instantiation systems are evident, these systems still require the input from an individual to ensure they deliver the desired efficiency. To create an automatic instantiation system requires both knowledge of the parts within the engineering artefact and knowledge of the relationships between those parts. Clearly this purports a relationship between this category of engineering change support systems and structural knowledge. Indeed, instantiated structural knowledge is used to model both the parts within the engineering artefact and the relationships between those parts. In addition, expected structural knowledge is used to inform which of the parts within the engineering artefact to modify. However, in comparison to impact analysis systems, the outputs from automatic instantiation systems are in an instantiated form as the engineering artefact is updated automatically. To that end, automatic instantiation systems use instantiated and expected structural knowledge and create instantiated structural knowledge (see Figure 9).

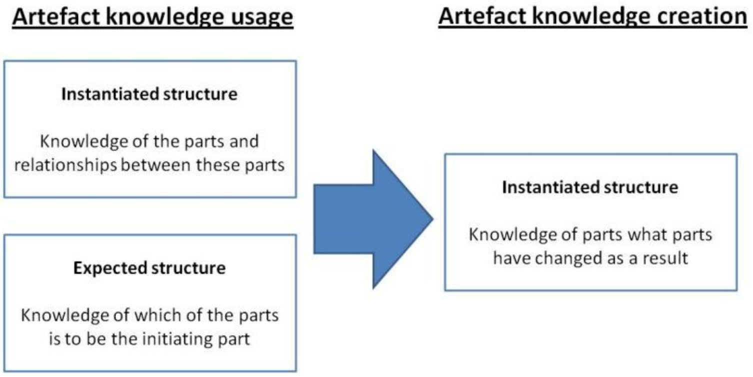


Figure 9 - Automatic instantiation systems

3.2.2.3 Summary

Based on a review of nine impact analysis systems and four automatic instantiation systems, different types of artefact knowledge have been discussed as being both used and created in the preparation and usage of these systems. Given that impact analysis systems contribute to the act of analysing and automatic instantiation system contribute to the act of instantiation, and given the different types of artefact knowledge used and created by these systems, a further insight into the relationship between artefact knowledge and the engineering change management process has been offered. To this end, the artefact knowledge that is used and created through the enactment of the activities that compose the engineering change management process, based on engineering change support system literature is presented in Table 9.

Table 9 – Relationship between artefact knowledge and the engineering change management process based on engineering change support system literature

Artefact knowledge usage							Activity	Artefact knowledge creation						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
							Identification phase							
							Discussing							
							Realising							
							Generation phase							
							Documenting							
							Solution development							
							Selecting							
							Prediction phase							
X	X	X	X				Analysing			X			X	X
							Composing							
							Planning							
							Testing							
							Approval phase							
							Authorising							
							Implementation phase							
							Ensuring							
		X	X				Instantiating				X			

3.2.3 A model of artefact knowledge usage and creation

In sections 3.2.1 and 3.2.2, artefact knowledge has been demonstrated to relate to the engineering change management process, based on both process and support system literature. Establishing the types of artefact knowledge that are used and created through the enactment of the activities that compose the engineering change management process, an initial model was presented. A further model was then offered based on the types of artefact knowledge that are used and created through the enactment of thirteen engineering change support systems. Whilst these models can exist in isolation, integrating the content of these demonstrates current knowledge of artefact knowledge and engineering change management process relationships. As such, an integrated model of these relationships can be seen in Table 10.

Table 10 - Artefact knowledge usage and creation during the engineering change management process

Artefact knowledge usage							Activity	Artefact knowledge creation						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
							Identification phase							
			X				Documenting							
							Realising							
							Generation phase							
			X				Documenting							
							Solution development							
							Selecting							
							Prediction phase							
X	X	X	X				Analysing			X			X	X
		X					Composing							
							Planning							
	X						Testing					X		
							Approval phase							
							Authorising							
							Implementation phase							
							Ensuring							
		X	X				Instantiating				X			

3.3 Discussion

Based on the review of both engineering change management process and support system literature, artefact knowledge has been demonstrated to relate to the engineering change management process. This demonstration has facilitated the presentation of a model of artefact knowledge and engineering change management process relationships (see Table 10). From this model, it is evident that artefact knowledge is both used and created during the enactment of six of the activities, culminating in a total of fifteen relationships. As such, these fifteen relationships provide a demonstration of what is currently known in regard to how artefact knowledge relates to the engineering change management process.

However, taking a critical view of this model and applying some simple examples to this demonstrates that this model is not yet complete and that certain relationships are currently omitted. For example, although work has been done to provide descriptions for the act of solution development, there is a lack of clarity on the artefact knowledge that is used and created. Whilst the output of this act is discussed, specific elements of artefact knowledge are not described in significant detail. This leads to the position in which it is assumed that expected functional knowledge is required to ensure that the change does not compromise the design intent; however, this is not known whether expected functional knowledge is actually used. Furthermore, as a result of this activity a solution that overcomes the need to change is produced, leading to the assumption that the output of solution development is structural. Again however, literature does not inform whether a relationship between structural knowledge and the act of solution development exists. Given these examples, the model itself is not considered to represent the types of artefact knowledge that are used and created through the enactment of the activities that compose the engineering change management process. Due to this lack of knowledge, future research work is required to establish what other relationships also exist.

3.4 Chapter summary

This chapter has offered an insight into the relationship between artefact knowledge and the engineering change management process based on published literature. Presenting seven types of artefact knowledge, these have subsequently been related to the activities that compose the engineering change management process. As such, six of the twelve activities have been established to either use or create artefact knowledge composing a total of fifteen relationships. However, whilst this analysis of literature has demonstrated fifteen relationships, the existence of further relationships has also been argued. As such, it has been reported that to gain an insight into these relationships, further research work is required.

In the past two chapters, engineering change management literature has been discussed from both an activity and a knowledge perspective. In the next chapter, the discussions associated with these perspectives are elaborated upon outlining the motivation for carrying out the research work reported in this thesis. This culminates in the presentation of the two research questions that this thesis aims to answer.

Chapter 4 - RESEARCH QUESTIONS AND REQUIREMENTS

In the previous two chapters, reviews of engineering change management literature have been presented. These reviews have focussed on two main areas: the activities that compose the engineering change management process and the types of artefact knowledge that are used and created through the enactment of these activities. As such, both a description of the activities that compose the engineering change management process has been presented as well as a model of the usage and creation of artefact knowledge through the enactment of these activities. Accompanying these, discussions outlining the state of knowledge with regard to engineering change management process activity enactment during the product lifecycle and what types of artefact knowledge are used and created during the enactment of these activities have been presented. Building on these discussions, this chapter defines the two research questions that this thesis has been prepared to answer, outlining the requirements associated with these research questions and the perceived benefits of answering these.

To achieve this aim, the following chapter is split into four sections. Section 4.1 presents a discussion on what is currently known in terms of the activities that compose the engineering change management process, as outlined in chapter 2, and what knowledge gaps exist. Following this, section 4.2 then details a discussion on the limitations of the model of artefact knowledge and engineering change management process relationships as presented in chapter 3. Section 4.4 then proceeds to tie together the previous two sections through the presentation of the research questions that this thesis has been prepared to answer, highlighting four research requirements that these questions impose upon the research. Finally, in section 4.4, the chapter is summarised.

4.1 Engineering change management process activities

In chapter 2, a review of associated literature has demonstrated that the engineering change management process composes five distinct phases: identification, generation, prediction, approval and implementation. Further, within these phases a total of twelve activities have been identified. Through the enactment of these activities, the processing of engineering changes is executed in a controlled manner (Rouibah et al., 2003). However, the review of literature has demonstrated that whilst there are similarities between a number of engineering change management processes not all processes appear to follow the five phases, nor are the twelve activities enacted in each case. To that end, a question exists over which activities are actually enacted during the processing of engineering changes and why these activities are enacted in certain cases and not others.

Reflecting this observation, Tavčar and Duhovnik (2005) and Pikosz and Malmqvist (1998) have reported that the engineering change management process can be influenced by four factors: the organisation in which the engineering change management process is being run, the market in which the engineering artefact is being sold, the nature of the engineering artefact itself and the production quantity. A further insight into factors that can influence the engineering change management process is also offered by Rouibah and Caskey (2003). In this paper, an observation is offered that engineering change management processes are often more formal during the detailed design and production stages of the product lifecycle. Given the insight that the formality of the engineering change management process can be influenced by the stage of the product lifecycle, this could indicate that other aspects of the engineering change management process may vary during the product lifecycle as well. In such an instance, presenting the engineering change management process as the same throughout the product lifecycle may not accurately reflect the nature of how engineering changes are managed in reality.

To date, little research exists that demonstrates whether the engineering change management process is the same at different stages of the product lifecycle or not. Whilst a supporting observation from Rouibah and Caskey (2003) suggests that a more formal process exists in the latter stages of product development, no research has been found that has sought to identify any variations at different stages of the product lifecycle. Filling this gap, this thesis presents empirical evidence to support an argument on whether the engineering change management process is the same at different stages of the product lifecycle or not.

Carrying out research into variations in the engineering change management process within the product lifecycle would fill this knowledge gap, through consideration of the practical implications that the outcome of this research will bring to both engineering change theory and practice, the justification for this work is reinforced. From a practical perspective, without knowledge of variations in the engineering change management process at different stages of the product lifecycle, engineering change practitioners could be enacting activities that are inappropriate for the stage of the lifecycle that the product currently exists within. This would inevitably result in the loss of engineering change management process efficiency, leading to an increased cost associated with the processing of engineering changes. Furthermore, from a research perspective, knowledge of which activities are enacted during which lifecycle stages would help focus the development of solutions to contribute to the processing of engineering change during different stages of the product lifecycle. For example, if it was known that the planning of when and how to implement the generated solution was enacted only in a specific product lifecycle stage then techniques to develop more appropriate methods for this could be developed. Given the joint industrial and academic impact of this research, this is considered to be a valid course of investigation for an engineering doctorate.

4.2 Artefact knowledge and the engineering change management process

Through the review of literature reported on in chapter 3, artefact knowledge has been demonstrated to be both used and created during the engineering change management process. This demonstration has enabled the presentation of a model that highlights the specific types of artefact knowledge that are used and created through the enactment of different engineering change management process activities. Contributing to the development of this model, the reviewed literature has extended beyond descriptions of engineering change management processes, gaining a further insight from literature on engineering change support systems as well. This has facilitated the preparation of a model that composes fifteen such relationships. However, based on some simple examples it can be suggested that this model may have missed a number of relationships between artefact knowledge and the engineering change management process. For example, based on literature it is not clear whether the expected function is used during solution development or not. However, if this type of artefact knowledge is not used during solution development a risk emerges in which the new solution may compromise the design intent of the engineering artefact. As such, this leads to a question over what other relationships exist between artefact knowledge and the engineering change management process that are not currently described in literature.

To date, little research has been found that has focused on formalising the relationship between artefact knowledge and the engineering change management process. This represents a knowledge gap that is addressed in the proceeding chapters contained within this thesis. Filling this gap, this thesis presents empirical evidence to demonstrate the existence of relationships between artefact knowledge and the engineering change management process. In this instance, rather than focussing on variations within the product lifecycle, this portion of the research work aims to establish what types of artefact knowledge are used and created during the enactment of the activities that compose the engineering change management process.

Reinforcing the motivation for carrying out this research work, it is envisaged that output from this research could again contribute to both engineering change management theory and practice. From a practical perspective, engineering change management processes require the input from a number of engineering change practitioners who can be distributed across different development sites (Chen, Shir et al. 2002). This leads to the distribution of the engineering change management process and decentralisation of activity enactment. In such instances, artefact knowledge is required to enact these activities appropriately; however, it is currently not known what types of artefact knowledge is required. This could lead to the situation in which engineering change practitioners are enacting activities without the usage of the appropriate types of artefact knowledge. For example, if an engineering change practitioner was responsible for analysing generated solutions that overcome the need to change based solely on structural knowledge, the effects upon the behaviour and function of the engineering artefact could be ignored leading to additional problems during the developmental process. As such, this research work would act as an indicator of the types of artefact knowledge that are used and created during the engineering change management process. Based on this, further work could then inform whether this was appropriate or not.

In addition, from a future research perspective, this information could also be useful for the generation of future engineering change support systems by highlighting the types of artefact knowledge that are required to enact the described activities. Currently engineering change support systems focus on supporting specific types of artefact knowledge during the acts of analysing and instantiating. However, from this research further relationships could be identified leading to the development of future engineering change support systems that support these types of artefact knowledge and activity relationships.

4.3 Contributing to engineering change management practice

In the previous sections, the knowledge gaps that this thesis has been prepared to fill have been presented. In addition, the impact of the findings of the research has been speculated upon and discussed. However, to ensure that this impact is achieved, additional work will be required to translate the findings from the research into usable statements that could be readily adopted. Whilst the focus of the research work is based upon filling the knowledge gaps presented previously, it is also necessary that clear recommendations are offered that link to these contributions. Therefore it is important to reflect this need in the research questions at this stage.

4.4 Research questions and requirements

Based on the knowledge gaps discussed in the preceding section two distinct, yet interrelated, research questions are proposed:

RQ 1. How does the engineering change management process vary at different stages of the product lifecycle and, based on this, what recommendations can be offered to improve the future management of engineering changes?

RQ 2. What types of artefact knowledge are used and created during the engineering change management process and what can be taken from this to improve the engineering change management process?

Forming the focus of the research reported on in this thesis, these research questions impose a number of requirements on the associated research. The first requirement addresses the need to align research work with philosophical assumptions about the world and reality (Reich 1994). Maguire (2010) argues that whilst the philosophical assumptions should be addressed, a chicken and egg type situation occurs, as whilst adoption of specific philosophical assumptions can constrain the scope of the research questions so the research questions can also constraint the philosophical assumptions. Given the nature of the research questions and the domain in which this research work is to be executed, appropriate philosophical assumptions that permit a human centric research methodology are required. As such, the first requirement is presented as:

1. To adopt an appropriate research philosophy that provides grounding for the design of a human centric research methodology required to answer the research questions.

Following the adoption of a specific research philosophy, constraints upon the research methods and methodology emerge (Easterby-Smith, Thorpe et al. 2002). Given that the research reported in this thesis aims to answer two interrelated research questions, a methodology through which insights into both could be attained was required. As such, the second research requirement was set as:

2. To design a robust and justified research methodology through which the activities that are enacted and artefact knowledge that is used and created during the engineering change management process can be captured.

Given that data is central to any research project, the chosen methodology requires the implementation of distinct methods to enable this data to be collected in a robust and scientific manner (Tenneti 2007). However, the nature of engineering change places further constraints upon the available data collection mechanisms. To maintain the industrial context of engineering change, the researcher must apply appropriate mechanisms in a situation where they have little control over the enactment of engineering change and be in a position in which engineering changes will be occurring at the time of the investigation. As such, the third requirement is presented as:

3. To apply methods for data collection in which the researcher has little control over the enactment of the engineering change management process and in which the engineering changes occur at the time of the investigation.

Finally, caused by the adoption of a specific research philosophy, Easterby-Smith et al. (2002) inform that this has a stark impact upon the validity of the output. As such, the output of the research must be demonstrated to satisfy the constraints placed upon it by the selection of a specific research methodology. As such, the final requirement is presented as:

4. To ensure that the output from the research methods be treated in such a manner as to provide an insight into the research questions in a valid manner.

To propose an answer to these research questions, these research requirements must be addressed. To that end, these research requirements are addressed in advance of the execution of data collection and analysis, forming the justification for the research design reported in the following chapter.

4.5 Chapter summary

This chapter has been prepared to summarise and discuss the findings from the literature review and to explicitly define the research questions that the work reported in this thesis has been carried out to answer. From this, two distinct yet interrelated research questions have been proposed. In addition, to offer answers to these research questions requires certain requirements to be satisfied to ensure that the approach to answering these is robust and valid. As such, four research requirements have been defined.

Considering these research requirements, the following chapter proceeds to define how the research is to be carried out in a manner that satisfies these requirements.

Chapter 5 - RESEARCH DESIGN

The aim of this chapter is to detail how the research reported on in the subsequent chapters of this thesis have been designed in order to satisfy the research requirements proposed in chapter 4. Addressing the first research requirement the chapter commences, in section 5.1, with a discussion of research philosophies, describing what is meant by the term research philosophy, what research philosophies exist and which is the most appropriate for adopting to answer the research questions proposed. Addressing the second and third research requirements, section 5.2 then proceeds to present the research methodology that has been applied, focussing on the data collection and analysis techniques that have been used within this study. Finally, addressing the fourth research requirement, research validity is discussed in section 5.3, before the key points from this chapter are summarised in section 5.4. Summarising the content of this chapter, an overview of where the four defined research requirements are addressed is presented in Figure 10.

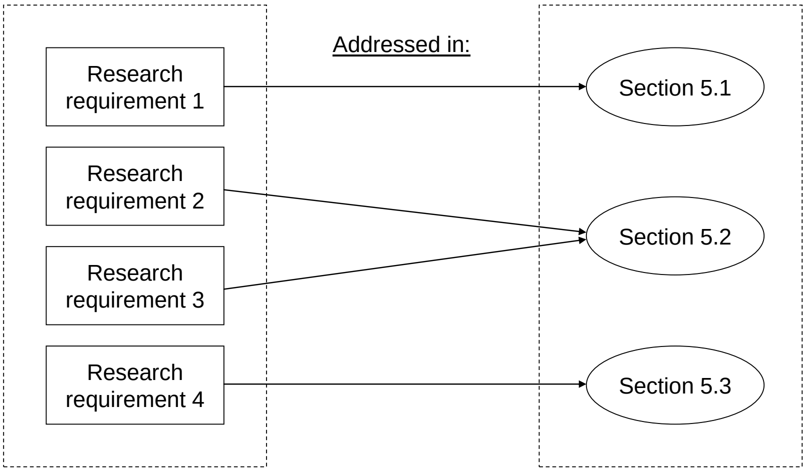


Figure 10 - Overview of chapter

5.1 Research philosophy

Reich (1994) argues that all research is based on assumptions and prejudices about the world, how the world is perceived and how best it can be understood. These assumptions are said to be personal and are entrenched in how each individual perceives the world. As a longstanding source of debate, no definitive answer can be provided to define the most accurate way in which the world can be perceived. However, it is important to understand that different perceptions exist as the philosophy that entrenches these perceptions influences the very the nature of research (Easterby-Smith, Thorpe et al. 2002). In light of this, the role of the researcher is to recognise these different perceptions and rationalise the most appropriate to adopt within the context of the specific research project. A robust research design should therefore not only define how the method of enquiry was applied, but how and why the method was selected in the first place (Reich 1994).

Reflecting the first research requirement, the following section describes the selection of an appropriate research philosophy that facilitates and provides justification for the selection of the specified research methodology. To achieve this, the concept of philosophical perspectives is first introduced, providing a description of the three most frequently cited perspectives of ontology, epistemology and methodology. It then progresses to present an overview of three different worldviews, created through adopting different stances on the ontological and epistemological perspectives. Finally, the section concludes with a justification for the selection of one of the worldviews, post-positivism, considered to be the most appropriate for guiding the research work reported on in this thesis.

5.1.1 Philosophical perspectives and worldviews

Debates on research philosophy can be broadly categorised by different philosophical perspectives. These perspectives are built upon fundamental questions about reality, how it is interpreted and how this impacts upon research. Love (2002, p.410), Easterby-Smith et al. (2002) and Reich (1994) argue the existence of three philosophical perspectives: ontology, epistemology and methodology. Ontology is concerned with establishing the nature of reality and with exploring what is real. This covers fundamental questions such as, is what we know knowledge about the real world or is our interpretation of this world biasing what we know? Epistemology is the study of the nature of knowledge and is concerned with how we come to know and in what form that knowledge is. Methodology is also concerned with how we come to know, but is considered in a more practical context, with the aim of defining how knowledge can be captured. It is also worthwhile noting that other perspectives have also been proposed in this debate. For example, Horvath and Duhovnik (2005) propose axiology, ethics and history as further philosophical perspectives. However, given the omission of these philosophical perspectives in similar research work, these are not further discussed within this thesis.

Easterby-Smith et al. (2002) discuss the ontological and epistemological perspectives as containing different prejudices, characterised by their extreme views. At the ontological extreme, reality can be considered to be either objective or subjective (Reich 1994). Through an objective ontology the researcher believes that reality exists independently of the observer, meaning that it can be objectively observed and measured. Conversely, through a subjective ontology the researcher believes that reality is socially constructed and depends on the interpretation of the specific observer. In this case, reality can be described but not proven. Likewise, epistemology is also characterised by extreme views. At one extreme, knowledge is considered to be obtained through a decomposition of phenomena into its simplest building blocks that can be measured to understand causality (Easterby-Smith, Thorpe et al. 2002). At the other extreme, knowledge is considered to be obtained through an understanding of the complexity of a problem with the focus on understanding relationships and meanings to build a picture of what may be occurring.

Based on the interrelationships between the philosophical perspectives, the concept of worldviews has been introduced (Reich 1994). Reich (1994) proposes due to the critical link between ontology, epistemology and methodology a worldview represents a combinations of these perspectives. However, more recently, Beech and Johnson (2005) have argued that a philosophical aspect of a worldview is covered by a combination of ontological and epistemological perspectives only. As such, methodology can be considered to be a practical rather than a philosophical perspective that is fundamentally linked to ontology and epistemology (see Figure 11). Reflecting the extreme positions of both ontology and epistemology, two major and opposing philosophical worldviews are considered: positivism and social constructivism (Easterby-Smith, Thorpe et al. 2002).

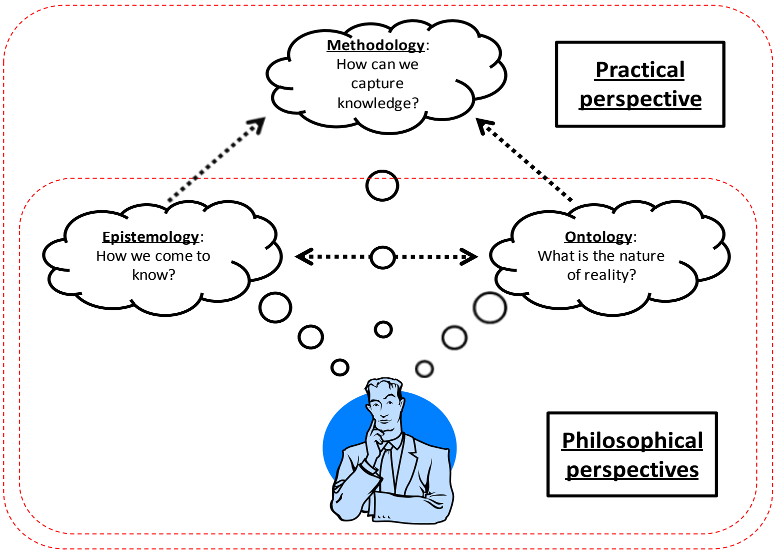


Figure 11 – The multiple perspectives that create a worldview

A positivist philosophical worldview defines that the researcher is independent or external to the boundaries of the study, and is neither affected or affects the subject of the research

(Remenyi, Williams et al. 1998). This leads to the understanding that the properties of the external world should be measured whilst ensuring objectivity, rather than being inferred subjectively through sensation, reflection or intuition (Easterby-Smith, Thorpe et al. 2002). As such the output should be reducible to physics, rendering metaphysical speculations as worthless, with the theoretical parts being translatable into statements (Hjørland 2005). In short, positivism is anti-metaphysical and focuses on observable phenomena with the aim of developing statistical models of the output. As such, positivism has a significant influence upon the methodology, as it constrains the research on quantitative data, creating repeatable statistical models based on a large number of samples (Remenyi, Williams et al. 1998).

At the other end of the worldview spectrum lies social constructivism (Easterby-Smith, Thorpe et al. 2002, Ates 2008). This worldview suggests that reality is determined by people rather than external or objective factors, viewing the researcher as an intrinsic part of the researched subject and the main driver behind the science (Remenyi, Williams et al. 1998). The goal of the social constructionist is therefore not to gather facts or measure how certain patterns occur, but to understand and appreciate the different ways people analyse their experiences (Easterby-Smith, Thorpe et al. 2002). This means that the researcher should explain why people have different experiences, in preference of searching for external causes which impact upon their behaviour. In this sense a mathematical model is of little use with the output being more verbal, diagrammatic or descriptive in nature (Remenyi, Williams et al. 1998). Again, social constructivism has a significant influence upon the methodology, as knowledge is based on qualitative data with the aim of developing theories that are typically based upon a small sample size. In the absence of large sample size case, multiple sources of evidence are therefore required.

Contrasting positivism and social constructivism, post-positivism is a research philosophy situated between these extreme worldviews. Building upon the limitations of pure positivist and social constructivist research, Popper (1959) argues that hybrid research philosophies can better enable the researcher to capture and represent the reality about the phenomena under investigation. In post-positivism, Trochim (2000) proposes that an external reality exists; however, all observations of this reality are error laden and as such to represent reality requires a synthesis of a number of error laden sources. In fact Trochim (2000) goes further stating that whilst the goal of science is to represent reality with the upmost correctness, actually achieving this is not possible due to the fallibility of human observations. This leads to a position in which problems cannot be fully understood in isolation but through links and relationships between multiple data sources. Nevertheless, whilst recognising that all theories are revisable, a post-positivist endeavours to establish a more enduring truth, using a combination of qualitative and quantitative data capture and analysis techniques (Popper 1959).

To summarise, an overview of the characteristics of positivist, social constructivist and post-positivist philosophical worldviews is presented in Table 11.

Table 11 - Summary of characteristics of research worldviews

Perspective	Composition	Worldview		
		Positivism	**Social constructivism**	**Post-positivism**
Ontology	**The world**	External, objective	Internal, subjective	External, subjective
	The researcher	Independent to study	Part of what is observed	Independent to study but introduces errors and biases that cannot be mitigated against
Epistemology	**View of analysis**	Reduced to lowest possible level	Complexity retained	Reducible but cannot be fully understood in isolation
	Aim	Define causality and fundamental laws	Describe what is happening	Present a more enduring truth
Methodology	**Data**	Quantitative	Qualitative	Both quantitative and qualitative
	Output	Statistical	Theoretical abstraction	Descriptive
	Relative sample size	Large	Small	Small
	Sources of evidence	Small	Large	Large

A product development research environment, within which the phenomenon of engineering change exists is complex comprising of people, artefacts, tools, processes, organisations and the environment (Wang 2008) and involves a number different disciplines (Pahl and Beitz 1996, Horvath and Duhovnik 2005). Product development has been referred to as a complex human activity that defies simple explanation (Fulcher 1998) discouraging the researcher from executing strict positivistic studies in favour of more human centric and constructivist approaches. In such an environment the adoption of an appropriate philosophical worldview through consideration of the philosophical perspectives is not necessarily straightforward. Within the limits of positivism, post-positivism and social constructivism, the scientific norm tends towards positivism, with the aim of research projects being to identify fundamental truths of the universe. However, knowledge associated with product development has been proposed as being acquired from the natural, social, and technical sciences, with part of it being strongly related to human assets and the involvement of the human in product development practice (Horváth 2004). Research into product development does not always seek directly observable and universal laws in the same manner as the positivist community due to the behaviour and multiple interpretations of the humans involved. As such, a softening of the strict positivist worldview that also perceives value from human interpretation and behaviour is almost becoming an emerging standard for research in product development. This has led to a rise in the adoption of more hybrid worldviews, mirrored by the trend to apply social research methods to research in product development (Beitz 1994, Reich 1995, Green, Kennedy et al. 2002).

5.1.2 Adopted worldview

To recap, the aim of the work presented in this thesis is twofold. Firstly, this thesis aims to report on what engineering change management process activities are enacted at different stages of the product lifecycle and secondly to report on what types of artefact knowledge are used and created during the enactment of these activities. To this end, this research involves establishing the activities and the artefact knowledge that are used and created by individuals who are involved in the processing and management of engineering changes.

Capturing knowledge that is associated with individuals who are involved in the processing of engineering changes draws parallels with psychology and other social research fields due to the involvement of human beings and organisations (Dixon 1987). Whilst Horváth and Duhovnik (2005) suggest that there has been a growing appreciation that designing is a social process, the management of engineering change can also be recognised as a social process too due to the interaction between the actors who are involved in the process (Chen, Shir et al. 2002). Given this realisation, the adoption of a philosophical worldview that perceives value in the richness of human knowledge and interaction is appropriate. This rejects the constraints of positivism in favour of social constructivist and post-positivist worldviews. Reinforcing this rejection, the emphasis of the work reported on in this thesis is on describing a process that couldn’t exist without human beings, hence favouring a more human centric research approach. However, a single process has been demonstrated to exist in organisations by a number of authors, e.g. (Pikosz and Malmqvist 1998, Tavčar and Duhovnik 2005, Eckert, de Weck et al. 2009). Representing a single, shared reality, the internal and individual ontological view of the world considered by social constructivists is not appropriate either. In such circumstances and based upon the discussion presented above of the three reported research methodologies, the most suitable worldview to adopt in this process is that of post-positivism. As such, a post-positivist worldview has been adopted in this work.

5.2 Research methodology

Following the selection of an appropriate research philosophy, the second and third requirements relate to the selection of an appropriate research methodology. Recognising Reich's (1994) concern that some researchers consider methodology and methods as the same, and neglect the true meaning of methodology: the theory of methods, the following section describes not just what method was adopted, but why such a method was adopted. It begins in section 5.2.1 with a description of data collection strategies, focussing on those presented by Yin (2003). The sampling strategy is then described and rationalised in section 5.2.2, before the selection criteria is the presented in section 5.2.3. An overview of the case study methodology is then presented in section 5.2.4, highlighting the case selection strategy, data collection protocol and data analysis process. Finally, an overview of the survey strategy is present in section 5.2.5.

5.2.1 Data collection strategy

Data is central to any research project and has to be collected in a robust and scientific manner to ensure rigour and integrity (Tenneti 2007). To facilitate this collection, a number of data collection strategies exist. Yin (2003) summarised potential strategies, identifying how the form of the research question; whether the researcher has control over events under investigation and whether the events under investigation occur at the time of the investigation can aid the researcher with their selection (see Table 12). To demonstrate why specific research strategies have been selected for this research, the potential strategies are subsequently discussed and rationalisation for the selection offered.

Table 12 - Relevant strategies for different research questions (adapted from (Yin. 2003))

Strategy	Form of research question	Researcher has control over events under investigation?	Events under investigation occur at the time of the investigation?
Experiment	how, why?	Yes	Yes
Survey	who, what, where, how many, how much?	No	Yes
Archival analysis	who, what, where, how many, how much?	No	Yes / No
History	how, why?	No	No
Case study	how, why?	No	Yes

Experimental analysis is a method for investigating the behaviour of a system by altering one variable at a time and keeping the rest fixed or constant (Antony 1998). From this, knowledge of the relationships between the variables can be achieved, the effects on the analysed system can be predicted and hence the properties of the changed variable found. This approach has been likened to a trial and error approach, as Antony et al. (2003) argues that changing one factor at a time to achieve the stated goal requires a combination of luck, intuition and experience to succeed. Furthermore, this relies on the assumption that the researcher can control each of the variables or events under consideration and that the experiments are executed in real-time.

Another strategy available to the researcher is the survey. A survey is a collection of related questions on a specific topic. This can be an effective technique to gain an insight into a problem area from multiple viewpoints; however, there are a number of issues associated with the use of surveys, with one of the most pertinent issues relating to respondent apathy (Janes 2001). This can emerge as inaccurate results, low response rates and ultimately incorrect conclusions being drawn. Twenty first century delivery techniques, in particular the use of the internet, look to combat these issues, providing a number of advantages, such as global-reach, low administration cost, speed and timeliness (Evans and Mathur 2005). Surveys do not rely on the control of variables or events under consideration.

Archival analysis is the utilisation of detailed documented records (organisational documents, survey records, etc.). Care must be taken when analysing archival records, as some records which may be quantified, may still be inaccurate (Friedman and Sage 2004). Similar to archival analysis, historical strategies review situations that have occurred in the past. This strategy is particularly useful when there is little or no control or access to the behaviour of the research area (Yin 2003). Histories are therefore used to find out information about "dead" data, in situations when access to contemporary data is prohibited.

When access to contemporary data is available but the researcher has little control over the events under investigation, then Yin (2003) recommends that the most appropriate research strategy is that of a case study. A case study is an empirical enquiry that investigates real-life phenomenon over which the researcher has little control. It is particularly useful when the boundaries between the phenomena and context are not clearly evident (Yin 2003). Although there is some resistance to the validity of case study research (Yin 2003), it is widely accepted that case study research strategies can be adopted with sufficient scientific rigor leading to successful advances in knowledge. Evidence of this success can be demonstrated by the number of successful case studies being published in top US and European journals (Dul and Hak 2008). Friedman and Sage (2004) report that case studies "…support a holistic understanding and interpretation of the systems of action, or interrelated activities engaged in by the participants or actors in the case situation subject to study."

Reflecting that the researcher has little control over the phenomenon in question and that the phenomena under investigation occurs at the time of the investigation, Yin's (2003) framework offers the guidance that both case study and survey strategies are suitable to adopt. Case study strategy has been reported as being popular in the operations management field (Voss, Tsikriktsis et al. 2002) and has been suggested as the optimal method for investigations of organisational change (Pettigrew, Woodman et al. 2001). Furthermore, case studies have been adopted by a number of authors as the main research methodology in a range of papers on engineering change, e.g. (Pikosz and Malmqvist 1998, Barzizza, Caridi et al. 2001, Tavčar and Duhovnik 2005). Conversely, comparatively few papers have presented the results of surveys. Nevertheless, insightful contributions based on surveys have been offered that act to better inform the reality of engineering change as practised in industry (Huang and Mak 1999, Huang, Yee et al. 2003).

Whilst current theory defines that case studies and surveys are the most appropriate research strategies to adopt within the constraints that have been outlined, in the case of this research project another key factor that influences the decision of which strategy to adopt also exists. As the research project was sponsored by an external company (Babcock International Group) and the researcher was embedded within this company for the period of the research, there existed an opportunity to take a more ethnographic approach to the research. In such an instance, the researcher was well placed to conduct a case study, enabling a deeper understanding of the intricacies and nuances of the cases. To then take the findings from the case study and determine whether there was any correlation with the wider field of engineering, a survey could be conducted. This data collection strategy is consistent with the adoption of post-positivism, in which a key component of this philosophy is the use of multiple means of accessing data. As Trochim (2000) proposes, it is only through the usage of multiple, inherently error laden sources that an improved representation of reality can be offered. As such, this thesis reports on research work based upon the use of both case study and survey research strategies.

5.2.2 Sampling strategy

In parallel with the selection of a data selection strategy, the selection of a sampling strategy was also considered. With the first research question being time based, the researcher is confronted with a decision over how to conduct the investigation, and is presented with two possibilities: a longitudinal or a cross sectional study (Yee and Niemeier 1996). A longitudinal study involves repeated observations of the same phenomenon in the same setting over an extended period of time. Conversely, a cross-sectional study involves the sampling of a population at pre-defined times.

The adoption of either technique has both benefits and limitations for any research study. Generally, within longitudinal studies the same individuals are tracked and as such offer an improved basis for making causal claims by ensuring causal interference is minimised (Shklovski, Kroaut et al. 2004). However, in certain instances the phenomenon that is being studied can span periods of time that prohibit this type of investigation. To mitigate this, cross-sectional studies enables the researcher to sample similar cases at predefined times. This enables the researcher to then make judgements of how the phenomenon in question would evolve within a longitudinal study without the necessity to invest the extended periods of time needed (Levin 2006). However, Levin (2006) states that as cross sectional studies are carried out at one point in time, they have a limited ability to infer causality.

As with other studies, the adoption of either technique introduces errors and biases that will affect the outcome (Trochim 2000). Starting with a longitudinal study, this technique would enable the researcher to identify how the engineering change management process evolves within a specific organisation as the engineering artefact proceeds through the various lifecycle stages. Sampling the activities and knowledge that are used and created over a period of time would therefore enable the researcher to draw conclusions about how the process has changed within the selected case as the project has moved through the various product lifecycle stages. However, as reported by Griffin (1997), the period it takes to develop engineered products varies significantly depending on the type of product. Whilst Prasad (2003) reported that the market is forcing the reduction of these periods, when considering the stages of the product lifecycle beyond that of development it has been observed that these periods can stretch into decades. Reflecting this insight, executing a longitudinal study of a product would require a period of time that is beyond that permitted by a doctoral research project, if an industrial context was to be maintained. As such, a cross-sectional data collection technique was adopted.

5.2.3 Selection criteria

Adopting a cross-sectional data collection technique forces the researcher to collect data from multiple different sources or cases. In the context of this research, these cases reflect different industrial engineering projects. In this circumstance, care must be taken in the selection of these cases as to not introduce known influencers into the collected data (Levin 2006). Given the aims of this study are to establish both the activities that are enacted during the engineering change management process at different stages of the product lifecycle and the artefact knowledge used and created through the enactment of these activities, it is important that any known influencing factors should be mitigated. As such, as reported by Pikosz and Malmqvist (1998) it is currently known that variations in the engineering change management process can be caused by organisational, market and product issues, whilst Tavčar and Duhovnik (2005) reported that the engineering change management process can be effected by whether a product was to be mass or individually produced. To ensure comparability between sources, similarities in the organisation, market, product and production quantity were maintained during the selection of cases, whilst the stage of the product lifecycle was varied. In addition to the factors that are known to influence the engineering change management process, a secondary requirement was also placed upon the cases. To ensure that appropriate research could be carried out, the researcher must be permitted access to information from within the organisation.

To summarise the above discussion, these case selection requirements are presented in Table 13.

Table 13 - Case selection requirements

Constraint	Known influencer	Selection strategy	Requirement
Organisation	Yes	Maintain consistent	The cases must originate from the same organisation or organisations that have significant similarities.
Market	Yes	Maintain consistent	The market in which the organisations trade must be the same or significantly similar across the cases.
Product	Yes	Maintain consistent	The products that are developed by the organisations must be similar across the cases.
Production quantity	Yes	Maintain consistent	The quantity of products that are being produced must be similar across the cases.
Lifecycle	No	Vary	The cases must be at different stages of the product lifecycle during the period of study.
Access to information	-	-	The researcher must be able to access information from within the organisations.

5.2.4 Case study overview

Delivering an overview of the case study strategy reported on in this thesis, the following section is separated into four sections. In section 5.2.4.1 an overview of the case selection strategy is presented, reporting how the case selection requirements informed the selection of the sampled cases. In section 5.2.4.2, the process by which the data was captured is reported before the data analysis process is presented in section 5.2.4.3. Finally, in section 5.2.4.4 the case study strategy is summarised outlining the data source used, research method and research outputs.

5.2.4.1 Case selection strategy

Yin's (2003) methodology emphasises the appropriate selection of cases to study. In particular, one of the first steps is to identify whether the research should be based on single or multiple cases. Yin (1984) argues that single cases can be vivid and illuminating if they are critical, extreme or unique. Miles and Huberman (1994) also report that whilst multiple cases offer the researcher a deeper understanding of processes and outcomes of cases, a significant proportion of research examines single cases. In such instances, the challenge is to disentangle what is unique in that case from what is common to other cases (Eisenhardt 1989). Eisenhardt (1989) suggests that whilst there is no ideal number of cases; however, between four and ten cases are desirable for theory building using a case study methodology. In a more recent publication Voss et al. (2002) suggested that from a review of recent case studies, between three and thirty case studies was the norm. However, to answer how many cases are required cannot be answered on a statistical basis (Miles and Huberman 1994), instead requiring conceptual judgement. In general, Handfield and Melnyk (1998) suggest that to identify the key variables and linkages between these variables a "few" focussed case studies are required. Moreover, Dyer and Wilkins (1991) report that a number of the more important studies that have advanced knowledge of organisations and social systems have only used single or low quantity case studies.

Whilst a range of authors have quantified the number of cases that should be conducted, the main thrust of these arguments is not wholly based upon the quantity per se. Fundamentally, case study research is conducted to uncover unique insights that could have been missed in other approaches to data collection. In such an instance, applying a number to the question of how many cases that should be conducted, in such a generic manner, may lose the focus on establishing the uniqueness of the cases: the main driver of case study research. Conducting an increased number of cases would inevitably deliver results that had a greater statistical significance. However, case study research aims to present rich descriptions and the unique attributes that are fundamentally associated with each case rather than comparing and contrasting specific points. With this knowledge, the researcher set out to establish cases that could provide the most interesting comparisons, within the time and access constraints imposed by engineering doctorate research.

Given the sponsorship for this study being provided by Babcock International Group, this provided an opportunity to select cases from within a single organisation. This satisfied the first of the selection criteria presented in section 5.2.3 and has been presented as being a valid course of case based research by Voss et al. (2002). Furthermore, as Babcock were currently running a number of design to order projects, with similar products and production quantities that were at different stages of the product development cycle, this provided an suitable opportunity to satisfy the case selection requirements. To that end, a number of projects were considered and discussed with a senior manager within the company. Based on current theory into the number of cases (as presented above), time and logistical constraints and what potential projects were currently being run within Babcock that fitted the case selection criteria, it was decided that three cases should be selected. As such, three engineering projects were selected: the S80 project, the QEC project and the HMS Illustrious refit. These were selected based on the stage of the product lifecycle that they were currently within, the availability of the individuals involved to participate in the research, the logistics associated with conducting the case studies and potential to establish unique and interesting findings. Of these, two of the projects were being run by Babcock - Engineered Solutions in Rosyth, UK and one by Babcock – Integrated Technologies in Bristol, UK. An overview of pertinent project characteristics can be seen in Table 14.

Table 14 - Project characteristics

Project characteristics	Case project 1 (CS1)	Case project 2 (CS2)	Case project 3 (CS3)
Project title	S80 project	The QEC project	HMS Illustrious refit
Product lifecycle stage	Conceptual design	Detailed design / production	In-service
Organisation	Babcock International Group – Integrated Technologies (Bristol)	Babcock International Group – Marine and Technology Division (Rosyth)	Babcock International Group – Marine and Technologies Division (Rosyth)
Market	Design to order	Design to order	Design to order
Product	Submarine torpedo launching system	Aircraft carriers for the Royal Navy	Refitting of new equipment on existing aircraft carrier
Production quantity	Six	Two	One

5.2.4.2 *Data collection protocol*

In addition to selecting a case study data collection strategy for the research project, a clear method for collecting the data itself was also required. Eisenhardt (1989) reports that both qualitative and quantitative methods of data collection and analysis are suitable for case studies and Hartley (2004) suggests that within a specific case a combination of data collection methods can be used. Further, in case study research Maguire (2010) suggests that of these data collection methods, interviews is the most common.

Literature informs that three fundamental types of interview exist: structured and semi-structured and unstructured, each offering different benefits and limitations. In an unstructured interview, little attention is placed of defining these questions prior to the interview taking place and as such the interviewer is not constrained to a single line of questioning. This technique is generally regarded as being suitable for instances in which the researcher has little knowledge of the phenomenon under investigation, but is limited in situations when a consistent approach is required across different interviewees. In this instance, structured or semi-structured techniques are recommended. Of these, semi structured interviews represent a method of enquiry that is more flexible than structured interviews allowing the questions to be modified and new questions to be proposed during the interview as a result of the interviewee's response. This typically provides a view into the interviewee's world, thoughts and feelings (Hove and Anda 2005). Semi-structured interviews can be conducted on an individual basis with a single interviewer and interviewee or within a group, otherwise known as focus groups (Morgan 1997). To provide a greater level of control over the interview progression and allow a less constrained view of the engineering change management process, the interviews were undertaken on an individual basis and followed a semi-structured format.

To select the interviewees, a request was initially made to a senior representative within the project. This senior representative was then requested to select a cross section of individuals within the project, with the main emphasis on establishing a profile of individual experience to cover each of the stages of the engineering change management process. These individuals consisted of both technical and project focused individuals (see Table 15), to collect several viewpoints of the same phenomenon (Collins and Rainwater 2005). Following selection, the interviewees were sent requests to attend an interview at a specific time and location from the senior project representative.

Table 15 - An overview of the interviewee profile

Case project	Number of technical focussed interviewees	Number of project focussed interviewees	Total number of interviewees
CS1	3	2	5
CS2	6	0	6
CS3	4	1	5
Total	**13**	**3**	**16**

Whilst the interviews were semi-structured, they were guided by the development of specific questions. Prior to the research interviews these questions were tested with a pilot study consisting of three interviews and modified accordingly. The interview questions were designed around the funnel model as reported by Voss et al. (2002). In this method broad, open ended questions are asked first, with the questions becoming more specific and detailed towards the end of the interview:

- What are your responsibilities within the current project?

- Could you describe to me how change is managed in your current project?
- What methods do you use to communicate change within your current project?
- Could you describe to me the engineering change process in your current project?
- In what capacity are you involved with this process?
- Can you describe to me how you go about [*insert relevant change phase*]?
- What are the key activities and difficulties in [*insert relevant change phase*]?
- What knowledge do you require to perform these activities and in what form does that knowledge come?
- What knowledge do you generate as a result of these activities and in what form?
- Where does this knowledge go to (who uses it)?
- What is the main aim of performing these activities?

In order to capture what was discussed during the interviews, a decision was taken to record these with a digital audio recorder and create verbatim transcripts of the discussions. Yin (1984) reports that audio recordings of interviews should be executed when the exactness of the discussion is important. However, Voss et al. (2002) purports that digital recording can be seen as a substitute for listening and can inhibit the responses provided by interviewees. In addition, the post processing time involved with transcribing the data can be significant. Nevertheless, as the exactness of the discussion was deemed important each interview was recorded and a verbatim account of the discussion was transcribed.

Given that the request to participate in this research was communicated through a senior company representative, it is considered that this could have had an influence upon the interviewees’ responses. This could have resulted in individuals being hesitant to share their knowledge or being conservative in their expression of this. However, given that the researcher was based within this company for the period of the study, this presented an opportunity to conduct the research in a more ethnographic manner than is usually available to university based researchers. In such a case, the interviewer was able to probe deeper to obtain the unique views of the individual rather than the merely the surface level process based upon an existing knowledge of some of the issues and concerns within the cases.

5.2.4.3 Data analysis process

Following the completion of the interviews and transcription of the interview recording, the data underwent a data analysis process. The aim of this data analysis was to interpret the collected data in a manner that provided an insight into the research question. To achieve this, Eisenhardt (1989) proposes that this should be done in two forms: individually (within case analysis) and collectively (cross case analysis). The process through which this was achieved is described in the following two subsections respectively.

Within case analysis

Within the three cases, the same process for analysing data was executed. Following the verbatim transcription of the recorded interviews the text contained within the transcripts then underwent a process referred to as coding (Glaser and Strauss 1967, Miles and Huberman 1994). During this process, phrases that provided an insight to the activities that composed the engineering change management process, or the inputs and outputs to these activities that were contained within the transcripts were identified and categorised. Decomposing the interview data in this manner therefore enabled the extended transcripts to be broken down into key statements. From these key statements, a case profile of the engineering change management process was established.

During the coding process two different coding techniques were used: open and closed (Miles and Huberman 1994). To identify the activities that could be associated with the engineering change management process an open coding technique was used. This meant that the range of possible activities had not been set a priori; instead this range evolved throughout the coding process to provide the required flexibility to assess these activities. Conversely, when an activity had been identified, the inputs and outputs of this activity were coded based on a closed code. In this technique, the seven types of artefact knowledge outlined in chapter 3 were used to categorise the inputs and outputs. As such, the output of the coding process for each of the interview transcripts was an individual insight of the activities that were enacted within the engineering change management process and the types of artefact knowledge that were used and created by these activities. Synthesising these individual views then enabled a case profile to be developed that detailed the activities that had been enacted and the artefact knowledge that had been used and created through the enactment of the activities within the three cases. To illustrate the data collection and analysis process Figure 12 is presented.

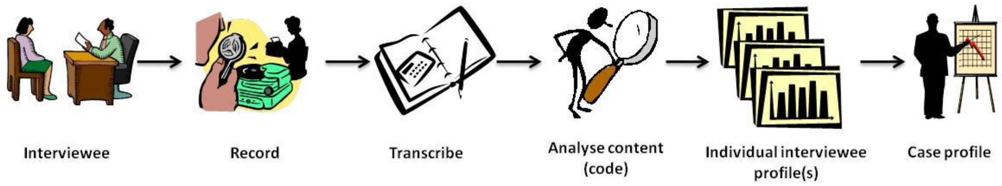
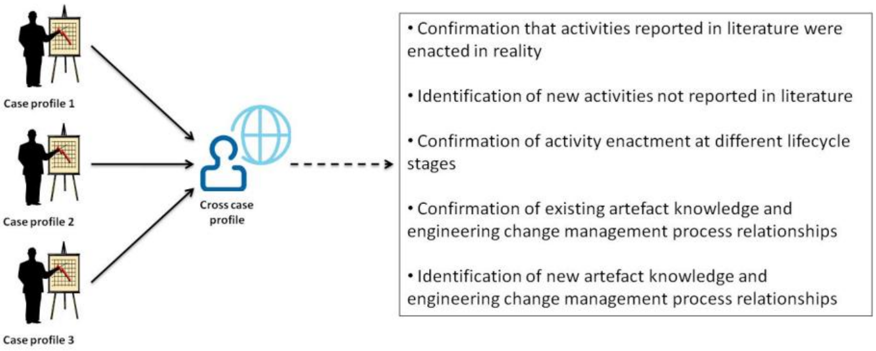


Figure 12 - Overview of data collection process

Cross-case analysis

Following the analysis of the three cases, the results were then cross referenced to enable general conclusions to be made (Eisenhardt 1989, Miles and Huberman 1994, Voss, Tsikriktsis et al. 2002). To achieve this, the activities that had been identified from the case study were collated, providing confirmation of that the activities that had been reported in literature were enacted in reality. In addition, activities that had not been reported in literature were established before but the existing and new activities were discussed in the context of specific lifecycle stages. The types of artefact knowledge that relate to activities within the engineering change management process were also collated from each case. As with the activities, the relationships between artefact knowledge and the engineering change management process were then cross referenced against the literature to confirm the existence of those relationships that are currently known. Further, any relationships that had been identified from the case study, but not from literature were also presented. An overview of the cross case analysis is presented in Figure 13.



- Confirmation that activities reported in literature were enacted in reality
- Identification of new activities not reported in literature
- Confirmation of activity enactment at different lifecycle stages
- Confirmation of existing artefact knowledge and engineering change management process relationships
- Identification of new artefact knowledge and engineering change management process relationships

Figure 13 - Cross case analysis overview

5.2.4.4 Case study summary

To summarise how the case study strategy has been applied within the context of this research work, Figure 14 is presented. From this diagram it is evident that engineering change practitioners act as the data source. Using semi-structured interviews the knowledge that is possessed by these engineering change practitioners is elicited and transformed into research outputs. As such, from the case study, three outputs are established: confirmation of the activities that compose the engineering change management process; a description of whether these activities are enacted at different stages of the product lifecycle and, a developed model of artefact knowledge and engineering change management process relationships.

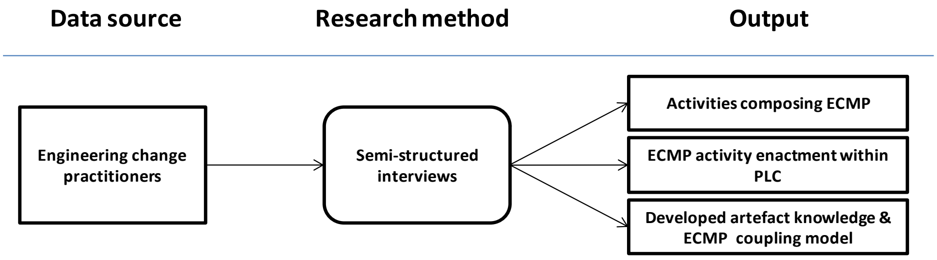


Figure 14 - Summary of case study method

5.2.5 Survey overview

Whilst case study based research can produce complex insights into contemporary events, it has been criticised within academic literature for its inability to generalise the results beyond the specific case (Yin, 1994). Reflecting the post-positivist philosophy, the findings from the case study were subsequently triangulated through obtaining the views of engineering change practitioners in the wider industrial community. Adopting a survey strategy requires consideration and justification of the design of both the questionnaire itself, its associated administration strategy and analysis technique (Peterson 2000). To demonstrate and justify these, the following section is decomposed into five sub sections. In the first section, the inclusion and population criteria are presented. In the second, the sample and error rate associated with the data is discussed and calculated and the administration strategy associated with the delivery of the questionnaire reported. In the third, the structure of the questionnaire is discussed whilst in the fourth the data analysis process is outlined. Finally, a summary of the survey strategy is presented presenting the data source used, research method and research outputs.

5.2.5.1 Inclusion and population criteria

To achieve the aim of the survey and establish whether the findings from the case study could be generalised beyond the specific cases required the input from a range of other engineering change practitioners. However, given the nature of cases sampled in the case study and the limitations placed upon the research as defined in the selection criteria presented in section 5.2.3, inclusion criteria were developed to ensure the comparability between the outputs from the case study and survey. These inclusion criteria were first used to constrain the selection of appropriate organisations and engineering projects, ensuring that these were comparable with those sampled in the case study. Mirroring the insights offered by Pikosz and Malmqvist (1998) and Tavčar and Duhovnik (2005) the four constraints, presented in section 5.2.3 as organisation, market, product and production quantity, were cross referenced against the cases selected in the case study.

Focussing on the nature of the cases selected, it is apparent that there are a number of similarities that can be elaborated upon to permit sampling within the wider engineering community. Focussing on the organisation, whilst all the companies were from Babcock International Group, the type of sampled organisation is that of a multinational engineering organisation. Further, the type of market in which the companies operated is that of the design to order market, in comparison to the design to sell market. Moving on to the product, whilst each of the products were Defence orientated engineering artefacts, the nature of these engineering artefacts meant that they could be considered to be highly customised physical engineering artefacts. Finally, as the production quantity of the engineering artefacts in the sampled cases ranged from one to six, this can be referred to as a low product quantity in comparison to a mass produced item. This is summarised in Table 16.

Table 16 - Survey inclusion criteria

Constraint	Description
Organisation	Multinational engineering organisation
Market	Design to order market
Product	Highly customised, physical engineered artefacts
Production quantity	Low

In addition to the inclusion criteria, to ensure that the correct population from within cases that satisfied the inclusion criteria was sampled a further set of inclusion criteria were developed. Termed population criteria these criteria acted as a mechanism to ensure that the views of the correct individuals were obtained. As such, the individuals who were asked to complete the questionnaire must be involved in some capacity with the processing of engineering changes (identifying the need to change, generating solutions to overcome the changes, impact assessing the solutions, authorising the solutions or implementing these) and focus predominantly on the technical processing of engineering changes rather than project or administrational processing. To provide support to the selection of the correct individuals, the population criteria were translated into possible job roles. As such, a list of potential job roles was offered, including: CAD/CAM operators, chief engineers, designers, design managers, engineering managers, engineering liaison officers, lead engineers, production engineers, production managers, production supervisors, project engineers, project leads, technical leads, etc.

5.2.5.2 Response rate and administration strategy

Given the quantitative nature of a survey, to ensure statistical certainty of the output requires a number of responses (Chambers and Skinner 2003). In lieu of sampling an entire population, researchers often sample a representative set of candidates and extrapolate the results to the wider population (Bartlett, Kotrlik et al. 2001). However, to ensure that enough candidates are sampled to satisfy the statistical certainty of the extrapolation, a number of responses are required that forces the researcher to make a number of key decisions. Whilst there are no definitive rules for specifying the exact number of responses required, a balance between the desired precision against the increased cost associated with larger studies is required to be established. Literature also informs that the researcher should not expect to receive a completed and usable questionnaire for each questionnaire sent out as typical response rates can be as low as 20% (Yu and Cooper 1983). An overview of the response rate and sample size is presented in section 8.1.

DeLamater and McKinney (1982) reports that every survey administration introduces and exacerbates response effects, including refusing to answer questions, giving incomplete answers or not following instructions. Selecting the most appropriate administration strategy is therefore an important factor to consider in survey based research. Within survey based research there are two main methods for administration, both with their own set of benefits and limitations: structured interview schedules and self-administered questionnaires. In structured interviews, the questions are asked orally to a single interviewee and the responses are recorded by the interviewer. This process can be executed either over the telephone or face to face. The second method for delivery is self-administered questionnaires, in which the respondent is asked to fill in a document based questionnaire in isolation. In this form, the questionnaire can be delivered to the respondent by a range of means including email attachments, post or via publishing on a website.

Kiesler and Sproull (1986) outline some of the benefits of these different administration strategies. They report that the use of an orally based administration strategy is more likely to result in the respondent trying to please the researcher than in a document based strategy. However, orally administered surveys can also increase the response rate. As such, self-administered questionnaires generally result in a reduced response rate, but can increase the reporting of negative information and attitudes. Beyond the selection of oral or document based administration, the selection of electronic or paper based techniques is an important consideration. Acknowledging the reported benefits of improvements in data quality, fast delivery of data and reduced costs Tourangeau and Smith (1996) report that building up to the mid 1990s, trends in survey data have shown a significant increase in the use of the electronic format.

Considering the benefits and limitations of the various combinations of strategies, within this survey a document based self-administered strategy was adopted. Prepared within Microsoft Word, the questionnaire was emailed to a representative within the case companies who coordinated the propagation of the questionnaire to selected representatives from within the project. Upon completion the questionnaires were then either emailed directly to the researcher or posted to the University department for collection. Given this administration strategy the number of questionnaires that had to be sent out to achieve the required response rate was significantly reduced.

5.2.5.3 Questionnaire structure

In survey based research, the questionnaire represents the data capture method for the individual responses. As such, the importance of an effective questionnaire structure has been reported (Peterson 2000). With key objectives of maximising response rate and ensuring that the output of these responses are in a usable form, Peterson (2000) discusses that the effective design of a questionnaire can contribute to achievement of accurate and valid results.

Given the quantitative nature of the survey, an opportunity to go beyond mere qualification of activity enactment and artefact knowledge usage and creation was presented, providing an opportunity to test an insight that had emerged from the case study. Emerging from the case study, it was identified that whilst processes for managing engineering changes existed within the reviewed cases, that not all activities were always enacted for every engineering change. As Huang and Mak (1999) and Jarratt et al. (2011) report, engineering changes can vary in size from minor modifications to entire redesigns of products and associated processes and as such it is perhaps inevitable that certain engineering changes do not go proceed through the same activities every time. In light of this insight and opportunity, the researcher decided to enquire not only about whether an activity was enacted, but how frequently the activity was enacted during the engineering change management process as well.

The questionnaire itself was paper based and consisted of seven A4 pages, including one introduction page and seven pages of questions. On the introduction page an overview of the project was provided along with the researcher’s contact details and a space for the respondent to provide their job title, number of years experience in the engineering industry and the stage of the product lifecycle that their project was currently in. Following this, the questionnaire commenced to enquire how frequently a specific activity was enacted for each engineering change that is experienced within the project. Provided with five options: never (0%), occasionally (1-33%), sometimes (34 – 66%), frequently (67-99%) and always (100%), each of the activities that were identified from both the case study and from literature were described. In addition, a space was provided for the respondent to include any further activities that had not been established from either the case study or literature review. In the final section, the questionnaire then asked what types of artefact knowledge were used to enact each of the activities and created as a result each of the activities. In this section each of the activities were listed across the top of the page and the specific knowledge types provided down the side. As such, the respondent was asked to consider what type of artefact knowledge each activity used and created and to mark the corresponding box. An example questionnaire that was used within the survey can be seen in Appendix B.

5.2.5.4 Survey data analysis process

Following the return of a sufficient number of completed questionnaires, the data contained within these underwent analysis to transform this into a format that could provide a valid source of evidence to provide further clarity to answering the research questions. Given that the first research question focused on establishing what activities were enacted at different product lifecycle stages the first stage of the analysis was to sum all responses that demonstrated activity enactment. Cross referencing these against the stage of the product lifecycle that the engineering project was said to be within, it could then be established what percentage of respondents stated that the activity was enacted within their product lifecycle stage.

In addition to this, to test an insight that emerged from the case study, further analysis was undertaken on the enactment frequency data. Separating the responses into three bins of approximately equal range (0 – 33%, 34 – 66% and 67 – 100%), the total number of individuals who stated that a specific activity was enacted within these ranges was summed.

Multiplying the median of the frequency range against the number of respondents within the ranges and summing the output, the mean activity enactment frequency was established.

Finally, to establish what types of artefact knowledge were used and created through the enactment of the activities that compose the engineering change management process, a final analysis was undertaken. Summing all the number of positive responses that highlighted that a specific type of artefact knowledge was either used or created, this was subsequently divided by the number of negative responses to establish the percentage of positive respondents.

The data that was collected through the survey and the calculation method can be found in Appendix C.

5.2.5.5 Survey summary

To summarise how the survey strategy has been applied within the context of this research work, Figure 15 is presented. From this figure it is evident that engineering change practitioners again act as the data source. Using a survey the knowledge that is possessed by these engineering change practitioners is elicited and transformed into research outputs. As such, from the survey, three main outputs are established: a quantification of which engineering change management process activities are enacted at different stages of the product lifecycle; the frequency of enactment of these activities at different stages of the product lifecycle and, a developed model of artefact knowledge and engineering change management process relationships.

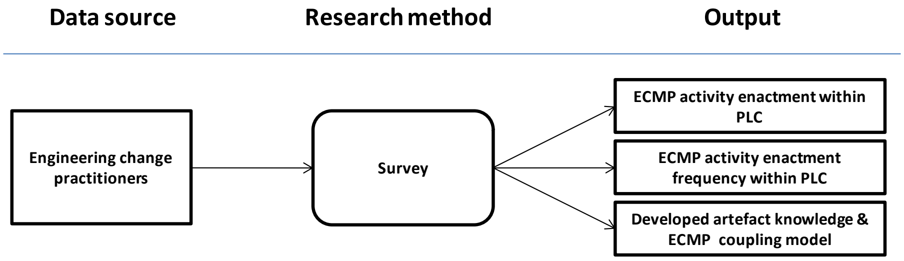


Figure 15 - Summary of survey method

5.3 Validity

Validity, how one can judge the plausibility, sturdiness and conformability of the conclusion (Miles and Huberman 1994) is an important consideration in any research project (Maxwell 2005). Easterby-Smith et al., (2002) suggest that validity is fundamentally related to research philosophy, linking philosophical assumptions to questions that should be considered. As such, from a positivist perspective validity is concerned with establishing whether a research instrument measures what it is supposed to measure. Conversely, from a post-positivist perspective validity is concerned with establishing whether the researcher has gained full access to the knowledge and meaning of the informants.

One strategy for increasing the validity of the results when adopting a hybrid philosophy perspective such as post-positivism is termed triangulation (Denzin 1970, Jick 1979, Brinberg and McGrath 1985, Yin 2003). Triangulation is a multi-method strategy in which the focus of the research is investigated from a number of different perspectives (Yeung 1995). Triangulation can be applied effectively in a research project, as Jick (1979) reported that researchers can obtain a more accurate view of a certain phenomenon by viewing a number of different sources on the same phenomenon. Triangulation is as important consideration in the validity of the results and should be incorporated into four areas of research consideration: data sources, methods, investigators and theories (Denzin 1970).

Data source triangulation refers to the formation of a single body of data through the integration of data from multiple sources (Wang 2008). In this research project two data sources are considered: published literature and engineering practitioners. Published literature has been used not only to highlight the knowledge gaps, but also to demonstrate the current knowledge of the activities that compose the engineering change management process and the artefact knowledge that is used and created through the enactment of these activities. Extending this, engineering practitioners have been used to inform what activities are enacted at different stages of the product lifecycle. Methodological triangulation requires more than one method of enquiry to be used to gather data. In this research project a three methods of enquiry are used: content analysis of published literature, semi-structured interviews (used within the case study) and a survey. As such, it is through the integration of the evidence from these three research methods that answers to the research questions are offered. For an overview of data source and methodological triangulation used in this research refer to Figure 16.

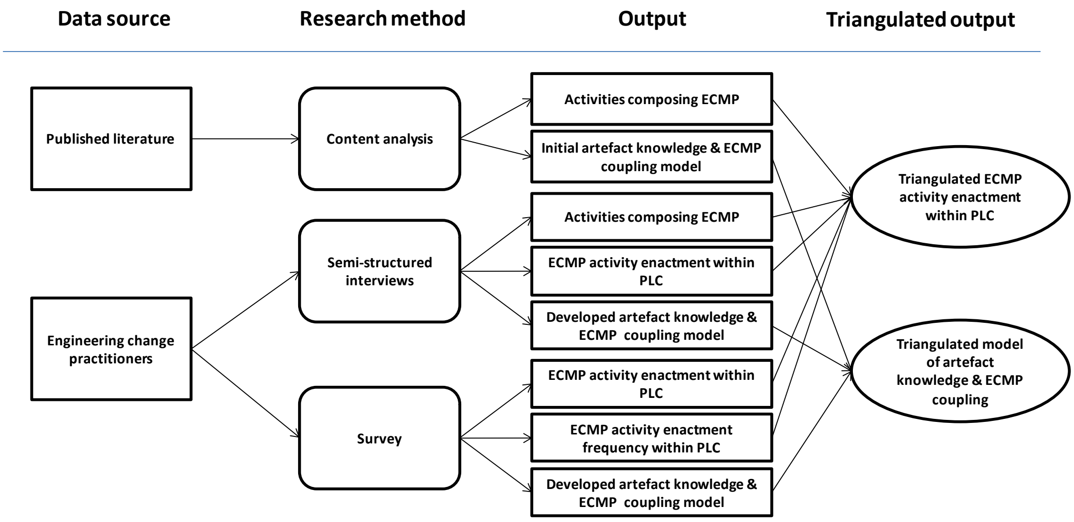


Figure 16 - Data source and methodological triangulation used in this research

Investigator triangulation looks to involve multiple observers in an investigation rather than an individual observing alone (Denzin 1970). Whilst multiple investigators can improve validity, the nature of a doctoral research project limits the investigator to the author of this thesis alone. Finally, theoretical triangulation aims to involve more than one theoretical paradigm in order to interpret the phenomenon under enquiry from different perspectives (Jick 1979). To achieve this, different perspectives of the same phenomenon should be adopted to establish how these perspectives may impact upon the findings. However, theoretical triangulation has been presented as being an element that is not often achieved within an investigation (Denzin 1970). Mirroring this finding, theoretical triangulation is not considered within this research project.

However, given that the research is based upon a limited number of cases and companies, the findings from the research cannot be immediately extrapolated to produce a representation of all of engineering practice. Whilst the applicability of the findings has been limited by the case selection strategy, even within this the statistical significance is not sufficient to represent all cases. In this situation, it may not be accurate to generalise the findings from this research to all engineering cases. Nevertheless, this thesis still contributes by presenting a unique view of engineering change management practice from which recommendations are made that could be inferred in a range of cases that is constrained to scope provided in section 1.1.

5.4 Chapter summary

The chapter has presented the design of the research that has been undertaken to answer the research questions reported in the previous chapter. Discussing philosophical perspectives in terms of ontology, epistemology and methodology, and reporting the differences between three worldviews, post-positivism was argued to be the most appropriate to adopt for this research project. Following this, the research methodology was discussed, focussing not just on the reporting the application of research methods, but justifying the selection of the research methods within the constraints of the adopted worldview. Validity was also discussed, highlighting how triangulation was used to increase the validity of the research output. This outlined that whilst the recommendations could be inferred to other engineering cases, the specific findings could not be considered to be wholly representative of engineering change management practice as a whole.

The following chapter proceeds to present an analysis of the engineering change management process in each of the three cases, describing the activities that are enacted and the artefact knowledge types that are used and created during this process.

Chapter 6 - INDIVIDUAL CASE RESULTS

The aim of this chapter is to present the results of the three individual cases, in accordance with the method described in chapter 5. As such, this chapter has been split into three, describing the results for each of the cases in turn. Within the individual cases, a similar structure has been adopted to the presentation. Firstly, a brief description of the engineering project is offered to provide some contextual background to the case. Following this, the details of individuals that were interviewed are presented based upon their role, experience and focus within the engineering change management process. A narrative of the engineering change management process within the specific case is then presented, to provide an overview of engineering change management within the case. Following this, the engineering change management process is decomposed into its constituent activities, with artefact knowledge describing the input and output of these activities. Finally, the case is summarised, detailing the key findings from the case study.

6.1 Case 1 (CS1) – S80 project

The S80 project was a technical design and manufacture project that was contracted to deliver six torpedo launching systems for a specific class of submarine platforms. With over ten years of feasibility study, and an expected eight further years before contract sign off, by the definitions presented in chapter 2 at the time of the analysis the S80 project was within the conceptual design phase.

The design of the launch system was described as being heavily constrained, with over 1,000 requirements coupled with strict interfaces between the launching system and the surrounding platform. The launch system itself consisted of two main sub-systems: the weapons handling system and weapons discharge system. Of these, the weapons discharge system, whilst being exposed to new requirements represented a modification of an existing design to fit these requirements. The weapons handling system on the other hand was fundamentally different to previous designs, with a new method of weapons handling being designed.

Within CS1, a total of five individuals were selected to participate in the interviews. Specifically two design managers (weapons discharge and controls), the project leader, a project manager (weapons handling) and a lead engineer (weapons discharge) were interviewed. Between these individuals over 150 years had been cumulatively spent within the engineering industry and an average of just over four years each being spent on CS1. The time in the current position, engineering experience and time of the current project on the interviewees can be found in Table 17.

Table 17 – Interviewee overview from CS1

Interviewee	1	2	3	4	5
Title	Design manager (weapons discharge system)	Project leader	Lead engineer (weapons discharge system)	Project manager (weapons handling)	Design manager (controls)
Time in current position	4 years	15 months	11 years	1 year	2 years
Engineering experience	36 years	36 years	29 years	16 years	37 years
Time on current project	10 years	15 months	4 years	4 years	2 years

The selection of these interviewees was executed in such a manner as to gain an overview of the entire engineering change management process. Given that different individuals enact different activities during the engineering change management process (Rouibah and Caskey 2003, Jarratt, Eckert et al. 2011), it was important to obtain the insight from at least one individual from each phase of the product lifecycle. In total, one individual had expertise of the identification phase, two of the generation phase, three of the prediction phase, two of the approval phase and one of the implementation phase. This expertise is depicted in Figure 17.

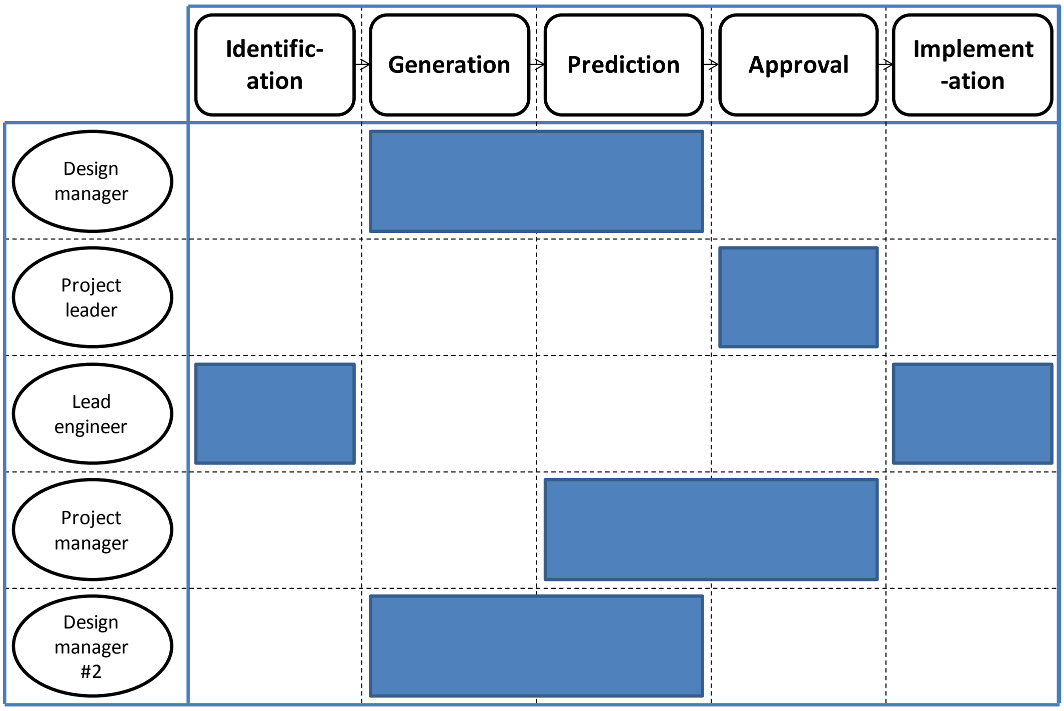


Figure 17 - CS1 interviewee engineering change management process phase expertise

6.1.1 Engineering change management process narrative

CS1 can be described as a discrete development project that was being run concurrently with other projects that contributed to the design and development of a submarine platform. As such, during the product development cycle of the launch platforms, other systems were being developed at the same time by other companies who had an input into the submarine platform design. To place constraints on the development of these systems, interfaces had been set up between these systems. These interfaces represented input and output parameters between these systems. For example, one of the interface parameters described was the flow rate of hydraulic fluid that was deliverable to the launch system whilst another interface was the permissible hole size in the submarine hull to permit the loading and unloading of the torpedoes. These interfaces acted to constrain the design of the launch system. However, if these parameters were found to be insufficient or if an engineering change within the design space propagated to impact upon these interfaces, then a formal, documented engineering change management process was initiated.

For changes that propagated out with the CS1 design space by modifying one or more of the prescribed interfaces, a formal method of engineering change management was initiated. Following the recognition of the problem by a designer during the development process or by a team of senior engineers during a design review, a solution was prepared to overcome this problem by the design team. This solution was then impact assessed by the same design team and distributed to other engineering practitioners as appropriate to determine whether the change was absolutely necessary, initiating the production of a documented contract change proposal. This contract change proposal was a text based document containing four sub-sections: details of the proposed change; justification of the proposed change; effect of proposed change and approval. Within the contract change proposal the first three sub-sections were filled in by a representative from within CS1 and delivered to the customer for approval. At this stage, the customer could either agree to the change and hence modify the interface parameter or reject the change out right. Considering that the change was accepted then the proposed solution was then implemented and the interface parameter modified. This process is presented in Figure 18.

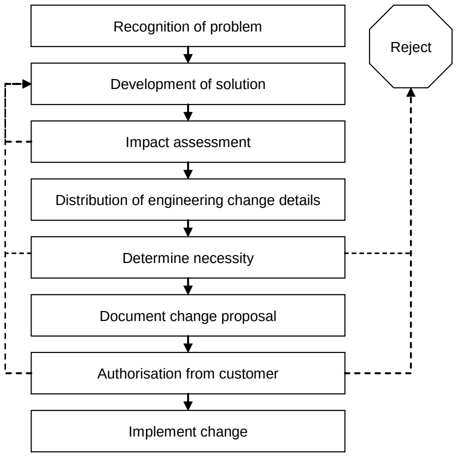


Figure 18 - Engineering change management process for interface modifications

For engineering changes that were maintained within the CS1 design space no formal mechanism for processing engineering change was observed. Engineering changes were found to be managed on an ad hoc basis, with designers and project managers collaborating informally and communicating verbally; eradicating the need for engineering change documentation. As such, after an engineering change was identified as being required, typically a number of representatives from the design team would collaborate over a computer screen, rapidly progressing through the generation, prediction and approval phases of the engineering change management process in a dynamic and iterative manner. Once the solution had been approved by the design team it was then implemented. This led to a situation where for a single engineering change the time between identification and implementation was relatively short. As such, the distinction between generation, prediction and approval phases became blurred with no clear definition of when one phase started and another finished. Following the implementation of a change made by the design team, these changes then underwent further evaluation both in informal and formal design reviews. In these design reviews senior engineers and project managers, referred to as the project team, evaluated the implemented solution based on a list of technical specifications. Following this, the project team either accepted the implemented solution or rejected the implemented solution, forcing the designers to prepare another solution. See Figure 19.

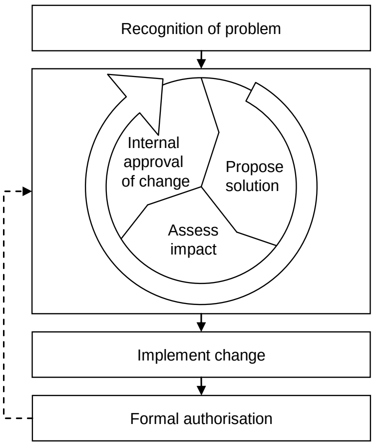


Figure 19 - Engineering change management process for internal changes

In addition to these processes for managing engineering change, another process flow was observed. Specifically, in some instances problems were identified, solutions created and implemented by a single individual or a small team. As such, they lack the appropriate level of approval from the management. This leads to a situation where, at a later date, unapproved implemented solutions were identified; usually during design reviews. Once identified these solutions undergo analysis conducive to the prediction phase of the engineering change management process prior to approval. If these changes were subsequently accepted then the appropriate approval is provided and the modification maintained. However, if the solution is rejected then the generated solution is rejected and removed from the design. See Figure 20.

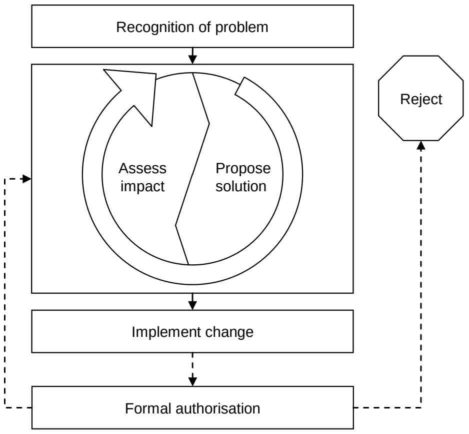


Figure 20 - Engineering change management process for designer led internal changes

Comparing the three engineering change management processes, it is evident that no single process can describe the entirety of how engineering changes are managed within this case. Instead, this case is characterised by formal and informal processes for the management of engineering changes. In general, there was a consensus between the interviewees that of these three engineering change management processes, the process that was described most frequently was that of the informal engineering change management process. As such, engineering changes were predominantly maintained within the CS1 design space with external changes being reported as being far less frequent. However, as the informal process has a lack of formal response and recording of an engineering change, the employees found it difficult to differentiate between standard product development activities and those associated with engineering changes. This was evident in the variations in the process that were described by the different interviewees.

What was also evident from the interviews, yet not explicitly described, was the focus on the development a technical solution that overcame the need for the engineering change in the optimum manner. Through involving a range of designers at the time of the development of the solution, a solution could be generated that had been bought into by different design disciplines at the time of the development. This enabled the individuals to develop a solution that worked best across all the disciplines in a timely manner. In such a situation, the interviewees reported that engineering change was less distinct and blurred with standard product development processes. This lack of formal processing has benefits; however, changing structural parameters in such an informal manner can lead to knock on changes further downstream.

6.1.2 Engineering change management process activities

Based on the interview transcripts a range of activities that compose the engineering change management process within this case has been established. Based upon the cross section of the interviewees' experiences with the engineering change management process, a total of ten activities have been identified with at least one of the activities being associated with each of the five phases of the engineering change management process. Considering each of the phases in turn, the activities that have been identified along with the types of artefact knowledge that each uses and creates is presented. To provide evidence for the activity and knowledge types, quotations are provided that have been taken directly from the interview transcripts. These quotations are followed by a reference that follows the code: ([interview number].[quotation time in interview (min/sec)].[quotation number from identified section])

Identification phase

Within the identification phase of the engineering change management process three activities have been identified: evaluating, realising and documenting.

Evaluating

Evaluation refers to the act of assessing the current state of the engineering artefact against product and managerial performance criteria (e.g. "…looking at the availability, reliability and maintainability calculations…" (5,25.41.1)). This was reported as being enacted by a panel of senior engineers on a formal basis at predefined periods during the conceptual design stage. Reflecting this definition, five types of artefact knowledge were reported as being used (expected function, expected behaviour, expected structure, instantiated structure and instantiated behaviour). Within the expected domain, the function, behaviour and structure were used to provide a baseline against which the instantiated structure and behaviour could be referenced. Cross referencing in this manner highlights any discrepancies between the desired state (expressed within the expected domain) and the current state (as expressed within the instantiated domain). As such, any identified discrepancies act as the mechanism for triggering the engineering change management process.

Realising

The act of realisation refers to the recognition of either a problem or opportunity with the engineering artefact: "…someone thinks that there is a better way of doing something" (2,11.38.1). Unlike evaluation, identification is not driven by a disparity in current and desired states, instead a realisation that the current state is deficient: "…felt that was not quite safe enough…" (5, 26.16.1). In this example, the interpreted behaviour has driven the individual to consider that safety is a concern without referring back to the expected domain. A further example can also be provided based on instantiated structural knowledge: "...the interface isn't where I need it to be" (1.21.58.2). In this example the individual has recognised a structural limitation without referring back to the expected structure. In addition, an interviewee was quoted as referring to "...a hydrodynamic flow issue" (3.5.22.1) that triggered the change process. This example of instantiated behaviour was reported as the motivation for the associated engineering change without referring back to the expected domain.

Documenting

Within the identification phase, documenting refers to the act of producing a text based record the specific problem or opportunity being addressed: "…we would have a documented critique on why something was not quite right…" (2,11.38.2). This documentation was observed to exist within a formal template if the change affected a design interface (a prescribed behavioural or structural constraint placed upon the design) and was enacted in each case when a change affected an interface. In comparison, if an interface was not affected, the documentation of the problem or opportunity was not necessarily enacted for each change. Nevertheless, in certain instances the problems were documented in emails or other forms of written communication.

Generation phase

Within the generation phase of the engineering change management process three activities have been identified: structuring, selecting and documenting.

Structuring

The act of structuring refers to the creation of a modified structure that differs from the existing structure of the engineering artefact: "Typically I'd expect someone to come up with a set of options that would resolve that problem…" (3,14,21.2). To guide this creative process, the expected function was reported as being used: "What we've got to do, is we've got to satisfy those requirements through whatever sub-systems or equipments that we are designing." (2.13.07.1). In addition, knowledge of the instantiated structure of the engineering artefact was reported as being used: "change a material on that boat, from this material to that material" (5.27.53.1). As a result of this activity, expected structural knowledge was created: "we've got to go to up the next size up" (5.0.00.3). Typically, this solution would be isolated to specific parts within the engineering artefact rather than the entire engineering artefact.

Selecting

The act of selection refers to choosing which of the possible design options to proceed with: "…to select the best." (4,14.49.3), "…what options we are going to move forwards with." (1,26.34.1). In this case, rather than a single solution being created that overcomes the need to change, multiple solutions were observed to be created during the generation phase. As such, through selection the best solution was chosen to proceed into the prediction phase. To facilitate this activity, knowledge of the expected structure of the proposed new solution was used: "…look at alternatives…" (1,8.42.1).

Documenting

Within the generation phase, documenting refers to the act of recording the generated solution in a textual format: "So if we have a change then again we will produce, you know, the change record sheets for this." (1,29.59.1). Representing a method for transferring information of an updated solution, this activity was observed to occur for each change that impacted upon a design interface. However, in some instances changes were also documented when they didn't impact upon the design interfaces. This record created a formal method of communication between team members within the project.

Prediction phase

Within the prediction phase of the engineering change management process two activities have been identified: analysing and distributing.

Analysing

The act of analysing refers to the forecasting of the impact of the proposed solution on the product, process and management domains: "…If I do this, what's the consequence?" (1,16.07.1), "…to provide a budget and the cost estimate…" (4,11.44.1). To achieve this, expected structural knowledge of the new solution was reported as being used "...the weapon shape changed..." (3.8.44.1) along with expected functional knowledge: "to see that it does meet the requirements" (4.21.37.1).

Within the product domain, to forecast the effect of modifying the structure of part of the engineering artefact on the engineering artefact as a whole, the influence this has on both the behaviour and the structure were reported as being predicted. As a result of analysis, two types of artefact knowledge were reported as being created: expected behaviour and expected structure. To present an example of expected behavioural knowledge creation: "if you are looking at torpedo tubes they're out in a sea water environment so, which is very corrosive ... how they might behave in terms of galvanic action" (3.14.31.1) and "... is safety effected, or interchangability is strength affected ..." (1.29.59.1). In addition, as the part has a physical interface with other parts within the engineering artefact, knowledge of the parts that are expected to require structural redesign is also created as a result of the analysis activity: "...as the weapon shape changed, we would have to modify the shape of the slide valve too" (3.8.44.1).

Distributing

The act of distributing refers to the proliferating of the proposed solution within the project team to gather the potential impacts associated with the change: "…need to be talking to our weapons discharge team…" (4,18.18.1), "…take it to the works to talk about fabrication, manufacturing techniques…" (1,21.58.3). To ensure that analysis activities were enacted by the most appropriate individuals within the project, knowledge distribution of the proposed change was enacted. As such, through considering parts and systems within the design that might be affected by the change, the correct individuals can be contacted to execute the required analysis.

Approval phase

Within the approval phase of the engineering change management process one activity has been identified: authorising.

Authorising

The act of authorising refers to the choosing of whether to provide the authority to proceed with the implementation of the engineering change or not: "…I will hear the case for, you know, what we want to make a change…" (2,18.29.1), "…we'll make the decision on what documentation it will also change…” (1,34.09.1) “…we will certainly have a discussion about why we would want to do that, you know, I may say stop.” (2,23,26.1). This activity, was found to use expected behavioural knowledge “I’ve received all the safety reports I’ve received the strength reports, I’ve seen the suppliers erm, err, availability for materials” (1.41.31.4).

Implementation phase

Within the implementation phase of the engineering change management process only one activity has been identified: instantiating.

Instantiating

The act of instantiating refers to the modification of the structure of the engineering artefact to reflect the new solution: “…we will make changes…” (1,21.58.1), “…make those changes.” (1, 21.58.2). To facilitate this activity, expected structural knowledge is required to guide the individual: “...we are going to change these LEDs from green on the tube control panel” (5.0.00.1).

6.1.3 Case summary

Within CS1 three different engineering change management processes have been identified as existing. The first was reported to be initiated when a change impacted upon the behavioural or structural interfaces between the system being designed and the neighbouring systems. In this process a formal and prescribed set of activities was observed, facilitated by a document based process. However, when changes were maintained within the system being designed and did not affect the interfaces with neighbouring systems, an informal and unstructured set of activities were reported as being enacted. This created a situation where engineering changes were not always processed in the same manner. Nevertheless, with variations in the processing of engineering changes and an unstructured set of activities being enacted, certain activities were identified as being enacted. As such, throughout both of the engineering change management processes, ten distinct activities have been identified: documenting, evaluating, identifying, documenting, structuring, selecting, analysing, distributing, authorising and instantiating.

To summarise the activities that have been reported as composing the engineering change management process a summary table has been produced (see Table 18). This table presents definitions for these activities and the types of artefact knowledge that are used and created by these activities.

Table 18 - Summary table of the engineering change management process activities in CS1

Phase	Activity	Definition	Artefact knowledge	
			Used	Created
Identification	**Documenting**	The act of textually recording the problem or opportunity	-	-
	Evaluating	The act of assessing the current state of the engineering artefact against product and managerial performance requirements	F_{exp} B_{exp} S_{exp} S_{ins} B_{ins}	-
	Realising	The act of recognising a problem or opportunity with the engineering artefact	S_{ins} B_{ins}	B_{int}
Generation	**Documenting**	The act of describing the generated solution in a textual format.	-	-
	Structuring	The act of creating a new structure that differs from the existing structure of the engineering artefact.	F_{exp} S_{ins}	S_{exp}
	Selecting	The act of choosing which of the possible design options to proceed with.	S_{exp}	-
Prediction	**Analysing**	The act of assessing the impact of the proposed solution on the product, process and management domains.	F_{exp} S_{exp}	B_{exp} S_{exp}
	Distributing	The act of identifying the individuals that are affected by the new solution and contacting these individuals to request their analysis.	-	-
Approval	**Authorising**	The act of choosing of whether to provide the authority to proceed with the implementation of the engineering change or not.	B_{exp}	-
Implementation	**Instantiating**	The act of modifying the structure of the design to reflect the new solution.	S_{exp}	-

6.2 Case 2 (CS2) – QE class project

The Queen Elizabeth class (QE class) project (see Figure 21) was a technical design and manufacture project contracted to deliver two aircraft carriers for the British Royal Navy. Representing a highly customised, low quantity product, the value of the development contract was estimated at almost £4 billion. With development started in 1999 and the vessels expected to enter service in 2015 and 2018, the product development period represented almost 20 years. Furthermore, each vessel had an expected length of approximately 280 metres, weight of 65,000 tonnes and a capacity to carry 40 aircraft.

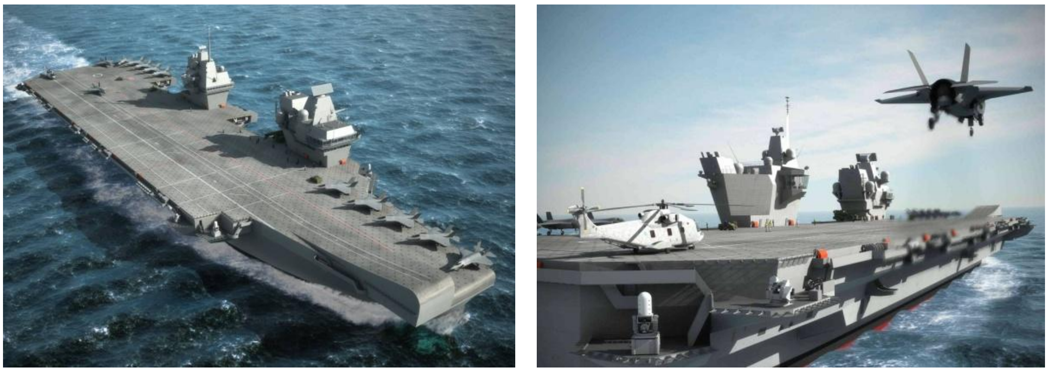


Figure 21 - Queen Elizabeth Class (QE class) aircraft carrier project images

To facilitate the development of the QE class in a manner that is sustainable to British shipbuilding capabilities, no one organisation was contracted to design and build the vessels. Instead, the QE class project has a number of prime contractors who collaborated to achieve concurrent development in a number of distributed development sites across the UK. In addition, rather than single prime contractors being responsible for the design and manufacture of the whole vessel, a decision was made that the ship should be subdivided into sections over which the different prime contractors had responsibility for the design and manufacture. Therefore, the design of the QE class has been developed by a number of different organisations working with a number of different project management systems.

From CS2, a total of six individuals were selected to interview. Again, the interviewees were selected based on their experience with the engineering change management process, representing a cross section of the phases involved. Specifically, one local delegated design authority, three designers, one project manager and one lead change engineer were interviewed. Across these individuals a total of 126 years of experience within the engineering industry was drawn upon. The experience that these interviewees had along with their title and engineering change management process phase specialisation can be seen in Table 19.

Table 19 - Interviewee overview from CS2

Interviewee	1	2	3	4	5	6
Title	Technical lead (mechanical)	Technical lead (electrical)	Local DDA (mechanical systems)	Technical lead (structural)	Stage 2/3 project manager	Lead change engineer
Time in current position	3 years	3 years	2 years	1 ½ years	3 years	3 years
Engineering experience	32 years	32 years	5 years	15 years	22 years	20 years
Time on current project	3 years	4 years	5 years	1 ½ years	2 years	3 years

Again, the selection of these interviewees was executed in such a manner as to gain an overview of the entire engineering change management process. In total, one individual had expertise of the identification phase, one of the generation phase, four of the prediction phase, one of the approval phase and three of the implementation phase. This expertise is depicted in Figure 22.

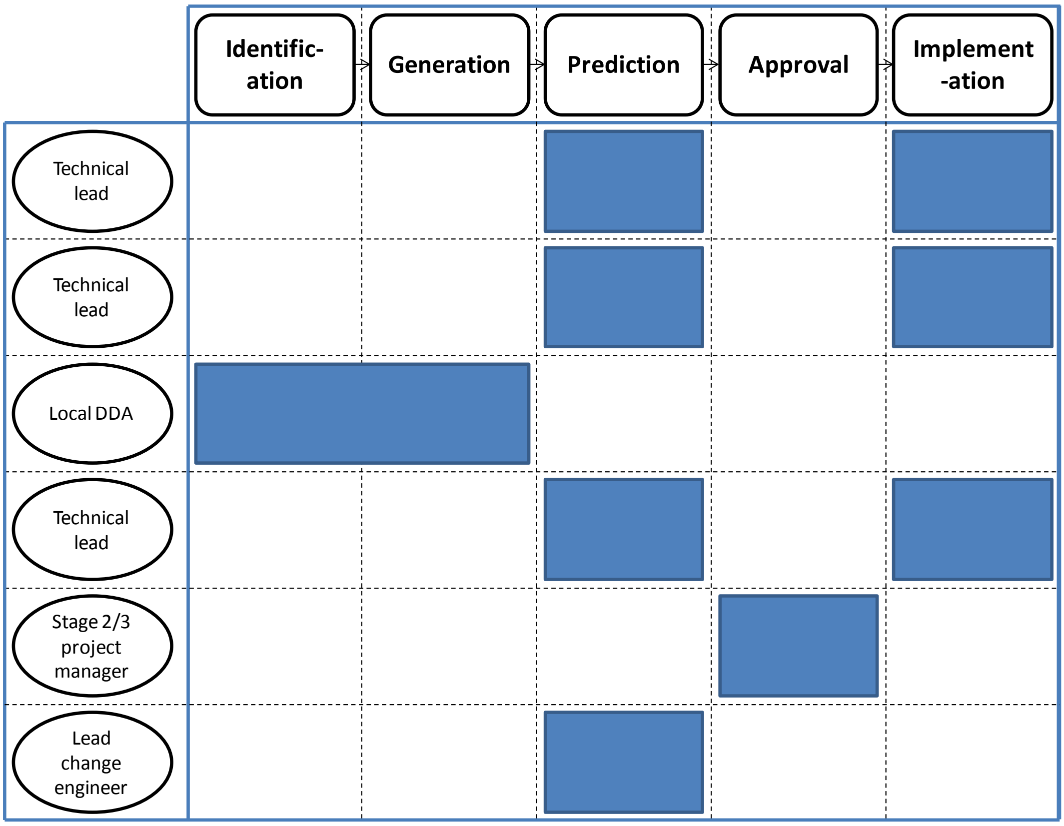


Figure 22 - CS2 interviewee engineering change management process phase expertise

6.2.1 Engineering change management process narrative

Within CS2 engineering changes were found to be managed as part of the project defined enterprise change management system. The enterprise change management system was based on a series of activities that involved a large number of project stakeholders, from a number of geographically distributed development sites. Whilst the focus was on designers, engineers and project managers, other stakeholders were also involved including fabricators, welders, supply chain managers, the project director and the customer; when particular expertise was required. To facilitate the management of these enterprise changes, the QE class project relied upon a process that prescribed activities to specific stakeholders. This created a detailed engineering change management process through which all changes during the product development cycle of the project were processed. Whilst this process was composed of a number of sub-activities, the basic phases reflected those reported in the literature review.

The engineering change management process was initiated by a designer identifying a problem or potential opportunity in respect to the product. Following this, the designer either prepared a description of this problem/opportunity and published this on an intranet based project forum or went straight to the delegated design authority (DDA) who was responsible for the specific part of the vessel that the problem/opportunity was in. If through the forum or meeting with the DDA the problem could not be overcome through an improved understanding, then a need to change was established. As such, the DDA was then responsible for coming up with a solution to the need to change. Through development with a small team of conceptual designers, a solution was created and documented, along with a description of the problem, into a document called an engineering change request. This document was then passed to the centralised change management team who read and interpreted the change, sending it out to the change manager within the effected sites (depending on the scope of the change).

Following the receipt of the engineering change request at the specific development site, the local change manager again read and interpreted the content of the engineering change request and sent it to the parties within the sites that were expected to be impacted. When the effected parties within the sites obtained the engineering change requests, these were again read and interpreted and a number of man hours associated with carrying out the changes detailed and passed back to the centralised change team. Depending on accuracy and detail of the content within the engineering change at this stage the effected parties may return the engineering changes to the design team for more information. However, if they are satisfied with the description, the impact is reported back to the centralised change team who collate all the figures and pass the total number of man hours and expected cost of the change to an approval board.

Within CS2 a number of approval boards were found to exist. These approval boards were established to consider different levels of change, taking into account considerations such as cost, impact on schedule, impact to existing systems, etc. As such, an engineering change request was then sent to the relevant board for approval. As a result of the approval, three outcomes could occur. First the request could be rejected outright hence ceasing the engineering change management process, secondly the change could be returned to the design team to develop a more appropriate solution or thirdly it could be approved as it is. Following approval a budget for the number of man hours quoted during the impact assessment was created within the project management system and the go ahead given to the impacted parties to carry out the work that they had quoted. See Figure 23.

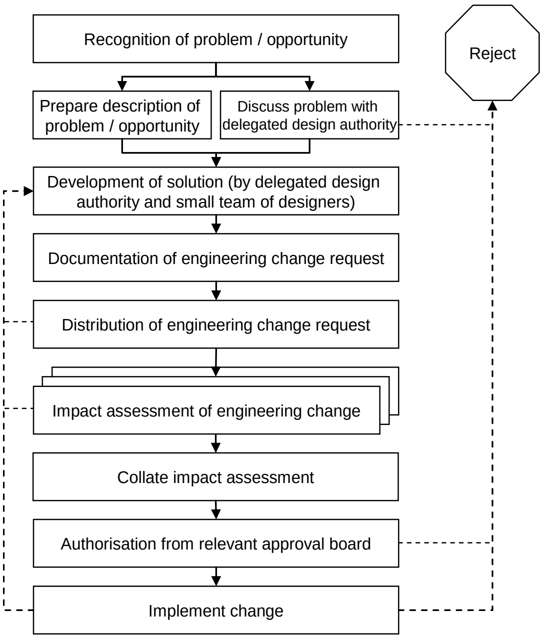


Figure 23 -The formal engineering change management process in CS1

In addition to the formal engineering change management process, a variation of this process was observed. Specifically, in some instances implementation occurred without prior approval. The average length of time between the creation of the document that describes the solution and approval being granted the average length of time was found to be approximately 126 days (Rowell, Duffy et al. 2009). Due to this some designers decide to "proceed at risk", implementing the solutions before the appropriate approval has been granted. As such, the engineering artefact would be modified following the generation of the solution, but may be rejected and removed at a later date. As such, the engineering change management process follows a different process with prediction and approval phases occurring after the implementation process. This process is depicted in Figure 24.

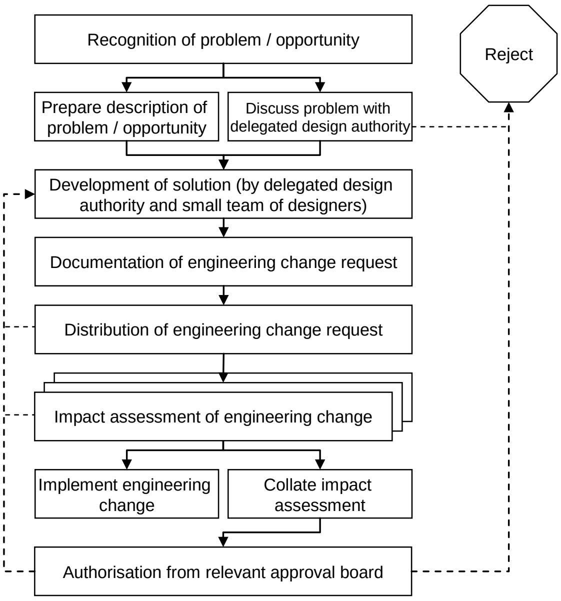


Figure 24 - An adapted engineering change management process to decrease the length of time to implement an engineering change

From the case study it was evident that the formal process for managing engineering changes was the process that was followed most readily in this case. This process was highly structured and was based predominantly around a documented framework that was used to communicate the engineering change. This structure and documentation created a consistent, yet inflexible process that was characterised by lengthy periods between identification and implementation, creating bottle necks at various points in the process. Another characteristic of this case was the number of engineering changes that were processed. At the time of the study, the number of formal changes that had been processed in the case stood at over 3,000. However, it was observed that this process was not only used for the processing of engineering changes as defined at the start of this thesis, but for contractual changes as well. Nevertheless the majority of the changes that were processed fitted within the definition provided at the start of this thesis. Of these, the scale of these changes was relatively small, covering the repositioning of equipment rather than fundamental redesigns of critical portions of the artefact's structure. To administer this, a dedicated change management team was required who were relied heavily upon to progress the changes through the formal route. To support the team, a complex information system and product data management tool was used, along with separate spreadsheets and other documentation. This approach, coupled with the volume of engineering changes, contributed to the lengthy processing times.

Due to the lengthy processing times, it was reported that a number of individuals who were responsible for implementing engineering changes commenced implementation prior to the provision of the authority to proceed. This strategy enabled the artefact to continue to be developed without having to wait to modify certain parts; however, risked additional work if the engineering change was rejected. Furthermore it caused configuration inconsistencies as the designers who were responsible for implementing the engineering change in the 3D model were not the same individuals who were responsible for updating other documentation. This demonstrated a general lack of appreciation of other stages in the engineering change management process in this case. Whilst individuals were, in general, able to discuss their own area of expertise, their knowledge of the roles that other individuals played within the engineering change management process were not as detailed.

6.2.2 Engineering change management process activities

Based on the interview transcripts a range of activities that compose the engineering change management process within this case has been established. Based upon the cross section of the interviewees' experiences with the engineering change management process, a total of twelve activities have been identified with at least one of the activities being associated with each of the phases. Considering each of the phases in turn, the activities that have been identified along with the types of artefact knowledge that each used and created is presented.

Identification phase

Within the identification phase of the engineering change management process, three activities were described: documenting, evaluating and realising.

Documenting

Documenting refers to the act of producing a text based record of the problem or opportunity: "…raise an FQR on stage one to say this isn't working…" (3,12.19.1). This was reported to be contained within a formal, documented template referred to as an engineering change request and was described as being enacted for each of the engineering changes that took place within the case.

Evaluating

Evaluation refers to the act of assessing the current state of the engineering artefact against product and managerial performance criteria: "...comprises design intent, which is what the designers design the system to do, so it doesn't meet that, and then we need to change" (3.3.33.2). To facilitate evaluation, expected functional, expected structural and instantiated structural knowledge were identified as being used. The expected function, expressed as the "design intent" or "what the designers design the system to do" (3.2.53.2), informs the identifier of the functions that the engineering artefact should achieve. In addition, the expected structure representing the physical parameters that the structure is meant to embody is cross referenced against the instantiated structure to establish any disparities: "this fitting has been modelled the wrong size" (1.5.00.1).

Realising

The act of realisation refers to the recognition of either a problem with the engineering artefact or an opportunity to improve the design: e.g. "…I have identified something that isn't right." (3,3.33.1), "…you've seen that problem; the problem has been identified…" (3,14.32.1). Unlike evaluation, realisation is not driven by a disparity in current and desired states, instead a realisation that the current state is deficient: "you'll have two parts and they don't go together" (1.8.28.1). In this example, the instantiated structure of the engineering artefact is deficient. As a result of this realisation, interpreted behaviour was reported as being created: "...they'll see an issue that's not working" (3.12.19.2), "...they have realised the system doesn't work" (5.0.00.1).

Generation phase

Within the generation phase of the engineering change management process, four activities were described: documenting, modelling, structuring and validating.

Documenting

Documenting refers to the act of describing the generated solution in a textual format: "…then I'd raise the ECR form, I'd bring that up in a template, I'd fill all the boxes in that I'd need to fill in on the front…" (3,4.22.1). This description was reported to be prepared on the same form as the description of the problem, enabling the reader to view both simultaneously. Furthermore, as with the description of the problem, the description of the solution was reported as being produced for each of the engineering changes within the project.

Structuring

The act of structuring refers to the creation of a modified structure that differs from the existing structure of the engineering artefact: "…that's not going to work, you need a release line valve in there…" (1,8.28.1). To create a modified solution, both the instantiated structure and the instantiated behaviour were reported as being used. For example, the instantiated structure, represented by the design schematics were stated as being required "...get all of the schematics out" (3.16.53.1). In addition, knowledge of system's dynamics in terms of instantiated behaviour were also described as being required: "...how the system operates" (3.10.25.1). As a result of this creation, an expected structure in terms of new ideas is created: "...you need a release line valve in there..." (1.8.28.1) "it's not actually going there, it's going there" (2.5.21.1) "you've got production drawings that have got to get changed" (3.4.22.4) "...I want to change that light from here to there" (3.4.22.5) "this is how we need to reroute it" (3.16.53.3), "this is what we want to do" (3.16.53.2).

Modelling

As an extension of the act of structuring, modelling refers to the transposition from generated ideas within a designer's head to diagrammatic models that are used to represent these ideas: "…supplemented that there is often, not always, but often drawings attached." (4,17.41.1) "…get that in an EDLAF sketch…" (5,19.30.1) "…there are things like sketches…" (6,1.05.10). As such, the output of modelling is expected structural knowledge and is diagrammatic in nature.

Validating

The act of validating refers to the checking that the problem or opportunity exists as have been described by the identifier: "…sometimes it is still digging the information, you would check that what you think you've seen is what you've seen…" (2,5.45.2), "…so it is up to us to, erm, double check the ECR to make sure that it is ok, erm, and that all of the relevant information is in there" (6,7.38.5). Essentially, this activity aimed to establish the validity of the reported problem or opportunity and the accuracy and completeness of the associated engineering change documentation.

Prediction phase

Within the prediction phase of the engineering change management process, three activities were described: analysing, composing and distributing.

Analysing

The act of analysing refers to the forecasting of the impact of the proposed solution on the product, process and management domains: "…whether it's going to have a knock on effect…" (6,1.05.2), "can you assess the impact on the model" (3.53.2), "…you've really got to look at the broader picture…" (3,4.22.2). To achieve this, the expected structure from the generation phase is required as an input: e.g. "this shoulder has changed in size" (1.3.53.1), "the pipe connections have changed and it's slightly bigger, I've got two pipes coming in just now" (1.3.53.4). In addition, instantiated structural knowledge of the existing engineering artefact is also used: "I'll have a look at the current unit, I'll have a look at the new one" (1.3.53.3), "this pipe is no longer going to be this size; it's going to be that size". As a result of analysing, expected structural knowledge was created in the form of the effects on the other parts within the engineering artefact: "I'm going to have to move that whole reel out the way" (1.3.53.6) "I'll have to alter these two, I'll have to alter each" (1.3.53.5), "areas that are affected, the equipment that is affected" (4.5.17.3).

Composing

The act of composing refers to collecting and summing the outputs from the various analysis activities: "…once the assessment is complete, the change manager from the originator will collate all the different answers from all the different industrial partners and will be able to provide the final estimate…" (6,1.05.7), "...we will then collate their answers together …" (6,7.38.4). This is executed quantitatively with the various estimates being produced in terms of cost and schedule impact being integrated into single figures before being sent to the relevant approval board.

Distributing

The act of distributing refers to the identification of individuals that are affected by the new solution and contacting these individuals to request their analysis: "…we raise it, put that into the system, identify the people that it is to go to.” (6,7.38.6), “We could have a look at the description and have, basically its best effort on what we think is going to be effected…then we will try and send it out to everybody” (6,8.49.1). Using a database that links specific sub-systems and areas within the engineering artefact to the individuals who are responsible for their development, the expected structure is used as a guide to inform these individuals to prepare an analysis of the change: “...you would have to contact the pipe routing guys, the HVAC guys, tell them that their stuff is going to have to go” (2.3.44.1)

Approval phase

Within the approval phase of the engineering change management process, one activity was described: authorising.

Authorising

The act of authorising refers to the choosing of whether to provide the authority to proceed with the implementation of the engineering change or not:: “…give it to me for confirmation…” (1,3.08.1), “…they then determine if the change is to be made or not” (4,5.17.6), “…who then review all the hours estimated to make the change” (4,5.17.5). In this case, the individuals responsible for the final approval were reported to base their decision primarily on the cost of implementing the new solution.

Implementation phase

Within the implementation phase of the engineering change management process, two activities were described: ensuring and instantiating.

Ensuring

The act of ensuring refers to the checking that the updated solution is being embodied within the design models: “…enterprise change notification tasks have to be created and sent back out to the industrial partners who are required to do the work” (6,1.05.8), “ we get a rework code, a booking code for the rework that comes through the IFS system. It obviously says, right...that ECR is approved, there’s the code for one of your men to book to.” (1.11.08.1). This activity was enacted to make sure that the expected structural knowledge from the generation phase was instantiated into the design models and that the budgets for the cost and schedule impact where adhered to.

Instantiating

The act of instantiation refers to the modification of the structure of the engineering artefact to reflect the new solution: "…then the work gets done." (6,1.05.9), "I'll have to alter these two" (1,3.53.3). As an input to instantiation, expected structural knowledge is required: "...there'll be a requirement to them to change their schematics" (3.16.53.1), with the output being the creation of an updated form of instantiated structural knowledge: "update all of the schematics" (3.17.24.1) and "change it in the model" (3.17.24.3).

6.2.3 Case summary

Within CS2, a single, prescribed and structured series of activities were found to compose the engineering change management process. As such, for each engineering change that occurred a similar list of twelve activities was enacted with these activities being managed by dedicated team of change management administrators. These activities were: documenting, realising, evaluating, modelling, structuring, validating, analysing, composing, distributing, authorising, ensuring and instantiating. Of these activities, all of these were reported to be enacted for each engineering change that was experienced within the case with the exception of modelling, validating and ensuring activities. This process was geared to provide accurate estimates for the cost and schedule impact of each engineering change and was driven by documented descriptions of the reason why the change was needed and a solution that overcame that need. However, this resulted in lengthy processing periods with the prediction phase taking 126 days on average (Rowell, Duffy et al. 2009).

To summarise the activities that have been reported as composing the engineering change management process a summary table has been produced (see Table 20). This table presents definitions for these activities and the types of artefact knowledge that are used and created by these activities.

Table 20 – Summary table of the engineering change management process activities in CS2

Phase	Activity	Definition	Artefact knowledge	
			Used	Created
Identification	**Documenting**	Preparation of a written statement of the problem or opportunity.	-	-
	Evaluating	The act of assessing the current state of the engineering artefact against product and managerial performance requirements	F_{exp} S_{exp} S_{ins}	-
	Realising	The act of recognising a problem or opportunity with the engineering artefact	S_{ins}	B_{int}
Generation	**Documenting**	The act of describing the generated solution in a textual format.	-	-
	Modelling	The act of transposing the generated ideas within a designer's head to diagrammatic models that represent these ideas	-	S_{exp}
	Structuring	The act of creating a new structure that differs from the existing structure of the engineering artefact.	S_{ins} B_{ins}	S_{exp}
	Validating	The act of checking that the problem or opportunity exists as has been described by the identifier.	-	-
Prediction	**Analysing**	The act of assessing the impact of the proposed solution on the process and management domains.	S_{exp} S_{ins}	S_{exp}
	Composing	The act of collecting and summing the outputs from the various analyse activities	-	-
	Distributing	The act of identifying the individuals that are affected by the new solution and contacting these individuals to request their analysis.	S_{exp}	-
Approval	**Authorising**	The act of choosing of whether to provide the authority to proceed with the implementation of the engineering change or not.	-	-
Implementation	**Ensuring**	The act of checking that the updated solution is being embodied within the design models.	-	-
	Instantiating	The act of modifying the structure of the design to reflect the new solution.	S_{exp}	S_{ins}

6.3 Case 3 (CS3) – HMS Illustrious refit

HMS Illustrious is one of three aircrafts carriers currently owned and operated by the Royal Navy. Launched in 1978, HMS Illustrious has undergone a number of modifications throughout its lifecycle. For example, in a previous refit a modification to the angle of the ski jump at the front of the vessel was installed to enable its compliment of aircraft to take off with greater payloads. In February 2010 HMS Illustrious docked at Babcock Marine's

Rosyth dockyard to undergo a refit due to conclude in 2011, including modifications to improve its fuel efficiency. During this period new equipment was installed and damage repaired.

Figure 25 - HMS Illustrious arriving and docked at Rosyth dockyard

With the design of the major upgrades occurring throughout the in-service phase of its lifecycle, and designed by a number of companies rather than just a single one, Babcock Marine’s role in the refit was primarily one of installation rather than design. However, during the installation process problems were found to occur due to a number of reasons which required engineering support to overcome. As such, modifications that went beyond the scope of the work associated with the refit were dealt with by specialist design teams based in Rosyth. During these instances engineering changes were found to occur.

From CS3 five individuals were selected to interview. These individuals were selected to represent a cross section of those involved with the engineering change management process. Specifically, the interviews consisted of four technical individuals and one process facilitator. The four technical individuals consisted of a technical team lead – constructive designer, a mechanical draftsperson, an electrical designer and a mechanical draftsperson (waterfront support). Of these, the first three were based in the design office, whilst the final interviewee was part of the engineering liaison team, responsible for clarifying simple problems and preparing problem statements and considered to operate between the engineering and manufacturing departments. The process facilitator had an overview of the entire process and who was responsible for encouraging the timely completion of the changes. Nevertheless, these interviewees had a combined experience of approximately 100 years. A breakdown of this data can be seen in Table 21.

Table 21 - Interviewee overview from CS3

Interviewee	1	2	3	4	5
Title	Technical team lead – constructive designer	Mechanical draftsperson	Project lead	Electrical designer	Mechanical draftsperson (waterfront support)
Time in current position	9 years	20 years	2 ½ years	9 years	16 years
Engineering experience	20 years	22 years	14 years	32 years	30 years
Time on current project	3 months	3 months	3 months	3 months	3 months

Again, the selection of these interviewees was executed in such a manner as to gain an overview of the entire engineering change management process. In total, one individual had expertise of the identification phase, three of the generation phase, three of the prediction phase, two of the approval phase and one of the implementation phase. This expertise is depicted in Figure 26.

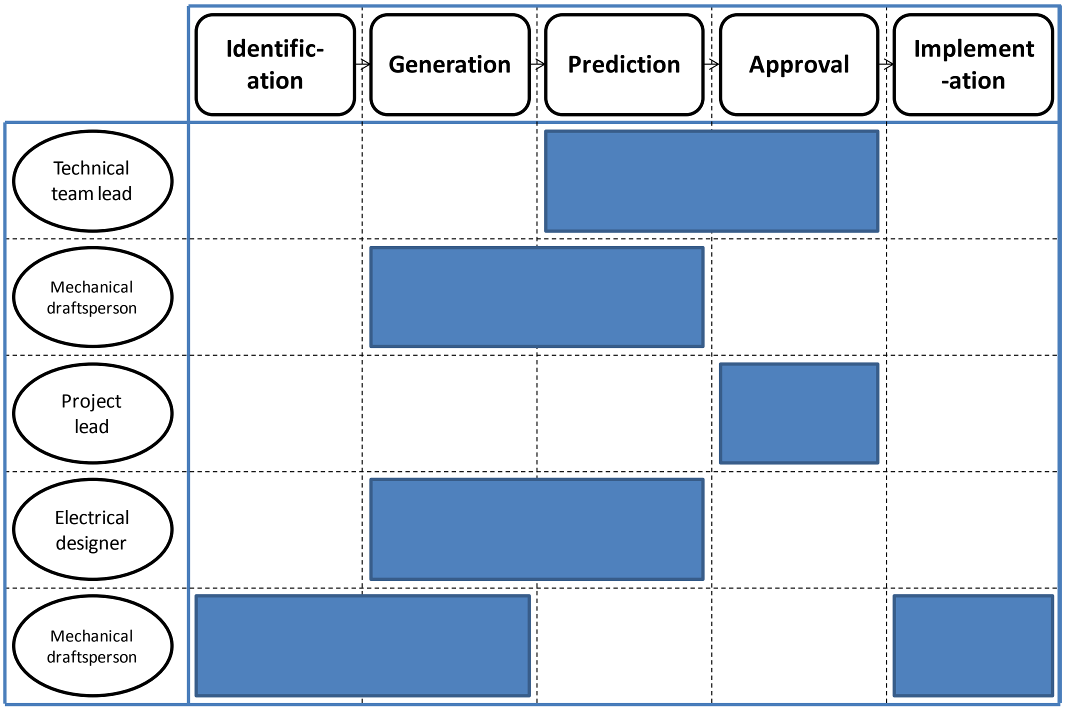


Figure 26 - CS3 interviewee engineering change management process phase expertise

6.3.1 Engineering change management process narrative

When a vessel enters Babcock Marine’s Rosyth shipyard for refitting it arrives with a predefined scope of work. In general the design has already been completed and the work associated with the refit is mainly based on physical installation of new equipment into the existing structure. However, during this process a number of problems can occur that require further clarification and in some instances prohibit physical installation of certain items. As such, for instances where physical installation is prohibited the engineering change process was found to exist. The engineering change process consisted of a number of activities that were facilitated by the creation and circulation of a single document: the engineering department liaison action form (EDLAF). This document was a single page that included about fifteen single phrase identifiers, for instance originator and date raised. In addition, it also contained two extended spaces for descriptions of the problem and the proposed solution. At three months in, interviewee number three described that there had already been 600 EDLAFs that had been raised and the last time an aircraft carrier had come for refit at Rosyth, 2,500 EDLAFs were raised in total.

In the first stage of the engineering change management process, problems were identified by those responsible for the physical act of installing the new systems. Upon realising the problem these individuals would prepare a textual description in the problem section of the EDLAF and forward this onto the relevant engineering liaison representative embedded in the waterfront team. Upon receiving this, the engineering liaison team would investigate the problem and if possible propose a solution to overcome this. However, if the liaison team were not able to offer a solution to the problem, the EDLAF would then be transferred to the design office to work-up an appropriate solution. With an aim of an eight hour turnaround, emphasis was placed on offering appropriate solutions quickly as to not detrimentally impact the refit schedule and so that material could be ordered as quickly as possible. As such, limited consideration was given to establishing the entirety of the impacts and with the lack of an official and external approval process, rapid implementation of the change to the physical structure of the product could be achieved. See Figure 27.

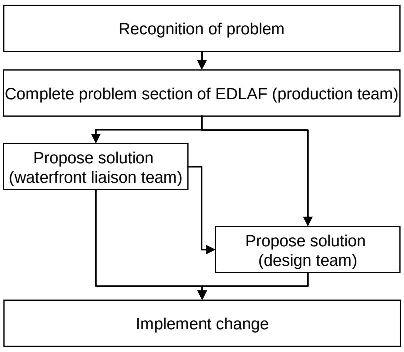


Figure 27 - Rapid engineering change process

However, engineering changes were reported to not always be handled in this manner. Quantified by the third interviewee as occurring in seven out of ten instances, EDLAFs contained not just a problem defined by the production team but the solution the production team propose to overcome this as well. In such an instance, the production team complete the solution part of the EDLAF with help from the engineering liaison team and submit it for approval to the design department. Subsequently the design department review the solution and offer their support if the design is deemed appropriate. If deemed appropriate, the solution is then physically implemented by the production department. However, if the solution is not deemed to be acceptable then a new solution is generated by the design team that is subsequently implemented by the manufacturing team. See Figure 28.

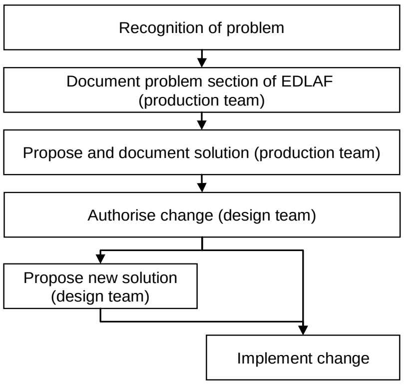


Figure 28 - Solution generation by production engineering change management process

Whilst the majority of changes were reported as being enacted by the one of the first two engineering change management processes, for certain engineering changes, approval could not be granted by the design team instead requiring input from the customer. For example, the third interviewee described that changes to the power requirements of a system in the vessel are closely controlled. Hence if changes to this are required then the customer must provide approval. In such an instance, three possible outcomes have been identified: the generated solution is accepted in its current form, it's rejected outright or it is passed back to the design team to produce another solution. See Figure 29.

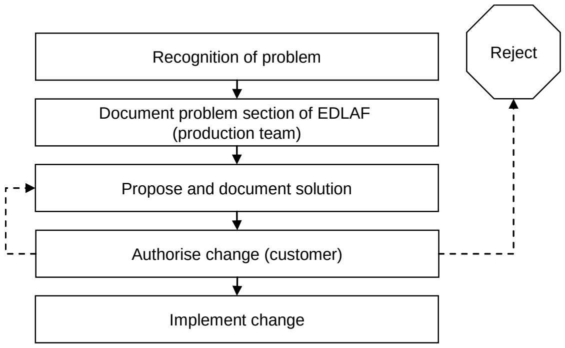


Figure 29 - Customer approval engineering change management process

In this case, three similar, yet subtly different processes for the management of engineering change exist with each of these processes being geared towards the timely implementation of the engineering change. These processes highlighted a pragmatic, flexible approach to engineering change management, with a focus on implementing the change as quickly as possible. To facilitate this, the processes were characterised by reduced and simplified paperwork requirements in which the accurate documentation was found to be as critical and getting work completed in a timely manner. As a result, documentation was generated as a record of the change rather than communication tool between different engineering change management process practitioners.

In addition, within this case it is apparent that the rejection of an engineering change can only occur in one of the three processes. Only when the change was of such a scale that the customer was required to authorise the implementation could a change be rejected. In the other processes, the need to change was accepted and as such a solution to overcome it was required. This demonstrates that engineering changes in this case were predominantly in response to problems rather than opportunities and hence required the implementation of a solution to overcome.

It was also evident in this case that attempts were made not to initiate the engineering change management process. If changes could be managed locally by the individuals who identified the problem, then they would proceed with implementing a solution without informing the design offices. Only when the problem was of a size in which the production representatives could not manage with the changes locally did the design office need to be involved. This was possible as the engineering changes generally had a limited impact meaning they did not require complex impact assessment procedures.

6.3.2 Engineering change management process activities

Based on the interview transcripts a range of activities that compose the engineering change management process within this case has been established. Based upon the cross section of the interviewees' experiences with the engineering change management process, a total of ten activities have been identified, with at least one of the activities being associated with each of the phases. Considering each of the phases in turn, the activities that have been identified along with the types of artefact knowledge that each uses and creates is presented.

Identification phase

Within the identification phase of the engineering change management process two activities were identified: documenting and realising.

Documenting

Documenting refers to the act of producing a text based recording of the problem or opportunity: "if there are changes at the ship when they are fitting stuff they would raise like an EDLAF [engineering data liaison action form]" (1,6.55.1), "…they write the problem down…" (4,3.18.2). This is predominantly raised by installation engineers tasked with implementing components into the physical product architecture. However, this activity was also reported as not occurring for each engineering change that took place, just the changes that required significant additional design effort.

Realising

The act of realisation refers to the recognition of either a problem with the engineering artefact or an opportunity to improve the design: "…they find a problem…" (4,3.18.1). To achieve this realisation, instantiated structural knowledge obtained from the actual physical integration of a new component with the existing physical artefact architecture: "You can't fit something in a certain position" (1.4.31.1). In addition, instantiated structural knowledge is used in the form of a design drawing and cross referenced against the actual structure of the product: "...stuff that's maybe missed off from the design ... like sockets or it could be penetration details and things like that" (1.4.31.2). As such. In this case instantiated structural knowledge is taken from both the structure as depicted on design drawings, the physical artefact itself and the component that is being integrated.

Generation phase

Within the generation phase of the engineering change management process four activities were identified: documenting, modelling, structuring and validating.

Documenting

Documenting refers to the act of describing the generated solution in a textual format: "…space for us to put a technical solution on it…" (2,3.06.1), "…I'll raise a query so they'll effectively fill out a piece of paper, hand it to the admin staff, who then go into the database and fill it in electronically." (3,1.33.1), "…fill it in with the problem in it." (3,1.33.2), "…we record it on that form." (5,1.12.1). This was reported as being enacted by either the individuals who identified the problem, or when a more complex solution is required, by the design department.

Modelling

As an extension of the act of structuring, modelling refers to the transposition from generated ideas within a designer's head to diagrammatic models that are used to represent these ideas: "…generate a new sketch…" (5,10.17.1), "...provide sketches or something for them to go ahead" (1.2.40.4), "...sketches, basically working drawings." (1.9.39.2), "...we can do sketches to manufacture things" (1.4.29.1), "...generate a new sketch which shows the correct layout." (5.10.17.1). As a precursor to modelling, expected structural knowledge in the form of a designer's idea from the structuring activity is required and used. As a result of modelling, expected structural knowledge is also created, only this time in the form of diagrammatic representations of these ideas: "...or if it's a technical change we would provide sort of drawings or sketches" (1.4.31.4).

Structuring

The act of structuring refers to the creation of a modified structure that differs from the existing structure of the engineering artefact: "...looking for sort of a way to get around something." (1,9.29.1) "…they'll come up with a solution that they want implemented…" (3,1.33.3) "…we have to supply them with a solution." (5,6.19.1). As an input, one type of artefact knowledge was identified: instantiated structure. Required to understand the surrounding constraints upon the new solution, two sources of instantiated structural knowledge were described. These included both the use of drawings of the engineering artefact: "...data pack drawings... 3D modelling stuff..." (1.9.29.1) and information taken from the physical artefact itself: "... go down to the ship, have a look" (1.11.28.1). In addition, the output of the structuring process is considered to be in an expected structural form, represented by solutions that exist within a designers head: "…it's really just a matter of sussing out what you think is going to bring up the solution…" (2,4.43.1)

Validating

The act of validating refers to the checking that the problem or opportunity exists as have been described by the identifier: "…we do a lot of validation … go down to the ship, have a look because of the datum pack could tell you that space is free, but these drawings were done years ago and a lot of them aren't maintained" (1,11.28.2) "I'd be asked to validate investigate it, read what they are saying, go back to the drawings, see if they are still valid…" (4,2.42.1) "…discussing that with other members of the team to see if that is going to resolve it." (2,4.43.2). Used during validation, one type of artefact knowledge was identified: instantiated structure. In order to establish whether the disparity between the actual and desired states of the engineering artefact existed as described by those who identified this, a review of the instantiated structure was performed. In this instance, this was reported as being performed by reviewing the design rather than the physical engineering artefact.

Prediction phase

Within the prediction phase of the engineering change management process only one activity was identified: analysing.

Analysing

The act of analysis refers to the forecasting of the impact of the proposed solution on the product, process and management domains: "...investigation into the drawing" (5.8.49.1). Used during analysis, one type of artefact knowledge was identified: expected structure, whilst expected behaviour was created by the analysis activity. Using the expected structural knowledge taken from a sketch, an investigation to establish the behaviour that can be expected was enacted: "...was strong enough" (3.7.24.1), "...make sure ... secured correctly to the deck and any other health and safety considerations are taken into account and it's useable as well" (3.7.24.3), "...that there were space envelopes" (3.7.24.2).

Approval phase

Within the approval phase of the engineering change management process only one activity was identified: authorising.

Authorising

The act of authorising refers to the choosing of whether to provide the authority to proceed with the implementation of the engineering change or not: " …we've to do this, can you confirm that this is correct…" (1,17.21.1). In this case, no clear decision making authority was identified. As the focus was on processing engineering changes as rapidly as possible, decisions were either being taken by the individual who identified the problem or if more complicated, the design team.

Implementation phase

Within the implementation phase of the engineering change management process two activities were identified: instantiating and ordering.

Instantiating

The act of instantiating refers to the modification of the structure of the engineering artefact to reflect the new solution: "…he'll just go ahead and do the work…" (1,10.28.2). Used during instantiation, one type of artefact knowledge was identified: expected structure. Detailing the physical modifications that require to be implemented upon the existing physical engineering artefact, the expected structure is communicated through sketches or drawings, "...he'll get the sketch drawings and then he'll just go ahead and do the work" (1.10.28.2).

Ordering

The act of ordering refers to requesting another company to provide the new equipment and material required to enable the change to take place: "…ordering up new pieces of equipment for them or new material" (1,10.28.1). Used during ordering, one type of artefact knowledge was identified: expected structure. Required to detail the structural parameters that the new equipment needs to instantiate, the expected structure is described as being embodied by sketches, "...new material on those sketches" (1.10.28.1).

6.3.3 Case summary

Within CS3, a single engineering change management process was observed that consisted of ten activities. These activities were: documenting, identifying documenting, structuring, modelling, validating, analysing, authorising, instantiating and ordering. However, within this process different engineering practitioners were observed to enact these activities in certain instances. As such, only realising, structuring, analysing, decision-making and instantiating activities were reported as being enacted for each engineering change, with the other activities being enacted on an as needed basis.

To summarise the activities that have been reported as composing the engineering change management process a summary table has been produced (see Table 22). This table presents definitions for these activities and the types of artefact knowledge that are used and created by these activities.

Table 22 - Summary table of the engineering change management process activities in CS3

Phase	Activity	Definition	Artefact knowledge	
			Used	Created
Identification	**Documenting**	The act of preparing a written statement of the problem.	-	-
	Realising	The act of recognising a problem or opportunity with the engineering artefact	S_{ins}	-
Generation	**Documenting**	The act of describing the generated solution in a textual format.	-	-
	Structuring	The act of creating a new structure that differs from the existing structure of the engineering artefact.	S_{ins}	S_{exp}
	Modelling	The act of transposing the generated ideas within a designer's head to diagrammatic models that represent these ideas	S_{exp}	S_{exp}
	Validating	The act of checking that the problem or opportunity exists as has been described by the identifier.	S_{ins}	-
Prediction	**Analysing**	The act of assessing the impact of the proposed solution on the product, process and management domains.	S_{exp}	B_{exp}
Approval	**Authorising**	The act of choosing of whether to provide the authority to proceed with the implementation of the engineering change or not.	-	-
Implementation	**Instantiating**	The act of modifying the structure of the product to reflect the new solution.	S_{exp}	-
	Ordering	The act of requesting another company to provide the new equipment and material required to enable the change to take place.	S_{exp}	-

6.4 Chapter summary

This chapter has presented the findings from the three distinct cases. Focussing on the activities that were enacted and the artefact knowledge that was used and created, the engineering change management process for each has been reported. From this, the engineering change management processes were found to vary in composition with between ten and twelve activities being reported in each. Furthermore, within each of the cases variations on the activities that were enacted were reported for different engineering changes. As such, within each case a number of activities were identified; however, due to these variations no definitive engineering change management process could be presented that represents how all of the engineering changes are processed within the case.

Based on the findings of the case study, the following chapter proceeds to present a cross case analysis to establish the commonalities and differences between these cases.

Chapter 7 - CROSS CASE ANALYSIS

The aim of this chapter is to present a cross case analysis of the findings from the individual cases presented in chapter 6. Reflecting this, the chapter commences, in section 7.1, with a discussion of the activities that composed the engineering change management processes in the three cases and the artefact knowledge that was reported as being used and created through the enactment of these activities. Aligning with the first research question, section 7.1.1 provides an insight into engineering change management process enactment across the product lifecycle. Subsequently, aligning with the second research question, section 7.1.2 proceeds to provide an insight into artefact knowledge usage and creation through the enactment of the activities that compose the engineering change management process. Following this, emergent insights that have been taken from the case study are presented in section 7.1.3. Finally, in section 7.2 the chapter is summarised, outlining the key insights that can be taken from the case study.

7.1 Engineering change management process: cross case discussion

Across the three cases presented in the previous chapter, a number of activities have been identified as composing the engineering change management process. Within this section, the similarities and differences that exist between the cases are reported and explored, with recommendations for engineering change management practice offered where appropriate. Providing an overview of the different activities that have been identified from the case study these are then cross referenced against the activities that have been identified from literature to highlight the correlations between these two sources.

Identification phase

From the case study, three activities have been identified as composing the identification phase of the engineering change management process: evaluating, realising and documenting.

Evaluating

Representing the first of two mechanisms for initiating engineering changes and identified in CS1 and CS2, evaluation refers to the act of assessing the current state of the engineering artefact against the desired state. With the desired state being represented by expected functional, behavioural and structural knowledge and the current state being represented by instantiated structural and behavioural knowledge, the cross referencing of these knowledge types is evident within the act of evaluation. As a result of evaluation, if the current state was found to not match the desired state of the engineering artefact then this would act as a trigger to begin the engineering change management process. The act of evaluation was found to occur in particular during formal design reviews, but also occur sporadically throughout the product development cycle.

As engineered artefacts are periodically reviewed throughout a product’s development cycle, the existence of this activity within CS1 and CS2, but not within CS3 is rationalised. During CS3 the design had already been completed and as such had previously been subject to review. Conversely, the design development was on-going in CS1 and CS2 meaning reviews were still actively taking place in these cases.

Given the relationship between formal design reviews and the identification of problems or opportunities, the importance of conducting design reviews is emphasised. Based on the knowledge that change costs more as the product lifecycle progresses (Kidd and Thompson 2000), to optimise the management of engineering change it is clear that effort must be expended early to increase the identification of problems or opportunities. In the context of the act of evaluation, this therefore leads to the conclusion that a distinct emphasis should be placed on conducting design reviews during the early stages of product development. This should act to help identify problems and opportunities early and hence reduce the total cost of change throughout the product’s lifecycle.

Realising

As the second of the two mechanisms for initiating the engineering change management process, the act of realising describes the recognition that a problem or opportunity exists with the current state of the engineering artefact. Unlike evaluation, this activity can be enacted without prior knowledge of the expected state of the engineering artefact. Instead, realisation occurs through perception of the current state of the engineering artefact (both instantiated structural and behavioural knowledge), with the realisation being based on interpreted behaviour knowledge. Across the three cases, the act of realising was found to occur throughout. However, as opposed to the act of evaluation in which the predominance of this activity was evident following formal reviews, realising was reported to be more sporadic, occurring throughout the product lifecycle.

As discussed in the previous section for the act of evaluation, there is a benefit in the identification of problems or opportunities early within the product lifecycle. Given the act of realisation represents the second mechanism for this identification, effort should be expended to support this act. To that end, forums should be established so an individual could raise a concern in an appropriate manner, such as in CS2. This should facilitate the process of determining whether an engineering change is required or not.

Documenting

Identified in all three cases the act of documenting during the identification phase refers to the preparing of a written statement of the problem or opportunity. Ranging from emails to posts on internal project forums, this written statement forms a knowledge transfer mechanism for communicating the problem or opportunity when geographical constraints prohibit verbal communication or when a record of why the change is needed is required. In CS1, documentation of the problem or opportunity was not reported for each of the engineering changes that took place: "…it's not as formal; we haven't got on S80 a form change proposal." (1.5.29.16.1). Instead, only changes that effected design interfaces or when a record of the change was required, was the problem or opportunity actually recorded. In comparison, in CS2 each engineering change was required to have a written problem or opportunity statement. Whilst it was observed that the process could be initiated by verbal communication, at some stage the problem or opportunity was required to be documented for the formal engineering change management process. In addition, in CS3, documentation of the problem or opportunity was required to be recorded. However, this was only the case for changes that required significant additional design effort, to provide an insight into the problem or to rationalise the new solution. As such, if the changes could be dealt with by the individual responsible for implementing the design, then no documentation was required.

Recording the need for each engineering change acts to legitimise the rework necessary to correct a defect or perform a product improvement, providing a record of the reason behind why the artefact has developed in such a manner. As such, the lack of documenting for any engineering changes within any of the cases could appear unjustified. However, in CS1, it was suggested that as the structure of the engineered artefact had yet to be finalised, implementing a requirement to document the reason for each engineering change could stifle innovation in the conceptual design stages and lead to an increased product development cycle length. Furthermore, as evidenced in CS3, if the need for the engineering change could be overcome by the individual responsible for carrying out the work, the problem or opportunity may never be recorded. This could lead to a situation in which the reasons behind the change taking place may never be known. It is therefore evident that when deciding whether to document the reason for an engineering change, a balance between the benefit of having a traceable design versus a design process that takes less time and is less bureaucratic must be struck.

Summary of identification phase

Summarising the activities that have been described as being associated with the identification phase of the engineering change management process Table 23 is presented.

Table 23 - Summary table of activities associated with the identification phase

Activity	Description	Discussion summary
Documenting	The act of preparing a written statement of the problem or opportunity.	Identified in all three cases; however, more prevalent in CS2 than in CS1 and CS3.
Evaluating	The act of assessing the current state of the engineering artefact against the desired state.	Identified in CS1 and CS2. Increased prevalence during formal reviews.
Realising	The act of recognising a problem or opportunity with the current state of the engineering artefact.	Identified in all three cases, with similar sporadic enactment evident in each.

Generation phase

From the case study, five activities have been identified as composing the generation phase of the engineering change management process: documenting, modelling, selecting, structuring and validating.

Structuring

Described in all three cases, the act of structuring refers to the creation of a new structure that differs from the existing structure of the engineering artefact. Typically, this activity is enacted wholly within a designer's head and is either acted upon by that designer or communicated verbally to a group of designers. Using knowledge of the current state of the engineering artefact in the form of instantiated behaviour and structure, the solution is constrained. In addition, expected functional knowledge was reported as being used to guide the development of the new structure. As a result of the structuring activity, expected structural knowledge is created based upon cognitive models of the new solution.

Enacted in each of the cases, structuring is considered to be one of the fundamental activities within the engineering change management process. Creating a new solution that overcomes the identified problem or capitalises upon the realised opportunity is fundamental to reducing the disparity between the current and desired states of an engineering artefact. As such, the enactment of this activity within each of the cases is in line with expectations.

Modelling

Identified in CS2 and CS3, the act of modelling refers to the transposition from generated ideas within a designer's head to diagrams, sketches or drawings that are used to represent these ideas. Acting as a method of communicating these ideas, modelling is used in situations where geographical constraints restrict the verbal communication of the proposed new solution or when complex solutions are required that benefit from additional description. The instantiation of the generated solution into a sketch or drawing is not however enacted for each engineering change, as described in CS2: "…there is often, not always, but often drawings attached" (2.4.17.41.1). As such, modelling is not considered to be a core activity within the engineering change management process. Instead the act of modelling is a supporting activity, used to aid understanding of the solution.

Given this activity is used to aid the understanding of a generated solution; it could have been expected to exist in each of the cases. However, as an engineering project progresses, the engineered artefact becomes increasingly detailed. As such, engineering changes have the potential to impact upon an increased number of structural parameters during the latter stages of a product's lifecycle. In such a situation, a model of the proposed solution could highlight the impacted parameters making this activity more prevalent in the latter stages of a product's lifecycle. However, the enactment of this activity may also be influenced by situations were geographical constraints restrict communication. This is demonstrated by a comparison between CS1 and CS2, where in CS1 it was more common for changes to be instantiated immediately into drawings of the engineering artefact, eliminating the requirement for models of these to be produced. Nevertheless, offering a model of the generated solution could clarify issues that are difficult to describe in words, contributing to a more efficient engineering change management process. As such, the individual who is responsible for communicating the new solution must determine whether the solution is simple enough not to need a supplementary drawing, diagram, sketch, etc.

Documenting

Identified in each of the three cases, documenting refers to the act of preparing a written statement that describes the generated solution. This could be in a formal format such as in an engineering change request or in an informal format such as emails or annotated drawings. However, this activity does not cover the drawing or modelling of the new solutions in any form, merely the description of this in words. The act of documenting was described as being essential in CS2 as this formed the basis for analysis activities. In CS1 this was also deemed to be essential for any changes that impacted upon the design interfaces; however, this was not required for changes that did not affect the design interfaces. In addition, the new solutions were meant to be recorded for each of the changes in CS3 so these could be detailed to the customer; however, this was not enacted for minor changes that were dealt with by the individuals tasked for implementing the existing designs.

Reflecting the act of documenting within the identification phase, recording the solution for all engineering changes was required in CS2, but not in CS1 nor CS3. However, given the lack of execution across the cases, documenting is not considered to be a key activity within the engineering change management process. Instead it is considered to be a support activity that is required when either widespread distribution of knowledge of the engineering change is required or a record of the change is needed. Nevertheless, care must be expressed when relying solely upon documents to inform of a generated solution as the words contained are open to interpretation by the reader. If a complex solution is generated, modelling should also be considered in parallel with documenting. As such, for each engineering change a decision must be taken by the individual responsible for generating a solution whether a written statement of the solution is required and if so would a drawing, diagram, sketch, etc. be a useful addition.

Selecting

Described in CS1 only, the act of selecting refers to the choosing of which of the possible design solutions to proceed to the prediction phase with. This selection activity can therefore be considered to be a decision making process from which the best solution from a set of solutions is chosen to proceed with: "…what option we are going to move forwards with" (1.1.26.34.1). As such, this activity was enacted upon the expected structural knowledge described as a result of structuring activities.

The act of selecting can only be enacted when more than one solution to a problem or opportunity has been generated. Jarratt et al. (2011) reported that this was not frequently executed in many engineering change management processes: a finding that was reflected in CS2 and CS3 in which only a single solution was ever developed. However, in CS1 multiple solutions were developed. Whilst developing multiple solutions would inevitably take more time than developing a single one, a more comprehensive exploration of the design possibilities constituted by the development of multiple solutions would increase the chance of developing a more successful solution. As such, the development of multiple solutions and selection of the optimum should be encouraged throughout the product lifecycle.

Validating

Described in both CS2 and CS3, the act of validating refers to establishing the integrity of communicated information. This activity was identified when different individuals were responsible for different phases of the engineering change management process. In CS2 and CS3, validation was enacted when a problem or opportunity was communicated to a separate team who were responsible for creating the new solution. As such, this activity aimed to establish the validity of the reported problem or opportunity. However, in CS2, validation was also enacted by the individuals who were responsible for distributing the solution, checking the accuracy of the statements and making sure that there was sufficient information for analysis activities to be enacted based on the supplied documentation. As such, the instantiated state of the engineering artefact was found to be used during this activity.

The act of validation was identified in CS2 and CS3 only. This can be justified as in these cases, the individuals who were responsible for generating a solution were not always those who identified the change in the first place. In comparison, in CS1 engineering changes were typically dealt with by teams of designers and engineers who worked closely with the individual who identified the problem or opportunity. The act of validation could therefore be suggested to be most prevalent when the engineering change management process was distributed between numbers of different engineering change practitioners. In general, the act of validating acts as a final check to ensure that an engineering change is necessary, prior to proceeding into the prediction phase. This activity therefore reduces the chance that a solution is rejected outright in the approval phase. Given the opportunity to reduce unnecessary effort being expended during the engineering change management process, this activity should be encouraged in all processes.

Summary of generation phase

Summarising the activities that have been described as being associated with the generation phase of the engineering change management process Table 24 is presented.

Table 24 - Summary table of activities associated with the generation phase

Activity	Description	Discussion summary
Documenting	The act of describing the generated solution in a textual format.	Identified in all three cases but only evident for all engineering changes within CS2. However, this act was required for engineering changes that affected the prescribed interfaces in CS1 and for engineering changes that required the customer's attention in CS3.
Modelling	The act of transposing the generated ideas within a designer's head to diagrammatic models that are used to represent these ideas.	Identified in CS2 and CS3; however, not enacted for all engineering changes in either of the cases.
Selecting	The act of choosing which of the design options to proceed with.	Identified in CS1 only.
Structuring	The act of creating a new structure that differs from the existing structure of the engineering artefact.	Identified in all three cases and enacted for all engineering changes. No enactment variations identified between the cases.
Validating	The act of establishing the integrity of the communicated information.	Identified in CS2 and CS3; however, not enacted for all engineering changes.

Prediction phase

Across the three cases, three activities have been identified as composing the prediction phase of the engineering change management process: analysing, composing and distributing.

Analysing

Described in each of the cases, the act of analysing refers to the forecasting of the impact that implementing the new solution will have upon the product, process and management domains. This activity was identified as using expected structural knowledge based on the new solution and considering it alongside the instantiated structure of the current engineering artefact. As a result of analysing, expected structural knowledge in terms of which other parts within the engineering artefact were going to be affected as well as the expected behaviour in terms of the physical and metaphysical attributes that would be impacted are forecast. In addition, cost and schedule impacts were established during this process.

Whilst analysis activities were identified within each of the three cases, this activity was identified as being enacted differently in each. In CS1 the act of analysis was enacted in parallel with structuring activities by small teams of designers who dynamically created and impact assessed the new solutions. Reflecting the focus on development of an optimum technical solution, these analyses were predominantly enacted to establish technical impacts upon the engineering artefact rather than the process or management domains. This is in comparison to CS2 where the focus of analysis is predominantly on establishing the cost and schedule impact as accurately as possible. As such, in this case, analyses were enacted by a number of different individuals who were impacted with the details being communicated based on a documented description of the engineering change. In CS3 due to the focus of the engineering change management process being on the speed of implementation and the changes themselves relatively small, this lead to a situation where an accurate analysis of the effects of the change were not required. As such, distinction between analysis and generation activities was not clear. Nevertheless, the effects of the change were established, based upon the expected behaviour that would emerge as a result of implementing the new solution. As an important step in the engineering change management process in each of the cases, the act of analysis should be encouraged in each engineering change management process. However, the depth of the analysis should be proportional to the scale of the engineering change and cover predefined objectives (e.g. time, cost, technical impact).

Distributing

Described in both CS1 and CS2, the act of distributing refers to the identifying and informing impacted individuals of the proposed new solution: “…talking to our weapons discharge team…” (1.4.18.18.1), “…take it to the works to talk about fabrication, manufacturing techniques…” (1.1.21.58.3). In CS1 this was enacted through a personal understanding of which individuals were responsible for the development of different parts within the engineering artefact. However, in CS2 a structured approach to distribution was reported. In this case, change administrators read the description of the proposed solution and interpreted the parts that would be affected within the engineered artefact. Following this they then cross referenced the affected parts against a matrix which identified which individuals were responsible for the development of these parts. As such, the engineering change document was then sent via email to these individuals: “…then we will try and send it out to everybody” (2.6.8.49.1). In CS3, distribution could not be considered to be a distinct activity as the emphasis of the engineering change management process was placed on rapid implementation of changes to avoid impacting upon the project schedule. As such, widespread distribution was not evident.

The act of distribution was only reported in CS1 and CS2. In comparison to CS3, in these cases the design team was large and as such required a number of individuals to analyse the impact of each engineering change. The act of distribution was therefore necessary to ensure that all of the team had an appropriate input into the analysis of the engineering change. The act of distribution as part of the engineering change management process is therefore dependent on the number of individuals within the engineering project. In this context, as the size of project team in CS1 and CS2 were much larger, then it is more likely that this activity was present in these processes.

Composing

Described in CS2 only, the act of composing refers to the formal collation and recording of the various effects associated with the instantiation of the proposed solution from different knowledge sources. These were predominantly reported to be cost and schedule impacts associated with implementing changes to the existing artefact and as such were collated quantitatively. As such, the level of the reported impact was referenced against set criteria that dictated which approval board the proposed solution was sent to. In CS1, the act of composing was not identified as a distinct activity. Instead, as solutions that overcome the need to change were predominantly generated, analysed and approved by small teams of designers, the collation and recording of the effects from multiple different sources was not evident. Furthermore, in CS3, the act of composing was not evident as engineering changes were required to be implemented as soon as possible. This meant that limited analysis activities were enacted and as such, the collation of these analyses was not evident.

Formal collation of the various impacts of an engineering change provides a global overview of the implications of implementing an engineering change. This offers a concise view of the impacts associated with an engineering change in a manner that supports the individual responsible for authorising of the engineering change. However, whilst this may benefit authorisation, it does require additional resources to collate all the various impact analyses into a single view. This inevitably adds cost to an engineering project and as such a balance should be struck between this and the amount of support the individual responsible for authorising engineering changes requires. Based on the evidence from the case study, this balance has tipped in favour of cost saving in CS1 and CS3. However, providing additional support to the authoriser is preferred in CS2.

Summary of prediction phase

Summarising the activities that have been described as being associated with the prediction phase of the engineering change management process Table 25 is presented.

Table 25 - Summary table of activities associated with the prediction phase

Activity	Description	Discussion summary
Analysing	The act of considering the effects upon the product, process and management domains associated with the implementation of a change.	Identified in all three cases; however, the emphasis of the activity was found to vary between the cases, leading to different outputs.
Composing	The act of collating and recording the impacts associated with the new solution.	Identified in CS2 only.
Distributing	The act of identifying the individuals that are affected by the new solution and contacting these individuals to request their analysis.	Identified in CS1 and CS2. Evidence of significantly wider distribution in CS2 than CS1.

Approval phase

Across the three cases, one activity has been identified as composing the approval phase of the engineering change management process: authorising.

Authorising

Identified in all of the cases, the act of authorising refers to the choosing of whether to provide the authority to implement the new solution or not. In CS2, this decision was reported to be fundamentally based upon the cost of the implementation. The schedule impact was also considered as a secondary issue; however, at this point there no consideration of the technical implications was evident. In CS1, for the formal engineering change management process in which changes propagated beyond the barriers of the company’s responsibility, the decision to implement was also taken on a financial basis; however, justification based on the technical implications was also required. However, for changes that were maintained within the design space in CS1, these were considered predominantly on a technical rather than managerial basis (cost, schedule impacts, etc.). Authorising in CS3 was provided in a different manner to that of the other cases. As the project requirement was for the artefact to maintain a specified scheduled maintenance period, the focus of the engineering change management process was on the rapid implementation of changes to the physical artefact. In such a situation, the modifications were relatively minor and the interfaces between the various sub-systems were well defined. Therefore, the decision on whether to implement the change or not was primarily based upon solutions that could be implemented as quickly as possible.

Whilst this activity was identified as being enacted in each of the cases, differences in the decision criteria between these cases have been identified. In CS1, decisions were based upon the technical implications, with the objective to select the best possible technical solution to proceed with. In CS2, this then shifts to a decision based upon the management domain; specifically on the cost and schedule impact of the change. Finally, in CS3, the decision is primarily made based upon the time that the new solution will take to implement. In addition, variations in the formality of the decision making process were also identified. In CS1, the decision to implement the new solution was made by a variety of different individuals coming to a consensus view of how to best overcome the need to change. This is in comparison to CS2 in which distinct decision making authorities were identified. However, in CS3 the decision making authority was less apparent, as the responsibility for approving changes could be executed by a number of different individuals.

The act of authorising is considered to be critical in any engineering change management process. From the case study it was found that a mixture of formal and informal decision making was enacted when considered whether to implement an engineering change. In each of the cases, authorisation was granted by explicit decision making authorities who usually held senior positions within the project. However, in simple cases it was reported that individuals could approve a modification on their own rather than waiting for formal approval. This informal approval helped speed the process up; however, it also meant that the configuration of the engineered artefact could be lost. To maintain progress during the engineering change management process but not lose configuration of the engineered artefact, an approach as taken in CS2 could be helpful. As such, multiple decision making authorities should be set up on the project with different authorities approving different levels of engineering change. In such a situation, the top decision making authority would only deal with the changes with the most significant impact whilst lesser design making authorities would authorise engineering changes with a less impact. In this case, all engineering changes would require distinct approval; however, the approval process would be speed up as different authorities would be responsible for different impacts of engineering change.

Summary of approval phase

Summarising the activities that have been described as being associated with the approval phase of the engineering change management process Table 26 is presented.

Table 26 - Summary table of activities associated with the approval phase

Activity	Description	Discussion summary
Authorising	The act of choosing of whether to provide the authority to proceed with the implementation of the engineering change or not.	Identified in all three cases; however, the decision criteria was found to be different in each.

Implementation phase

Across the three cases, three activities have been identified as composing the implementation phase of the engineering change management process: instantiating, ensuring and ordering.

Instantiating

Identified in all three cases the act of instantiating refers to the implementation of the approved new solution. This instantiation aims to eliminate the disparity between the current and desired states of the artefact by modifying the existing structure. Across the cases the instantiation of the changes was described differently reflecting the form that the engineering artefact embodied during the specific stage of the product lifecycle. In CS1 and CS2 the engineering artefact did not exist in a physical form, instead representations of the physical form existed as models in CAD packages and drawings. As such, the instantiation of the expected structure would result in the modification to these representations. However, in CS3 the engineering artefact existed in both a physical and non-physical form. In this situation the instantiation of the engineering change was executed upon the physical engineering artefact but not necessarily on the computer models and drawings. In CS3 this lead to a situation where the product itself was sometimes found to deviate from the drawings that are considered to represent the product in the non-physical domain.

The act of instantiation is considered to be a fundamental activity within the engineering change management process, representing the means by which the identified problem or opportunity is overcome. Given the interconnected, heterogeneous nature of engineered artefacts and their representations, care must be taken when instantiating an engineering change to ensure that all modifications to all of the impacted drawings, parts, documents, etc. are incorporated. As a product's lifecycle progresses, an increased number of drawings, part, documents, etc. are generated, increasing the likelihood that an engineering change could impact upon these as well. Therefore, attention should be paid to these throughout the product lifecycle; however, it should be noted that engineering changes are likely to require greater instantiation effort as the product becomes increasingly detailed.

Ensuring

Described in CS2 only, the act of ensuring refers to the checking that the new solution was being instantiated as described. To achieve this, in CS2 an engineering change notification (ECN) was created that provided the relevant budgetary codes to permit the instantiation of the change to take place and enable project management specialists to follow the progress.

Ensuring that engineering changes are being instantiated appropriately demonstrates a commitment to controlling the configuration of the engineered artefact. It could therefore be considered that this activity should be evident in engineering change management processes throughout the product lifecycle. In such a situation, the lack of ensuring during CS1 and CS3 appears to be unjustified. However, the act of ensuring has significant similarities with activities within configuration management. As such, it may have been considered in these cases that the act of ensuring is part of the configuration management process rather than the engineering change management process.

Ordering

Described in CS3, ordering refers to the act of requesting new equipment and/or materials to enable the proposed solution to be implemented. This activity was only identified in CS3 as this was the only case in which the engineering artefact existed in a physical state and as such new equipment was required to achieve the modified solution.

Nevertheless, whilst a physical engineered artefact only existed in CS3; the act of ordering would have been expected to have been reported in CS1 and CS2. The ordering of equipment and materials is not typically executed only when the design is complete; instead this occurs throughout the development of an engineered artefact. As such, a change to the design, even during the initial stages of development, could impact upon parts or components that have already been ordered. For example, in the design of a ship, the engines typically form an early procurement package as they dictate the power provided to the vessel. If an engineering change requires a modification to the power requirements, then a new engine must be ordered. Therefore, this must be ordered as soon as possible due to the long lead times associated with the provision of these types of products. To that end, attention should be paid to ensure that any procured parts that are impacted by an engineering change are ordered appropriately so as to not slow the project down throughout the product lifecycle. The lack of reporting of this activity in CS1 and CS2 acts to demonstrate that this activity may well have been omitted and could cause problems issues later in the product's lifecycle.

Summary of implementation phase

Summarising the activities that have been described as being associated with the implementation phase of the engineering change management process Table 27 is presented.

Table 27 - Summary table of activities associated with the implementation phase

Activity	Description	Discussion summary
Ensuring	The act of checking that the updated solution is being embodied within the design models.	Identified in CS2 only.
Instantiating	The act of modifying the structure of the artefact to reflect the new solution.	Identified in all three cases. Instantiation in CS1 and CS2 was found to involve the updating of the design only; however, in CS3 instantiation was found to include the updating of the physical engineering artefact as well.
Ordering	The act of requesting new equipment and/or material required to enable the change to be implemented.	Identified only in CS3.

7.1.1 Engineering change management process activity enactment

Across the three cases examined in this case study a total of fifteen activities have been identified. Of these, the identification phase was found to compose three activities, the generation phase five activities, the prediction phase three activities, the approval phase one activity and the implementation phase three activities. Offering an overview of the activities that have been identified across the case study as composing the engineering change management process, Table 28 is presented.

Table 28 - Activity enactment within the three cases

Phase	Activity	Case			Enacted in each case
		CS1	CS2	CS3	
Identification	**Documenting**	X	X	X	**X**
	Evaluating	X	X	-	**-**
	Realising	X	X	X	**X**
Generation	**Documenting**	X	X	X	**X**
	Structuring	X	X	X	**X**
	Modelling	-	X	X	**-**
	Selecting	X	-	-	**-**
	Validating	-	X	X	**-**
Prediction	**Analysing**	X	X	X	**X**
	Composing	-	X	-	**-**
	Distributing	X	X	-	**-**
Approval	**Authorising**	X	X	X	**X**
Implementation	**Ensuring**	-	X	-	**-**
	Instantiating	X	X	X	**X**
	Ordering	-	-	X	**-**

Based on these findings, seven activities were found to be enacted in each of the cases: documenting (identification), realising, documenting (generation), structuring, analysing, deciding and instantiating. Furthermore, evaluating, modelling, validating, and distributing were identified as being enacted within two of the cases with selecting, composing, ensuring and ordering being identified in only one of the cases.

Comparison with literature

From the case study, fifteen activities have been identified as composing the engineering change management process. In comparison, from the literature review twelve activities were identified. To establish the correlation between literature and the case study Table 29 has been produced. Using the descriptions of the activities from chapter 2 and the activities from the case study that are presented above, the correlating activities are marked with a cross in the corresponding box. In addition, activities that have only been identified in either literature or the case study are highlighted by greyed out boxes on the relevant side of the table.

Table 29 - Cross reference with literature

			Activities identified from literature review											
			Identification		**Generation**			**Prediction**				**Approval**	**Implementation**	
			Documenting	Realising	Documenting	Solution development	Selecting	Analysing	Composing	Planning	Testing	Authorising	Ensuring	Instantiating
Activities identified from case study	**Identification**	Documenting	X											
		Evaluating												
		Realising		X										
	Generation	Documenting			X									
		Structuring				X								
		Modelling				X								
		Selecting					X							
		Validating												
	Prediction	Analysing						X						
		Composing							X					
		Distributing												
	Approval	Authorising										X		
	Implementation	Ensuring											X	
		Instantiating												X
		Ordering												

Of the fifteen activities identified within the case study and the twelve activities identified from literature, ten of these have been identified as correlating. This leaves four activities from the case study and two activities from the literature as not correlating (see Table 30). Detailing these non-correlating activities, from the identification phase one activity was identified from the case study that was not reported in literature: evaluating. From the generation phase another activity was identified from the case study that was not reported in literature: validating. From the prediction phase, one activity was identified from the case study but not from literature: distributing. In addition, two activities were identified from literature: planning and testing. Finally, from the implementation phase, one activity was identified from the case study that was not reported in literature: ordering. In addition, one activity that had been identified from the literature review was found to compose two activities reported from the case study. Specifically, solution development during the generation phase of the engineering change management process was found to compose both modelling and structuring as identified in the case study.

As such, from both the case study and literature a total of seventeen activities have been identified as composing the engineering change management process.

Table 30 - Activity perspective correlation between case study and literature

	Activities identified		Correlating activities	Non correlating activities	
	Case study	Literature		Case study	Literature
Identification	3	2	2	1	-
Generation	5	3	3/4	1	-
Prediction	3	4	2	1	2
Approval	1	1	1	-	-
Implementation	3	2	2	1	-
Total	**15**	**12**	**10**	**4**	**2**

7.1.2 Artefact knowledge usage and creation summary

From the case study, artefact knowledge has been reported to be used and created for different activities during the engineering change management process. Across the three cases, twenty six different relationships between artefact knowledge and engineering change management process activities have been identified. Of the seven types of artefact knowledge, the usage and creation of these have been found to vary with some activities only using artefact knowledge, whilst others use and create artefact knowledge. In addition, some activities have been reported as using artefact knowledge in each of the cases, whilst others have been isolated to individual cases. Offering an overview of artefact knowledge usage and creation by the different activities within the engineering change management process, Table 31 is presented, in which the number in the corresponding box refers to a relationship identified in the corresponding case.

Table 31 - Summary table of artefact knowledge from the case study

Artefact knowledge input							Activity	Artefact knowledge output						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
							Identification phase							
							Discussing							
1,2	**1**	**1,2**	**1,2**	**1**			Evaluating							
			1,2,3	**1**			Realising						**1,2**	
							Generation phase							
							Documenting							
		3					Modelling			**2,3**				
		1					Selecting							
1			**1,2,3**	**2**			Structuring			**1,2,3**				
			3				Validating							
							Prediction phase							
1		**1,2,3**	**2**				Analysing		**1,3**	**1,2**				
							Composing							
		2					Distributing							
							Approval phase							
	1						Authorising							
							Implementation phase							
							Ensuring							
		1,2,3					Instantiating				**2**			
		3					Ordering							

Based on the evidence collected through the case study, a range of artefact knowledge types have been identified as being used and created during the enactment of the activities that compose the engineering change management process. Focussing on artefact knowledge usage, expected function, expected behaviour, expected structure, instantiated structure and instantiated behaviour have all been identified as being used by one or more activity. However, the interpreted behaviour and interpreted function were not identified as being used for any of the activities. Shifting the focus to the creation of artefact knowledge, the expected behaviour, expected structure, instantiated structure and interpreted behaviour were all identified as being created through the activities. However, the expected function, instantiated behaviour and interpreted function were not identified as being created. Further, in terms of activities, eleven activities were identified to use artefact knowledge in some form whereas only five activities were identified to create artefact knowledge.

Comparison with literature

From the case study, twenty six artefact knowledge type relationships with the activities that compose the engineering change management process have been identified. In comparison, fifteen artefact knowledge type relationships with the activities that compose the engineering change management process were identified from in literature. To depict the correlation between the findings from the case study and that from literature, Table 32 is presented.

Table 32 - Artefact knowledge usage and creation from both literature and case study

Phase	Activity	Input	Output	Literature	Case study	Correlation
Identification	Documenting	S_{ins}		✓		X
	Evaluating	F_{exp}			✓	X
		B_{exp}			✓	X
		S_{exp}			✓	X
		S_{ins}			✓	X
		B_{ins}			✓	X
	Realising	S_{ins}			✓	X
		B_{ins}			✓	X
			B_{int}		✓	X
Generation	Documenting	S_{ins}		✓		X
	Modelling	S_{ins}			✓	X
			S_{exp}		✓	X
	Selecting	S_{ins}			✓	X
	Structuring	F_{exp}			✓	X
		S_{ins}			✓	X
		B_{ins}			✓	X
			S_{exp}		✓	X
	Validating	S_{ins}			✓	X
Prediction	Analysing	F_{exp}		✓	✓	✓
		B_{exp}		✓		X
		S_{exp}		✓	✓	✓
		S_{ins}		✓	✓	✓
			F_{int}	✓		X
			B_{exp}		✓	X
			B_{int}	✓		X
			S_{exp}	✓	✓	✓
	Composing	S_{exp}		✓		X
	Distributing	S_{exp}			✓	X
	Testing	B_{exp}		✓		X
			B_{int}	✓		X
Approval	Authorising	B_{exp}			✓	X
Implementation	Instantiating	S_{exp}		✓	✓	✓
		S_{ins}		✓		X
			S_{ins}	✓	✓	✓
	Ordering	S_{exp}			✓	X

Of the twenty six instances of artefact knowledge being reported as being used or created by the activities that compose the engineering change management process from the case study and the fifteen reported in literature, six of these have been found to correlate.

However, nineteen of these instances from the case study and eight of the instances from literature have been found not to correlate. As such, a total of twenty seven non correlating instances of artefact knowledge have been identified between these two data sources.

7.1.3 Emergent insights

Whilst the research reported in the previous chapter was undertaken specifically to answer the research questions reported in chapter 5, through the case study further insights into engineering change management process variations between the three cases have emerged. In particular, four insights can be offered in response to the formality of the engineering change management process; the goals of this process; the clarity of the activity enactment and the engineering change management strategies within the three cases. These insights are presented in the following sections.

7.1.3.1 Process formality

Rouibah and Caskey (2003) first reported that the formality of an engineering change management process can vary at different stages of a product lifecycle. Offering the insight, “Engineering change after design approval or once production has begun is often more formal.” Considering formality as the existence of a recognised process for managing engineering changes and the proportion of engineering changes that follow this process the formality of the process was found to vary across the cases.

Within each of the three cases, a recognised process for managing engineering change was observed. These processes were highly developed in CS2 and CS3 and consisted of information systems for capturing and storing data associated with the engineering change. These information systems consisted of both paper documents and electronic databases that could be accessed by a range of individuals who were involved in the project. However, in CS1 the engineering change management process did not have such well developed information systems for managing engineering changes. Instead CS1 relied upon a single documented framework that was only used to communicate changes that propagated out with the prescribed design space. In addition, these were generally only accessible by the project manager, acting as a formal communication method between the project manager and customer.

Whilst recognised processes for managing engineering change existed in each of the cases, it was established that not all engineering changes followed these processes on each occasion. In CS1, only the changes that impacted upon interfaces and propagated out with the prescribed design space were processed through the recognised engineering change management process. Conversely, in CS2 the vast majority of engineering changes were processed following the recognised engineering change management process. Finally, in CS3 it was identified that whilst all engineering changes were meant to be processed through the recognised engineering change management process, not all engineering changes were. As such, when the three cases are compared with one another in CS1 the proportion of engineering changes that followed the recognised process could be considered to be comparably low, in CS2 as comparably high and in CS3 as comparably medium.

Rather than providing absolute representations of activity distinction and uniform activity execution, relative descriptions have been used to highlight the differences in the cases. As such, Table 33 details these variations.

Table 33 – Relative process formality of the engineering change management process in the three cases

Case	Existence of a recognised engineering change management process	Relative proportion of engineering changes that follow this process	Process formality
CS1	Yes	Low	**Low**
CS2	Yes	High	**High**
CS3	Yes	Medium	**Medium**

7.1.3.2 Process goals

Through this case study, the engineering change management process has been reported as being influenced by different goals. Across the three cases, these goals were found to differ. In total three distinct goals were identified: establishing the impact of a change as accurately as possible, development of a technical solution that overcomes the need to change as best as possible and greatest speed of implementation. Whilst these three goals were not found to be mutually exclusive, within each of the cases a clear recognition of the primary goal was apparent.

In CS1, the goal of the engineering change management process was identified as being to develop the optimum solution to overcome the problem or capitalise upon the opportunity. In this case, designers developed multiple solutions to overcome the need to change from which the best solution was selected to proceed with. This is reinforced by the existence of selection activities within CS1 only. In CS2, the goal of the engineering change management process was identified as being the accuracy of the analysed data. In this case, the focus was not upon developing an optimum solution, but on establishing the cost and schedule impact of the engineering change as accurately as possible. This is reflected in the observation presented by Rowell et al. (2009) who reported that on average an engineering change would take 126 days to proceed through the prediction and approval stages of the engineering change management process. Benchmarking this against literature, this represents a considerably longer cycle time than in airframe manufacture or mechanical controls industry (Blackburn 1992). In CS3, the goal of the engineering change management process was identified as being the speed of implementation. In this case, the focus was placed on overcoming problems as quickly as possible to avoid impacting the refit schedule. With a turnaround time set at eight hours for each engineering change, optimum solution development and impact analysis accuracy were substituted for speed of implementation.

Reflecting this observation, Table 34 highlights the primary engineering change management process goals in the different cases.

Table 34 – Primary goal of the engineering change management process in the three cases

Case	Process goal
CS1	Development of an optimum technical solution
CS2	Accuracy of impact assessment
CS3	Speed of implementation

7.1.3.3 Activity clarity

Within each of the cases, the interviewees were, in general, able to describe the process that engineering changes went through in their project. This involved high level knowledge of the process coupled with more detailed knowledge of the activities in which they were directly involved. However, in certain cases, the level of clarity in which the interviewees were able to articulate these activities was less pronounced. In particular, in CS1, the interviewees were able to outline the steps that they went through when processing an engineering change, but were unable to differentiate in any detail between the activities that they enacted. This led to a situation in which a number of the activities that composed the engineering change management process blurred into one another (as highlighted by Figure 19 and Figure 20). Furthermore, there was a question over the difference between engineering change and standard product development as the interviewees considered that as the drawings had yet to be finalised then any changes to the engineered artefact represented standard product development rather than engineering change activities.

By comparison, in CS2 the interviewees were better able to articulate the activities that they went through and intimate how this linked into the engineering change management process as a whole. In addition, as a distinct process was in place, a clear distinction between engineering change management process activities and product development activities was possessed by the interviewees. However, in CS3, the clarity of the activity definition was not as distinct as in CS2. Nevertheless, knowledge of what constituted an engineering change management process activity, rather than a standard product development activity was clearer than in CS1 as the drawings had been completed. As such, if the physical integration could not be achieved in the manner as described in the drawings, then the requirement for an engineering change was apparent.

Reflecting this observation, Table 35 presents an overview of the clarity of activities within the engineering change management process and between this process and standard product development activities.

Table 35 - Activity clarity overview

Case	Clarity between activities within the engineering change management process	Clarity between standard product development and engineering change management process activities
CS1	Low	Low
CS2	High	High
CS3	Low	High

7.1.3.4 Engineering change management process improvement initiatives

From the case study, it was evident that a number of initiatives had been put in place in each of the cases to improve the performance of the engineering change management process. These initiatives were not necessarily prescribed or endorsed by the management of the project, nor were they necessarily established for the sole reason of obtaining a performance improvement. Nevertheless, these strategies contributed to the timely execution of the engineering change management process either directly or indirectly.

One of the initiatives came from CS1 in response to engineering changes that had the potential to propagate out with the prescribed design space. Recognising that a formal engineering change management process was required to be initiated for any engineering change that impacted upon a design interface, special attention was paid to develop a solution that did not require any modifications to these. Alternative solutions would be generated and options explored to ensure that only in the worst case were requests to modify the design interfaces made. As such, only the most critical engineering changes required the modification of design interfaces and a formal approach to engineering change management. Limiting the impact of solutions was also practised in CS3. In this case, significant effort was made to enable changes to be made without needing the support of the design office and having to produce the required documentation that this entailed.

Again, in CS1 and CS3 the size of the team also contributed to a more efficient engineering change management process. In CS1 and CS3 the team was small, meaning that engineering changes could be dealt with on an informal process and did not always require the full rigour of a formal, documented approach. By comparison, in CS2 the team was significantly larger meaning that all engineering changes had to be processed in a formal manner leading to significantly increased time for the engineering change management process. However, to overcome this, it was found that a number of individuals implemented engineering changes prior to formal approval. Whilst this risked additional rework, it acted to reduce the time taken between the identification and implementation of a solution.

Finally, to decrease the time taken for an engineering change to gain approval and reduce the workload on a single decision making authority, a number of different approval boards were set up. In CS2, these boards had defined limits within which they could approve or reject engineering changes, tied to the financial and schedule impact of these changes. This enabled the small scale changes to be dealt with by a number of individuals, reducing the reliance upon a single decision making authority. This was also reflecting in CS3, where the authority to implement changes was delegated to the individuals who were responsible for carrying out the physical integration of the new part.

Acting as a summary, Table 36 presents the strategies that have been put in place in the cases to improve the performance of the engineering change management process.

Table 36 - Engineering change management strategies

Case	Engineering change management strategy
CS1	Ensure only the most critical changes require the modification of design interfaces; Operate in a small team to ensure changes can be dealt with locally
CS2	Establish a number of approval authorities and define their approval limits; Implement engineering change prior to approval
CS3	Delegate authority for small changes; Ensure only the most major changes require design support

7.2 Chapter summary

This chapter has presented a comparative analysis of the three cases reported on in the previous chapter. Focussing on the activities that were enacted within each of the cases, the similarities and differences between these have been reported. As such, of the fifteen activities that have been identified as composing the three engineering change management processes, only seven of these were found to be enacted in each of the cases. Further, variations between the enactment of the same activity within different cases have been reported. In addition, eleven of these activities were found to use or create artefact knowledge during their enactment, with a total of twenty six relationships between artefact knowledge and the activities that compose the engineering change management process. Finally, emergent insights into the formality, goals, activity clarity and improvement initiatives for the engineering change management process were discussed, with variations between the cases outlined.

Reporting on the second research strategy used to gain an insight into the research questions that motivate this research project, the following chapter proceeds to present the findings of the survey of the wider engineering community.

Chapter 8 - SURVEY FINDINGS

Reflecting the research design as presented in chapter 5, the following chapter presents the results from the survey that was executed to obtain the views of engineering change practitioners within the wider engineering community. To achieve this, the following chapter is divided into three main sections. To commence, in section 8.1 an overview of the response rate and demographic of the respondents is presented. Following this, in section 8.2 the results from the survey are presented. Separated into five subsections, the results are decomposed covering activity enactment during the product lifecycle; artefact knowledge usage and creation; activity enactment frequency; process formality and process goals. Finally, in section 8.3 the chapter is summarised with the pertinent points of this outlined.

8.1 Response overview

Applying the selection criteria outlined in chapter 4, a total if twenty nine companies were approached to participate in the survey. Of these, fifteen responded positively, returning one or more completed questionnaires. In addition, one company responded stating that they were not responsible for processing engineering changes and did not feel that they could complete the questionnaire satisfactorily.

Within the fifteen companies in which the questionnaire was proliferated, a total of 294 questionnaires were sent out. Of these, 85 were returned (29% response rate) from which 6 were discarded due to an insufficiency of information (7% discard rate). As such, a total of 79 usable questionnaires were returned and it is these that form the basis of data that has been captured. Categorising these into the specific stages of the product lifecycle, the number of questionnaires received from respondents within each of the stages varied from seventeen within the production and in-service stages to twenty seven within the detailed design stage. This information is summarised in Table 37.

Table 37 - Respondent return rate

Product lifecycle phase	Total completed questionnaires
Conceptual design	18
Detailed design	27
Production	17
In-service	17
Total	**79**

Of the 79 respondents a wide range of job titles were reported. In general, these covered technical professions with a range of engineers returning completed questionnaires. However, a number of project focused individuals also completed these questionnaires. To provide an overview of the job titles of the individuals who completed the questionnaires, Table 38 is presented.

Table 38 - Respondent job titles

Product lifecycle phase	Job titles
Conceptual design	Product manager; Steam turbine design engineer; FLC / FPC Ship design lead; Marine engineer; Principal design engineer; Chief engineer; Engineering manager – Systems; Mechanical design engineer; Estimating executive; Design manager; Mechanical engineer; Senior engineer; Principal engineer; Programme manager; Electrical engineer; Senior outfit engineer; Principal naval architect;
Detailed design	Project lead engineer; Senior systems engineer; Systems engineer; Senior mechanical designer; Mechanical designer; Senior systems consultant; Electronic designer; Business systems engineer; consultant systems engineer; External auditor / advisor reviewing work of component supplier for OEM; High activity source store – Ukraine; Piping engineer; Marine product engineer; Structural engineer; Engineering product group leader; Chief engineer; ANONYMOUS; Project engineer; Project engineer; Design manager; Design engineer; Engineering Manager; Principle engineer structures; Lead engineer – Nuclear products; Senior engineer; Detailed designer; Detailed designer;
Production	Senior project engineer; Project engineer; Engineering operations group leader; Steelwork manager; Engineering manager; Naval architect; ANONYMOUS; Senior design engineer; Detail designer; Lead detail designer (structural); Principal engineer; Engineering change manager; Design manager; Design engineer; Principal engineer; Senior engineer – heavy handling; Engineer;
In-service	Senior engineer (safety); Project support manager; Senior engineer; Lead electrical systems engineer; Design engineer; Project manager; Head of engineering; Project engineer – Change control; Engineering change and planning manager; Requirements and acceptance manager; Design manager; Design engineer; Engineering manager; Principal engineer; Head of engineering; Mechanical systems engineer;

Finally, to establish the respondents' experience profile, the questionnaire enquired about the length of time that these individuals had worked within the engineering industry, in years. Segregating the responses into ten year categories within the different lifecycle stages, a distribution of experience has been established. The profile across the product lifecycle stages is presented in Figure 30.

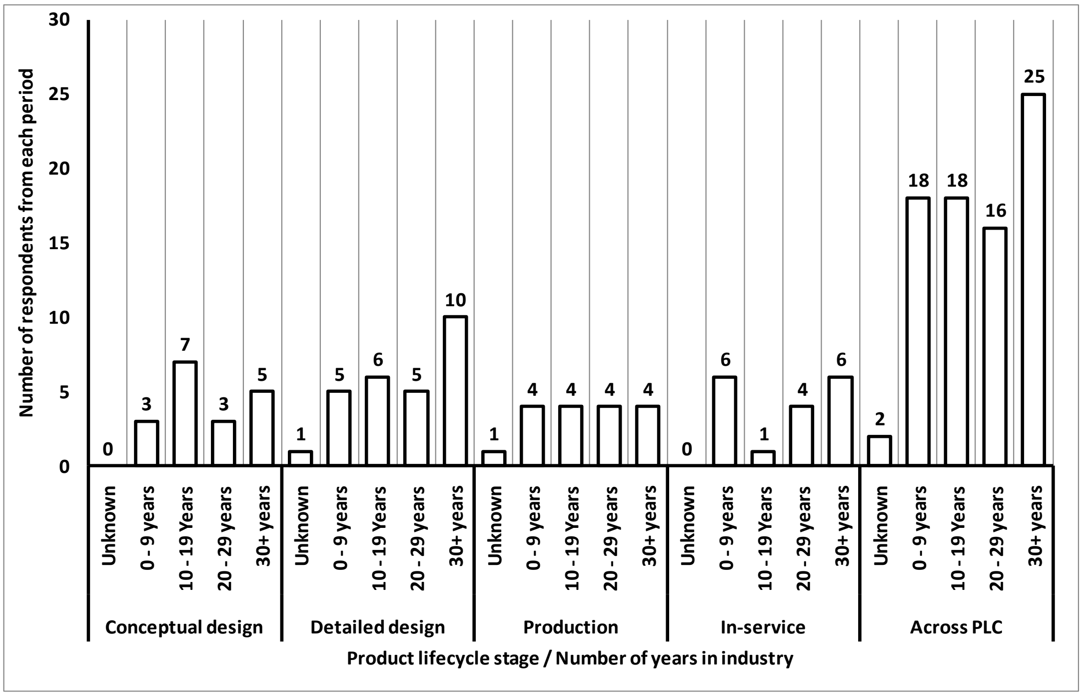


Figure 30 - Profile of respondents' industrial experience

8.2 Results

Aligned with the structure of the questionnaire the following section presents the results from the survey, offering an overview of the responses.

8.2.1 Activity enactment during the product lifecycle

Offering an overview of the percentage of respondents who indicated that an activity was never enacted at a specific product lifecycle stage, Table 39 is presented.

Table 39 - Percentage of respondents reporting that the activity was never enacted per product lifecycle stage

		Product lifecycle stage			
		Conceptual design	Detailed design	Production	In-service
Identification	Document	5.6%	0.0%	0.0%	11.1%
	Evaluate	5.6%	3.7%	0.0%	0.0%
	Realise	5.6%	0.0%	0.0%	0.0%
Generation	Document	5.6%	0.0%	0.0%	0.0%
	Model	5.6%	0.0%	0.0%	0.0%
	Select	5.6%	7.4%	0.0%	5.9%
	Structure	11.1%	0.0%	0.0%	0.0%
	Validate	11.1%	3.7%	0.0%	0.0%
Prediction	Analyse	5.6%	3.7%	0.0%	0.0%
	Compose	5.6%	3.7%	0.0%	0.0%
	Distribute	5.6%	0.0%	0.0%	0.0%
	Plan	5.6%	3.7%	5.9%	0.0%
	Test	11.1%	3.7%	5.9%	5.9%
Approval	Decide	11.1%	3.7%	5.9%	0.0%
Implementation	Ensure	22.2%	3.7%	0.0%	0.0%
	Instantiate	22.2%	3.7%	5.9%	0.0%
	Order	0.0%	0.0%	0.0%	0.0%

Based on the data received, it is evident that for each of the activities in each of the product lifecycle stages, over three quarters of respondents considered that these were enacted during the engineering change management process. However, variations across the product lifecycle were evident with a greater proportion of the respondents reporting that activities were never enacted during the conceptual design stage. In fact, only the act of ordering was reported to be enacted in all engineering change management processes during this stage. Similarly, in the detailed design stage, over half of the activities that compose the engineering change management process were reported to never be enacted by a portion of the respondents. On the other hand, in the production and in-service stages, over three quarters of the activities that compose the engineering change management process were reported to be enacted in each of the engineering change management processes.

In addition to the activities identified through the literature review and case study, the questionnaire presented the respondents with an opportunity to define any other activities that composed their engineering change management processes. From this section, a range of additional activities were reported: five from the identification phase, one from the generation phase, one from the prediction phase and four from the implementation phase (see Table 40).

Table 40 - Additional activities reported in survey

Engineering change management process phase	Activity	Product lifecycle stage			
		Conceptual design	Detailed design	Production	In-service
Identification	HAZOP (hazard and operability study)		X		
	HAZAN (hazard analysis)		X		
	safety related issues		X		
	Text supplemented with graphical results and diagrams		X		
	Client request				X
Generation	Technical query				X
Prediction	CDM coordination				X
Implementation	Embodiment of changes into drawings		X		
	Material orders		X		
	Planning updates		X		
	Build standard requests		X		

Within the identification the five additional activities that were reported were HAZOP, HAZAN, safety related issues, text supplemented with graphical results and diagrams and client request. Of these, safety related issues is not considered to be an activity, instead it is a reason for the initiation of the engineering change management process. Likewise, whilst a client request is an activity, this activity can be considered to be that of evaluation as the customer is has deemed that the current state of the engineering artefact does not meet the desired state and as such an engineering change is required. With HAZOPs and HAZANs, these represent formal mechanisms through which the engineered artefact is analysed from a safety perspective. In this instance, whilst the context is different to other acts of analysis, the forecasting of the impact of the change is considered to be a sub-category of the act of analysis and not engineering change management activities in their own right. However, based on the taxonomy presented in this thesis, supplementing the text provided through the act of documenting within the identification phase, with graphical results and diagrams does not appear to have been identified within the literature review or case study and can be considered to be a distinct activity.

Focussing on the generation phase, it is not known what the act of technical query refers to. The term technical query was also found within CS2 and represented a structured means through which the need to change was defined. However, it is unclear whether this is an activity in its own right and whether this belongs within the generation phase. Likewise, during the prediction phase, the term CDM coordination is reported, but not explained. Given the numerous acronyms of this nature, it is not possible to establish whether this is an activity in its own right or not.

During the implementation phase, four additional activities were offered: embodiment of changes into drawings, material orders, planning updates and building standard requests. The first and third of these activities (embodiment of changes into drawings and planning updates) appears to refer to the act of instantiation. In addition, the act of material orders appears to refer to the act of ordering. Finally, it is unclear what the act of building standard requests refers to and as such it existence within the engineering change management process cannot be considered. This lack of clarity is recognised as a weakness in the research methodology that is caused by the anonymity associated with the survey.

8.2.2 Artefact knowledge usage and creation

Offering an overview of the percentage of interviewees who indicated that a specific artefact knowledge type was either used or created through the enactment of the activities that compose the engineering change management process, Table 41 is presented.

Table 41 - Percentage of respondents reporting a specific artefact knowledge type usage or creation per activity

Artefact knowledge usage							Activities	Artefact knowledge creation						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
Identification phase														
60%	59%	55%	52%	58%	45%	45%	Documenting	25%	30%	27%	**22%**	**22%**	**21%**	25%
80%	**76%**	60%	**72%**	**71%**	59%	52%	Evaluating	25%	35%	37%	36%	25%	39%	28%
80%	**68%**	**71%**	63%	62%	53%	42%	Realising	41%	43%	42%	47%	32%	37%	32%
Generation phase														
60%	59%	55%	52%	58%	45%	45%	Documenting	**24%**	49%	48%	33%	27%	32%	28%
43%	48%	53%	59%	40%	25%	33%	Modelling	**23%**	37%	45%	59%	27%	28%	25%
64%	61%	53%	54%	56%	51%	56%	Selecting	**11%**	**17%**	28%	**24%**	**17%**	**14%**	**15%**
68%	65%	45%	53%	57%	48%	45%	Structuring	27%	37%	48%	49%	36%	41%	36%
57%	54%	44%	47%	53%	47%	49%	Validating	**13%**	**21%**	**19%**	**24%**	**18%**	**17%**	**21%**
Prediction phase														
63%	52%	47%	44%	44%	41%	44%	Analysing	27%	34%	32%	36%	33%	34%	32%
48%	38%	52%	52%	49%	43%	48%	Composing	**20%**	**20%**	30%	33%	29%	39%	42%
44%	46%	46%	41%	39%	32%	35%	Distributing	**18%**	28%	32%	28%	25%	**20%**	25%
43%	49%	57%	52%	39%	32%	28%	Planning	**19%**	33%	32%	26%	**17%**	**20%**	**23%**
47%	50%	38%	47%	47%	40%	42%	Testing	28%	33%	27%	27%	25%	28%	32%
Approval phase														
71%	**69%**	67%	61%	63%	64%	56%	Authorising	27%	39%	44%	29%	39%	36%	39%
Implementation phase														
24%	31%	38%	34%	31%	32%	31%	Ensuring	**15%**	**20%**	**23%**	**21%**	**20%**	**18%**	**23%**
36%	39%	47%	46%	39%	29%	36%	Instantiating	**21%**	28%	36%	47%	32%	26%	29%
25%	33%	33%	48%	25%	**22%**	25%	Ordering	**17%**	29%	**24%**	30%	**21%**	30%	**22%**

Based on results from the survey, each type of artefact knowledge was reported to be used during the enactment of each engineering change management process activity by between 22% and 88% of respondents. In addition, each type of artefact knowledge was reported to be created through the enactment of each engineering change management process activity by between 11% and 59% of respondents. With such a significant relationship between artefact knowledge and the activities that compose the engineering change management process, standard deviation has been used as a mechanism to establish the most scientifically significant relationships. As such, in Table 41, the relationships that are within the second standard deviation are highlighted, with those cells containing a grey background and white font demonstrating a comparatively strong relationship whilst those with a grey background demonstrating a comparatively weak relationship. In total, nine strong relationships have been identified and forty weak relationships have been identified.

8.2.3 Engineering change management activity enactment frequency

Applying the method of calculation described in chapter 4, the activity enactment frequency for the activities that compose the engineering change management process was calculated from the returned questionnaires and is presented is the following subsections. For a breakdown of the responses and method through which this calculation has been executed please refer to Appendix C.

8.2.3.1 Identification

Within the identification phase, three activities exist: documenting, evaluating and realising. The enactment frequency of these activities has been calculated based upon an analysis of the returned questionnaires. As such, the enactment frequency for these three activities throughout the product lifecycle is presented in Figure 31.

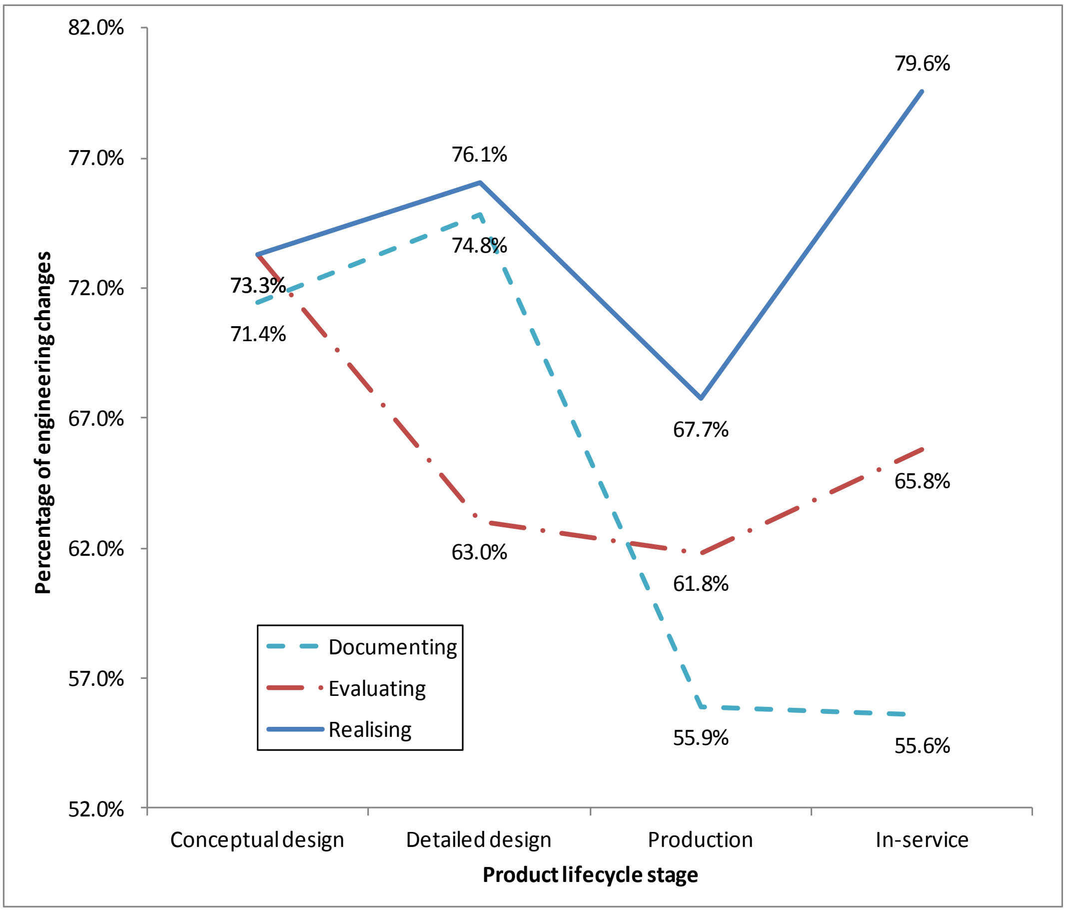


Figure 31 - Overview of activity enactment during the identification phase

Based on Figure 31, the act of documenting in the identification phase was found to be enacted for approximately three quarters of all engineering changes experienced during the conceptual and detailed design stages. However, this reduces to just over half of all engineering changes being documented in terms of why the change is necessary during the production and in-service stages.

The act of evaluating was found to be most prevalent in the conceptual design stage. However, whilst it was found to be less prevalent during the detailed design, production and in-service stages, the enactment frequency is relatively stable within these phases with approximately two thirds of all engineering changes undergoing this act.

The act of realising was found to be most prevalent in the in-service stage of the product lifecycle, enacted in the processing of approximately four fifths of all engineering changes experienced. By comparison, this activity was found to be enacted the least in the detailed design stage. During the detailed design and the conceptual design stage, this act was found to be enacted for approximately three quarters of all engineering changes experienced. In addition, the act of realising was found to be the most frequently enacted activity in all stages of the product lifecycle during the identification phase of the engineering change management process.

8.2.3.2 Generation

Within the generation phase, five activities exist: documenting, modelling, selecting, structuring and validating. The enactment frequency of these activities has been calculated based upon an analysis of the returned questionnaires. As such, the enactment frequency for these five activities throughout the product lifecycle is presented in Figure 32.

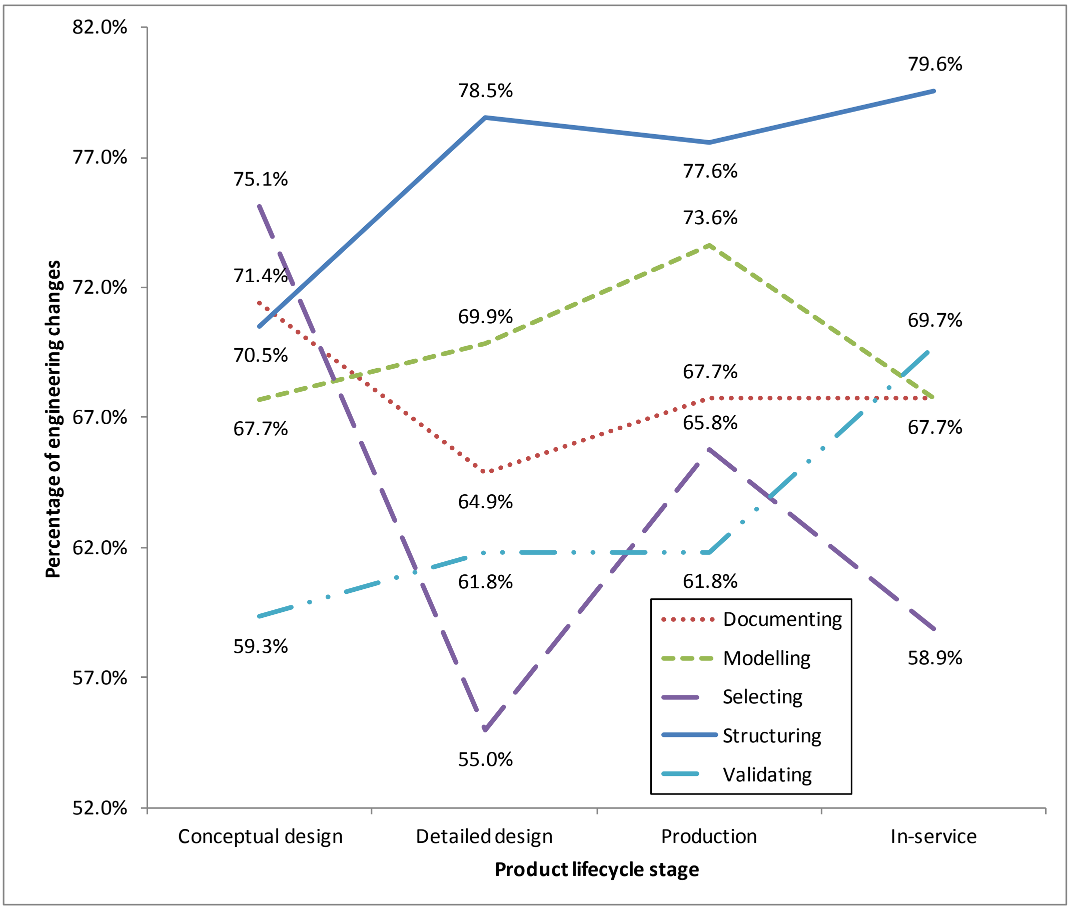


Figure 32 - Overview of activity enactment during the generation phase

The act of documenting during the generation phase was found to be enacted for a similar proportion of engineering changes during each of the stages of the product lifecycle: for about two thirds of all engineering changes experienced. Nevertheless, a small peak was evident within the conceptual design phase and a small trough in the detailed design stage.

The act of modelling was found to increase in relative frequency from the conceptual design stage to the production stage. However, this was then found to reduce during the in-service stage to similar levels as during the conceptual design stage.

The act of selecting was found to be more prevalent in the conceptual design stage than any other of the stages of the product lifecycle. Enacted in the processing of approximately three quarters of all engineering changes, this act was found to be the most frequently enacted activity within the generation phase of the engineering change management process during the conceptual stage of the product lifecycle. Further, this was least evident in the detailed design stage and in-service stages, enacted for just over half of all engineering changes, whilst during the production stage this was enacted by approximately two thirds of all engineering changes experienced.

The act of structuring was found to be least frequently enacted during the conceptual design stage. The enactment frequency was however found to increase as the product lifecycle progressed with approximately four fifths of all engineering changes undergoing the act of structuring during the in-service stage of the product lifecycle. However, a minor reduction of enactment frequency was found in the production stage. Nevertheless, the act of structuring was found the most frequently enacted activity within the engineering change management process during the detailed design, production and in-service stages of the product lifecycle within the generation phase of the engineering change management process.

The act of validating was also found to be least frequently enacted during the conceptual design stage. Further, whilst the enactment frequency was found to be the same during the detailed design and production stages, the enactment of this activity was generally found to increase as the product life progressed. As such, approximately 70% of all engineering changes underwent validation activities within the in-service stage of the product lifecycle.

8.2.3.3 Prediction

Within the prediction phase, five activities exist: analysing, composing, distributing, planning and testing. The enactment frequency of these activities has been calculated based upon an analysis of the returned questionnaires. As such, the enactment frequency for these five activities throughout the product lifecycle is presented in Figure 33.

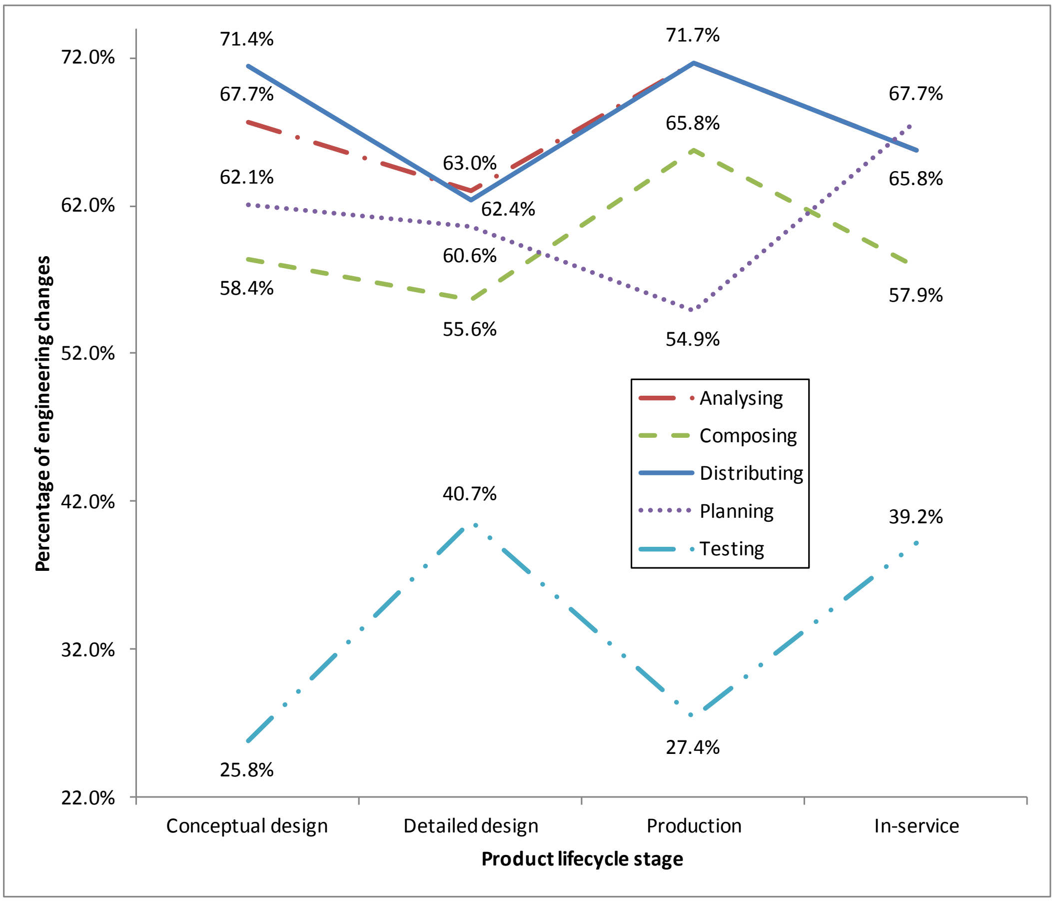


Figure 33 - Overview of activity enactment during the prediction phase

The act of analysing was found to be enacted at a relatively stable rate throughout the product lifecycle. As such, throughout each of the stages whilst minor variations were found, this act was found to be enacted for approximately two thirds of all engineering changes experienced. This enactment frequency was found to be the greatest throughout the prediction phase of the engineering change management process during the detailed design and production stages of the product lifecycle.

The act of composing was found to be enacted comparatively less frequently than the act of analysing in each of the product lifecycle stages. This was found to be enacted for just over half of all engineering changes within the conceptual design, detailed design and in-service stages. However, during the production stage, this frequency increased with the act of composing being enacted during the processing of approximately two thirds of all engineering changes experienced.

The act of distributing was also found to be enacted at a relatively stable rate throughout the product lifecycle, with approximately two thirds of all engineering changes experiencing this activity during their processing. However, whilst the profile of activity enactment broadly reflects that of the act of analysing, comparatively this activity is enacted more frequently within the conceptual design stage and less within the detailed design stage. As such, the act of distributing is the most frequently enacted activity during the conceptual design stage and equally the most frequently enacted activity during the production stage.

The act of planning was found to decrease in enactment frequency from the conceptual design stage to the production stage, with just over half of all engineering changes undergoing planning during the production stage. However, over two thirds of all engineering changes were found to be enacted during the in-service stage of the product lifecycle. As such, the act of planning was found to be the most frequently enacted activity that composed the prediction phase of the engineering change management process during the in-service stage of the product lifecycle.

Whilst the acts of analysing, composing, distributing and planning were found to be enacted in the processing of between approximately half and two thirds of all engineering changes throughout the product lifecycle, the act of testing was enacted significantly less frequently. This was evident as only a quarter of engineering changes were found to undergo testing activities within the conceptual design and production stages, and just over a third during the detailed design and in-service stages.

8.2.3.4 Approval

Within the approval phase, one activity exists: authorising. The enactment frequency of these activities has been calculated based upon an analysis of the returned questionnaires. As such, the enactment frequency for this activity throughout the product lifecycle is presented in Figure 34.

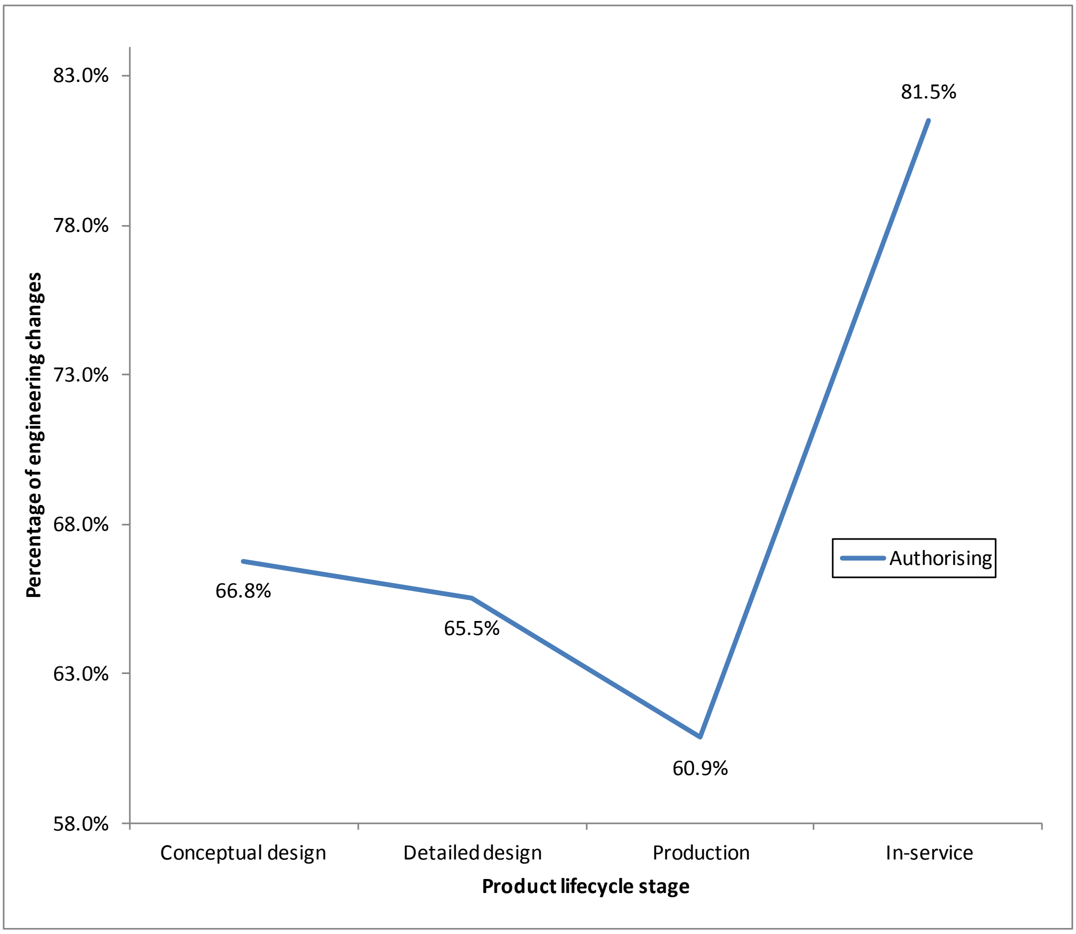


Figure 34 - Overview of activity enactment during the approval phase

From Figure 34 it is evident that the act of authorising is enacted for the majority of engineering changes that occur throughout that product lifecycle. This is enacted for approximately two thirds of all engineering changes during the conceptual design and detailed design stages. However, in the in-service stage the act of authorising shows a significant increase, being enacted in just over four fifths of all engineering changes experienced. Conversely, this activity was reported to be only enacted for approximately 60% of engineering changes in the production stage.

8.2.3.5 Implementation

Within the implementation phase, three activities exist: ensuring, instantiating and ordering. The enactment frequency of these activities has been calculated based upon an analysis of the returned questionnaires. As such, the enactment frequency for these three activities throughout the product lifecycle is presented in Figure 35.

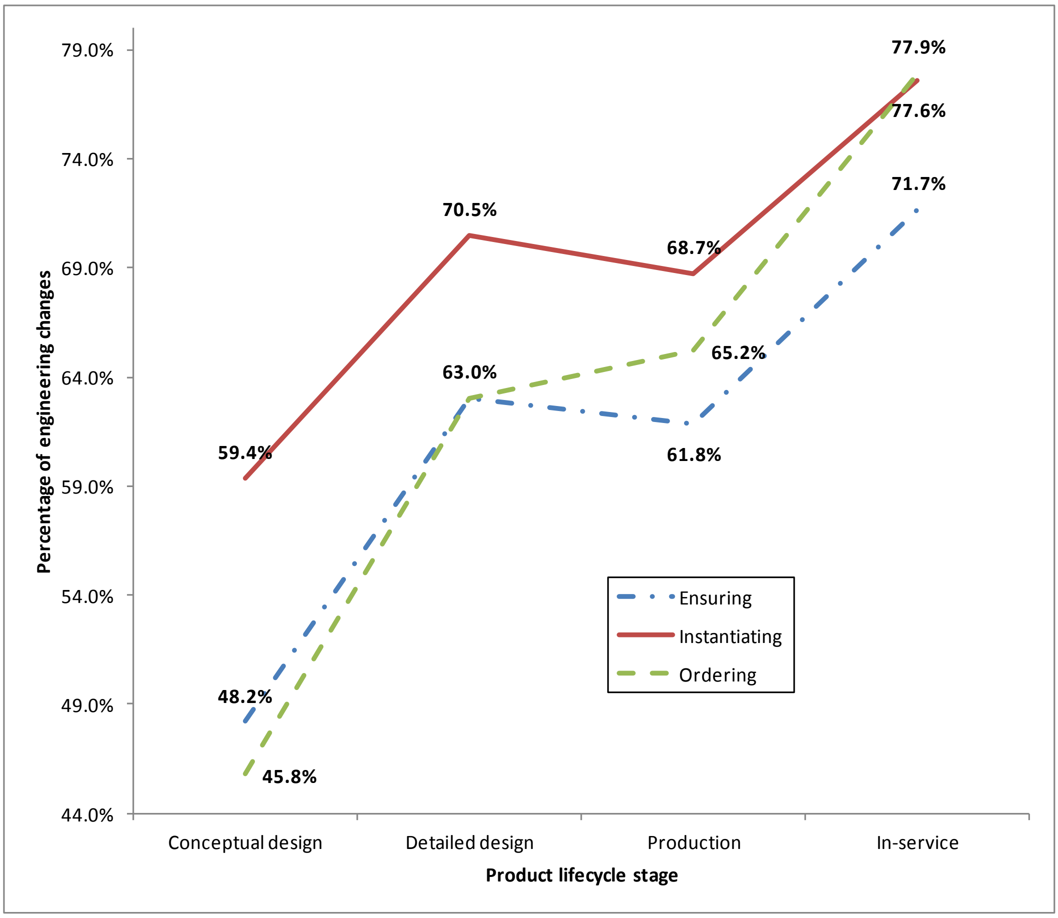


Figure 35 - Overview of activity enactment during the implementation phase

As a general observation, during the implementation stage, the enactment frequency of each of the activities that compose this phase increase as the product lifecycle progresses. However, whilst the acts of instantiating and ensuring broadly reflect this observation, during production fewer engineering changes are enacted in this stage than the detailed design stage. As such, the act of ensuring increases from under half of all engineering changes during the conceptual design stage to just over two thirds in the in-service stage. The act of instantiating is enacted during the processing of over half of all engineering changes in the conceptual design stage and in the processing of just under four fifths of all engineering changes in the in-service stage. Finally, the act of ordering is enacted in the processing of less than half of the engineering changes during the conceptual design stage, increasing to be enacted in the processing of just under four fifths of all engineering changes in the in-service stage.

8.2.4 Engineering change management process formality

An overview of the formality associated with the engineering change management process at different stages of the product lifecycle is presented in Figure 36. Offering an insight into the process formality, the questionnaire enquired as to whether a formal process for managing engineering change existed for the case upon which the questionnaire was completed. It then proceeded to enquire whether all engineering changes were managed through this process in the same manner.

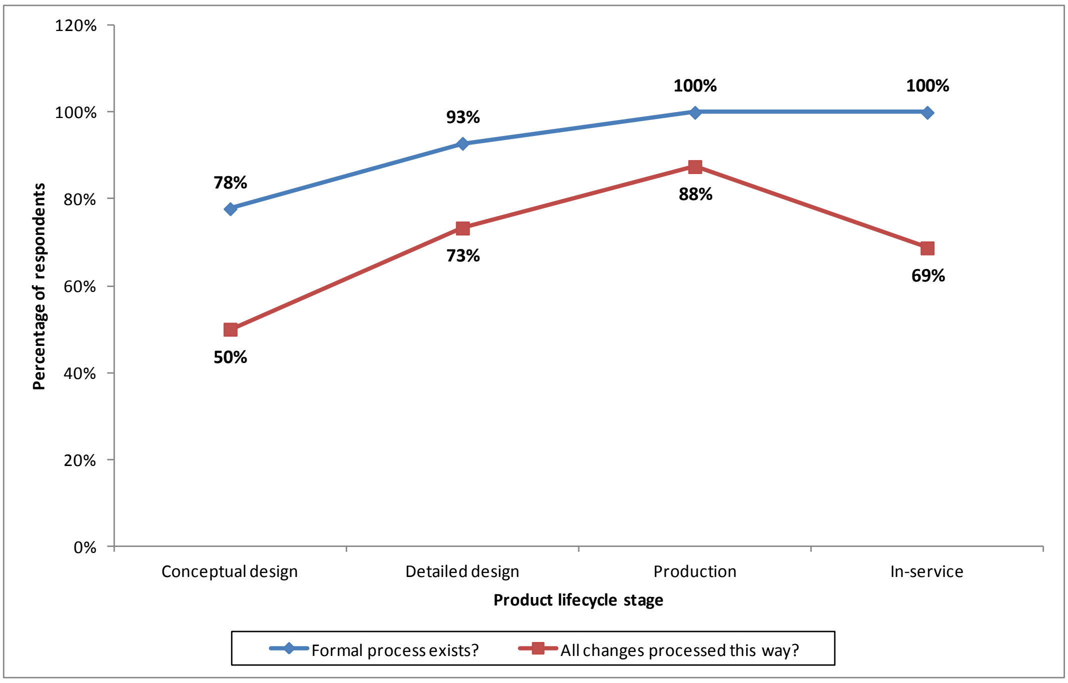


Figure 36 - Process formality overview

Based on the results, it is evident that formal processes for the management of engineering change exist throughout the product lifecycle. However, as opposed to during production and in-service stages, formal processes are not evident in all engineering change management processes during the conceptual and detailed design stages of the product lifecycle. In addition, the number of respondents who considered that all changes were managed through this formal process in the same manner peaked at 88% in the production stage. By comparison, fewer respondents considered that all engineering changes were managed through this formal process in the detailed design (73%) and in-service (69%) stages. Further, only half of all the respondents within the conceptual design stage reported that all changes were managed through the formal engineering change management process.

8.2.5 Engineering change management process goals

In addition to the formality of the engineering change management process, the respondents were also asked to rank the goal of the engineering change management process, based on three goals that emerged from the case study: accuracy of impact assessment, development of optimum technical solution and speed of implementation. As such, the percentage of individuals who stated that a specific goal was the most, second most and least important is presented in Table 42.

Table 42 - Relative importance of engineering change management process goals

Priority	Product lifecycle stage	Process goal		
		Accuracy of impact assessment	Development of optimum technical solution	Speed of implementation
1st	**Conceptual design**	38%	37%	27%
	Detailed design	50%	40%	10%
	Production	47%	29%	24%
	In-service	44%	38%	19%
	Across PLC	44%	35%	20%
2nd	**Conceptual design**	37%	53%	11%
	Detailed design	35%	53%	12%
	Production	38%	50%	13%
	In-service	20%	20%	60%
	Across PLC	33%	45%	22%
3rd	**Conceptual design**	12%	0%	88%
	Detailed design	7%	0%	93%
	Production	13%	20%	67%
	In-service	36%	43%	21%
	Across PLC	17%	15%	68%

As demonstrated by Table 42, the importance of the offered goals for the engineering change management process is broadly similar across the conceptual design, detailed design and production stages of the product lifecycle. As such, the most important goal was reported to be the accuracy of the impact assessment followed by the development of an optimum technical solution before the speed of implementation. However, in the in-service stage whilst the most important goal was said to be the accuracy of impact assessment, the second most important goal was the speed of implementation with the development of the optimum technical solution being the least important. Further, the percentage of respondents that considered the importance of specific goals during each of the product lifecycle stages was found to vary.

8.3 Chapter summary

This chapter has reported the findings of the survey that was executed gain an insight into the research questions based on a survey of the wider engineering community. Commencing with an overview of the responses, the survey was based upon 79 respondents and a response rate of 29%. In the following sections, the chapter proceeded to outline the results from the survey. Starting with activity enactment, this chapter reported that all seventeen activities were found to be enacted during the engineering change management process throughout the product lifecycle. However, the enactment frequency was found to be variable with different frequencies being apparent at different stages of the product lifecycle. Moving on, the following section outlined the importance of artefact knowledge during the engineering change management process, demonstrating that each type of artefact knowledge was both used and created during the engineering change management process. The formality of the engineering change management process was then reported, outlining that formal processes do not exist for all projects within the conceptual design stage and that within the latter stages of the product lifecycle all engineering changes follow the same process, with the exception of the in-service stage. Finally, the goals associated with the engineering change management process were presented. This was demonstrated to be the same in the conceptual design, detailed design and production stages. However, during the in-service stage the goals were demonstrated to have a different priority.

Given that the results from the case study and survey have been presented, the following chapter triangulates the results and phrases these in such a manner as to provide as to align with the research questions.

Chapter 9 - TRIANGULATED RESEARCH FINDINGS

In the previous three chapters, the results from the case study and survey have been reported. Building upon these, this chapter presents a triangulation of these results, cross referencing the findings from these data sources. However, this chapter does not propose an answer to the research questions per se, instead it presents a triangulation of findings from both the case study and survey in such a manner that an answer can be discussed in the following chapter. To achieve this, this chapter commences, in section 9.1, by triangulating the findings from the review of activity enactment during the product lifecycle. Then, in section 9.2, artefact knowledge usage and creation through the enactment of these activities is discussed. Based on the triangulation presented in sections 9.1 and 9.2, the insights that have emerged through the case study and survey are then discussed in section 9.3, outlining the primary findings from this research work. Bringing together all the findings from the research, section 9.4 presents two process models of engineering change management highlighting how the findings relate to one another. Finally, in section 9.5 this chapter is summarised.

9.1 Activity enactment during the product lifecycle

Based on a review of current literature, a five phase model of engineering change has been synthesised (see chapter 2), composing a total of twelve distinct activities. Subsequently, through the case study and survey the existence of these phases and activities was examined at different stages of the product lifecycle. Focussing first on the case study, it was found that in each of the reviewed cases, the five phase model of engineering change was adhered to, with at least one activity being enacted from each phase. Further, a total of fifteen activities were identified from the case study with two of the activities (structuring and modelling) representing a decomposition of one of the activities identified from the case study (solution development). In addition, two activities that were identified from literature (planning and testing) were not identified in the case study, whilst four activities (evaluating, validating, distributing and ordering) were identified in the case study but not identified in literature.

Focussing on the individual cases, the enactment of activities that composed the engineering change management process was found to vary from case to case. From this it was identified that seven activities were enacted in each of the three cases, a further eight activities were enacted in one or two of the cases and two activities reported in literature were not identified in any of the cases. As such, only the acts of documenting (identification phase), realising, documenting (generation phase), structuring, analysing, deciding, and instantiating were found to be enacted during each stage of the product lifecycle based on the case study. In comparison, the results from the survey demonstrated a far greater number of activities that were enacted at different stages of the product lifecycle. In fact, all of the seventeen activities that were included on the questionnaire were reported as being enacted during each stage of the product lifecycle at least three quarters of the respondents.

Triangulating the results from literature, the case study and the survey a total of eleven activities were identified as being enacted during the engineering change management process across all the data sources (see Table 43). Of the seventeen activities, seven of these were found to correlate based on their activity enactment during the product lifecycle in both the case study and survey.

Table 43 - Activity enactment: data source triangulation

		Activity identified in				Activity enactment across the product lifecycle		
		Literature	Case study	Survey	Correlation	Case study	Survey	Correlation
Identification	Documenting	✓	✓	✓	✓	✓	✓	✓
	Evaluating	X	✓	✓	X	X	✓	X
	Realising	✓	✓	✓	✓	✓	✓	✓
Generation	Documenting	✓	✓	✓	✓	✓	✓	✓
	Modelling	✓	✓	✓	✓	X	✓	X
	Selecting	✓	✓	✓	✓	X	✓	X
	Structuring	✓	✓	✓	✓	✓	✓	✓
	Validating	X	✓	✓	X	X	✓	X
Prediction	Analysing	✓	✓	✓	✓	✓	✓	✓
	Composing	✓	✓	✓	✓	X	✓	X
	Distributing	X	✓	✓	X	X	✓	X
	Planning	✓	X	✓	X	X	✓	X
	Testing	✓	X	✓	X	X	✓	X
Approval	Authorising	✓	✓	✓	✓	✓	✓	✓
Implementation	Ensuring	✓	✓	✓	✓	X	✓	X
	Instantiating	✓	✓	✓	✓	✓	✓	✓
	Ordering	X	✓	✓	X	X	✓	X
Total		**13**	**15**	**17**	**11**	**7**	**17**	**7**

In parallel to the enactment of the activities that compose the engineering change management process during the product lifecycle, variations in the enactment of these activities were also evident. As such, in the following sections the variations in the activities that compose each phase of the engineering change management process are offered based on a triangulation of the case study and survey data.

9.1.1 Identification

From the case study, survey and literature review, a total of three activities were found to compose the identification phase: documenting, evaluating and realising.

Documenting

This activity was evident within each of the cases in the case study; however, only during CS2 was this act a requirement for all engineering changes. Demonstrating some correlation with this finding, this act was most prevalent within the conceptual and detailed design stages.

Evaluating

The act of evaluating was only identified in CS1 and CS2 from the case study. By comparison, based on the survey the act of evaluating was evident throughout the product lifecycle. From this, a greater proportion of engineering changes were reported to undergo evaluation during the conceptual design stage than during the detailed design, production and in-service stages.

Realising

The act of realising was evident in all three cases in the case study. This was also established in the survey, with this activity being reported to be enacted by between two thirds and four fifths of all engineering changes experienced throughout the product lifecycle. However, the case study failed to identify that, in general, the enactment frequency of realising increased as the product lifecycle progressed.

9.1.2 Generation

From the case study, survey and literature review, a total of five activities were found to compose the generation phase: documenting, modelling, selecting, structuring and validating.

Documenting

From the case study, this act was evident in all three cases. However, only during CS2 was this required to be enacted for all engineering changes. The enactment of this act throughout the product lifecycle was reflected in the findings from the survey but the increased enactment reported in the case study was not found in the survey. Instead a relatively stable rate of enactment was found, with a small peak evident in the conceptual design stage.

Modelling

The act of modelling was reported to be enacted in CS2 and CS3 only. This finding is broadly reflected in the results from the survey as the greatest proportion of engineering changes were reported to undergo modelling in the detailed design and production stages. However, contrary to the findings from the case study, almost two thirds of all engineering changes processed during the conceptual design were reported to undergo modelling.

Selecting

The act of selecting was only reported in CS1. This finding is broadly reflected in the survey, with the act of selecting being enacted significantly more frequently during the engineering change management process in the conceptual design stage. However, this activity was also evident in the remaining three phases of the product lifecycle, with an increased frequency of enactment during the production stage.

Structuring

The act of structuring was evident in all three cases in the case study. From the survey, the enactment of this activity in each stage of the product lifecycle was also evident. However, this activity was reported to not be enacted during the processing of all engineering changes, conflicting with the findings from the case study. Nevertheless, of the seventeen activities that formed the focus of the engineering change management process, the act of structuring was found to be the most frequently enacted across the product lifecycle with over three quarters of all engineering changes being reported to experience this activity.

Validating

The act of validating was only evident in CS2 and CS3. Again, the findings from the case study are broadly reflected in the findings from the survey with this activity being enacted for approximately two thirds of all engineering changes experienced. However, contrary to the findings from the case study, this activity was found to be enacted in almost 60% of all engineering changes processed during the conceptual design stage. Nevertheless, as this activity was enacted least frequently during the conceptual design stage of the product lifecycle.

9.1.3 Prediction

From the case study, survey and literature review, a total of five activities were found to compose the prediction phase: analysing, composing, distributing, planning and testing.

Analysing

The act of analysing was evident in all three cases in the case study. The enactment of the act of analysing is also evident in the survey throughout the product lifecycle. This was found to be enacted at a relatively stable rate throughout the product lifecycle.

Composing

The act of composing was evident in CS2 only. By comparison, the findings from the survey demonstrated that this act was evident throughout the product lifecycle. However, this activity was most frequency enacted during the production stage of the product lifecycle, broadly reflecting the findings from the case study.

Distributing

The act of distributing was identified in CS1 and CS2, but not in CS3. Contrary to the findings from the case study, from the survey the act of distributing is evident throughout the product lifecycle, being the most frequently enacted during the conceptual design and production stages.

Testing

The act of testing was not evident in any of the cases in the case study. Conversely, based on the findings from the survey, this activity was reported to be enacted during each of the stages of the product lifecycle. However, this activity was found to be the least frequently enacted activity during each stage of the product lifecycle and the least frequently enacted across the whole product lifecycle.

Planning

The act of planning was not evident in any of the cases in the case study. Conversely, based on the findings from the survey, this act was found to be enacted at a similar rate across the product lifecycle.

9.1.4 Approval

From the case study, survey and literature review, only one activity was found to compose the prediction phase: authorising.

Authorising

The act of authorising was evident in all three cases in the case study. Reflecting this, the act of authorising was found to be enacted throughout the product lifecycle in the survey. Of note, the enactment frequency was found to be relatively similar during the conceptual design, detailed design and in-service stages, with around two thirds of all engineering changes experiencing this act during their processing. However, in the in-service stage this frequency was far greater, at over 80%.

9.1.5 Implementation

From the case study, survey and literature review, a total of three activities were found to compose the implementation phase: ensuring, instantiating and ordering.

Ensuring

The act of ensuring was evident in CS2 only. However, based on the findings from the survey, the act of ensuring was evident throughout the product lifecycle with an increasing enactment frequency as the product lifecycle progressed.

Instantiating

The act of instantiating was evident in all three cases in the case study. The enactment of instantiating was also evident throughout the product lifecycle in findings from the survey, with an increased frequency in the latter stages of the product lifecycle. However, this variation in enactment frequency was not evident in the case study.

Ordering

The act of ordering was only evident in CS3. This finding does not appear to immediately correlate with the survey, as ordering was found to be enacted throughout the product lifecycle. However, this activity was found to be enacted more frequently as the product lifecycle progressed, broadly reflecting the findings from the case study.

9.2 Artefact knowledge usage and creation

Based on a review of literature, a total of fifteen relationships between artefact knowledge and the engineering change management process were established (see chapter 3). These relationships were based upon six activities and seven types of artefact knowledge being either used or created. Focussing first on the case study, an increased number of relationships between artefact knowledge and the activities that compose the engineering change management process was established. As such, eleven activities were identified as using artefact knowledge whilst five activities were identified as creating artefact knowledge. Whilst the profile of artefact knowledge usage was found to vary for each activity, expected function, expected behaviour, expected structure, instantiated structure and instantiated behaviour were all reported as being used by one or more of these activities. In addition, whilst the profiles of artefact knowledge creation varied across the activities, expected behaviour, expected structure, instantiated structure and interpreted behaviour were identified as being created by one or more of these activities. As such, a total of twenty six relationships between artefact knowledge and the activities that compose the engineering change management process were reported.

In contrast to the findings from the case study and literature review, the results from the survey demonstrated that each type of artefact knowledge was used and created by each of the activities that compose the engineering change management process. However, the percentage of respondents that stated that they either used or created a specific type of artefact knowledge through the enactment of an activity varied from 11% to 80%, leading to the conclusion that not all types of artefact knowledge are used or created through the enactment of each activity. To establish the most statistically significant relationships, the relationships that composed the second standard deviation were established, indicating the existence of nine strong relationships and forty weak relationships.

For clarity the relationships discussed above are depicted in Table 44. Those cells marked with an x represent a relationship identified from the case study, those with a dark border represent a relationship from the literature review, those with a grey background represent a strong relationship from the survey and those with a hatched background represent a weak relationship from the survey.

Table 44 - Artefact knowledge usage and creation: data source triangulation

Artefact knowledge usage							Activities	Artefact knowledge creation						
Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function		Expected function	Expected behaviour	Expected structure	Instantiated structure	Instantiated behaviour	Interpreted behaviour	Interpreted function
							Identification phase							
			☐				Documenting				▨	▨	▨	
■ x	■ x	x	■ x	■ x			Evaluating							
■	■	■	x	x			Realising						x	
							Generation phase							
			☐				Documenting	▨						
		x					Modelling	▨			x			
		x					Selecting	▨	▨		▨	▨	▨	▨
x			x	x			Structuring				x			
			x				Validating	▨	▨	▨	▨	▨	▨	▨
							Prediction phase							
☐ x	☐	☐ x	☐ x				Analysing	☐	☐ x	☐ x				
							Composing	▨	▨					
		x					Distributing	▨					▨	
							Planning	▨				▨	▨	▨
	☐						Testing					☐		
							Approval phase							
■	■ x						Authorising							
							Implementation phase							
▨							Ensuring	▨	▨	▨	▨	▨	▨	▨
		☐ x	☐				Instantiating	▨			☐ x			
		x			▨		Ordering	▨		▨		▨		▨

KEY

☐	Relationship evident from literature review
x	Relationship evident from case study
■	Strong relationship evident from survey
▨	Weak relationship evident from survey

Triangulating the findings from the literature review, case study and survey demonstrates correlations between these different sources. In particular, of the twenty six relationships that were identified from the case study, five of these correlated with the nine strong relationships taken from the survey. However, of the fifteen relationships reported in literature, none of these were found to correlate with the strong relationships taken from the survey, whilst six of these correlated with the case study. Furthermore, none of the relationships identified from the case study, nor any of the relationships identified from the literature review correlated with any of the forty weak relationships found from the case study.

9.3 Emergent findings into the nature of engineering change management across the product lifecycle

Whilst the main motivation for this research has been to investigate engineering change management process activity enactment during the product lifecycle and establish what types of artefact knowledge are used and created engineering change management process, secondary findings, related to these have emerged during the research process. As such, the following section presents a triangulation of the findings from the case study and survey in regard to these insights.

9.3.1 Engineering change management process formality

As an emergent insight into engineering change management practice, the formality of the engineering change management process was found to vary across the product lifecycle based accounts offered by the interviewees taken during the case study: an observation also reported by Rouibah and Caskey (2003). In CS1, the engineering change management process was relatively informal, as whilst a recognised method existed for processing engineering changes was evident; a relatively low proportion of engineering changes actually followed this process. Nevertheless, in CS2 a recognised method for managing engineering changes was observed and each engineering change followed this process more frequently. Finally, in CS3 whilst again a recognised method for managing engineering changes existed, a lower proportion of changes followed this process than in CS3, but a higher proportion than in CS1.

Relating the cases to the stages of the product lifecycle, the findings from the case study were generally reflected in the findings from the survey. In the detailed design, production and in-service stages, the existence of a formal engineering change management process was reported by the 93%, 100% and 100% of the respondents respectively. However, within the conceptual design stage the majority (78%) of the respondents reported the existence of a formal engineering change management process. Nevertheless, whilst this does not correlate precisely with the findings from the case study, this reduction in the number of respondents reporting the existence of a formal engineering change in the conceptual design stage rather than the latter stages of the product lifecycle does support the claim that engineering change management is less formal in the early stages of the product lifecycle.

In addition, based on the case study, during the detailed design and production stages, all engineering changes were reported to be managed through the formal engineering change management process. However, within the conceptual design and in-service stages this was reported to not be the case, with engineering changes being processed on an ad hoc basis. Focussing on the findings from the survey, only a portion of engineering changes were found to follow the same formal process. This varied from 88% in the production phase to 50% in the conceptual design stage. As such, whilst all of the engineering changes were reported to be managed during the formal engineering change management process in the case study that covered the detailed design and production stage of the product lifecycle, a lesser proportion was found in the case study. The findings are summarised in Table 45.

Table 45 - Engineering change management process formality: data source triangulation

Product lifecycle stage	Existence of a formal engineering change management process?		All engineering changes follow same process?	
	Case study	Survey	Case study	Survey
Conceptual design	X	78%	X	50%
Detail design	✓	93%	✓	73%
Production		100%		88%
In-service	✓	100%	X	69%

9.3.2 Engineering change management goals

Finally, emerging through the case study, the engineering change management processes were found to be motivated by different factors in the different cases. As such, within CS1, the emphasis of the engineering change management process was on developing optimum solutions to overcome the need to change; within CS2 the focus was upon establishing the accuracy of the impact assessment whilst in CS3 the goal the focus was on the speed of implementation. Whilst these three goals are not necessarily mutually exclusive, during the different cases, different goals were reported as being more prominent. Relating the cases to stages in the product lifecycle, during the conceptual design stage the main focus of the process was on developing an optimal technical solution that satisfied the need to change most appropriately. During the detailed design and production stages this shifted to gaining the most accurate impact assessment of implementing the new solution and again in the in-service stage this shifted to implementing a solution as quickly as possible.

This emergent insight was subsequently tested during the survey. Contrary to the findings from the case study, based on the quantification of the results, each stage of the engineering product lifecycle was determined to have the same goal. Ensuring that the impact assessment was accurate was found to be the most important goal across each of the product lifecycle stages. However, during the detailed design and production stages, establishing the accuracy of the impact assessment was reported to be the most important goal by a greater percentage of respondents than during the conceptual design and in-service stages. This leads to conclusion that whilst accurately establishing the impact of an engineering change is the most important goal of the engineering change management process, the process is also influenced by additional process goals at different stages of the product lifecycle.

Table 46 - Process formality and goals: data source triangulation

Product lifecycle stage	Process goal	
	Case study	Survey
Conceptual design	Development of optimum technical solution	Accuracy of impact assessment (38%)
Detail design	Accuracy of impact assessment	Accuracy of impact assessment (50%)
Production		Accuracy of impact assessment (47%)
In-service	Speed of implementation	Accuracy of impact assessment (44%)

9.3.3 Design traceability

Rationalising how and why an engineered artefact has developed in a certain way during an engineering project is at the core of establishing a traceable design. The engineering change management process is closely related to this, with the recording of the need for change, the solution that has been put in place to overcome this need and the impact of the solution playing an important role. Storing this information for future reference therefore acts to reference to explain the design development and rationalise the current state of the engineered artefact.

In terms of the engineering change management process, three activities contribute to this reference. In particular, the acts of documenting within both the identification and generation phase and, to some extent, the act of collating within the prediction phase contributes to maintaining the traceability of the development of an engineered artefact. In previous discussions on these activities (see chapter 7), it was reported that the enactment of these activities depended on trade off between having a more traceable design and a process that takes less time and is less bureaucratic.

Reviewing the enactment frequency of these activities in both the case study and survey, it is evident that the result of this trade off has different outcomes at different stages of the product lifecycle. Given the increased frequency of these activities within the design stages of the product lifecycle, it can be concluded that a greater emphasis is placed on maintaining design traceability within the design stages. However, as the product lifecycle progresses, a lesser emphasis is placed on maintaining design traceability. Instead the engineering change management process is less well documented during these stages, leading to the development of an engineered artefact that is less traceable through the engineering change management process.

9.3.4 Verifying solution performance

The need to change from an existing to a new state fundamentally drives the initiation of the engineering change management process. As an activity within the prediction stage, the verification of the performance of the generated solution can ensure that correct impacts are predicted and that the new solution meets the requirements for the need to change. However, reviewing the enactment frequency of all of the activities within the engineering change management process, it is evident that this activity is the least frequently enacted (see section 9.1.3 for a discussion on the act of testing).

This lack of enactment demonstrates that solutions are typically implemented before they have undergone any form of verification. As such, it is only once the solution has been implemented that the true impact of the change can be determined. This means that as the result of the analysis activities, the output can only be considered to be an estimate of the impact. Therefore, any authorisation that is conducted upon this information must recognise this limitation; otherwise poor decisions could be made.

To verify the performance of a proposed solution, a trade off between the cost of conducting a test against the perceived benefit of conducting this test must be taken. This verification could range from conducting computer simulation to full scale prototype testing of discrete solutions, each with associated cost implications. It is clear from the survey that this is not frequently conducted during the type of engineered projects studied within this research project. This means that in the context of the analysed projects, the benefit of verifying the performance of the solution is outweighed by the cost of testing. However, there are peaks in enactment frequency during the detailed design and in-service stages suggesting that this activity is more frequently enacted within these stages. As such, during these stages, the performance of the generated solution is more likely to be verified.

9.3.5 Implementation likelihood

At the most basic level, the engineering change management process is concluded with one of two outcomes: either the generated solution is implemented or it is not. Based on the act of instantiation, it is evident that the likelihood that this implementation varies within the product lifecycle. As such, it can be concluded that a solution to an engineering change is more likely to be implemented as the product's lifecycle progresses. Conversely, this shows that a greater number of potential engineering changes are rejected during the design stages of a project. Likewise, focussing on the act of structuring, it is evident that solutions are more likely to be generated following the conceptual design stage. This indicates that potential problems or opportunities are less likely to be acted upon in the initial design stages of a product's lifecycle.

To rationalise this insight, it could be hypothesised that during the initial design stages, the problems and opportunities that are identified may not be as critical to overcome as those in the latter stages. As such, it is more likely that potential engineering changes would not be considered within the conceptual design stage. This would be a characteristic of a more reactive approach to engineering change management in which only when it becomes apparent that an engineering change is required does the engineering change management process commence.

9.4 Global model development

In the previous sections of this chapter, the findings from the case study and survey have been triangulated to outline the similarities and differences that have emerged. Building upon these, this section offers an integration of the findings within the thesis. This culminates in the presentation of a model that provides a global view of the research findings.

Based on the data collected throughout this research project, the nature of the relationship between artefact knowledge and the engineering change management process has become apparent. The usage and creation of artefact knowledge has been established as being required for all activities within this process. Building upon the findings outlined in Table 44, a process model has been developed that presents the activities enacted during the engineering change management process, the phases to which these activities belong and the possible process progression options (see Figure 37). This model also includes the relationships between the activities within the engineering change management process and the artefact knowledge types that are used and created during the enactment of these activities. For clarity, the darker coloured boxes represent activities and knowledge types that were found to demonstrate the most significant relationships.

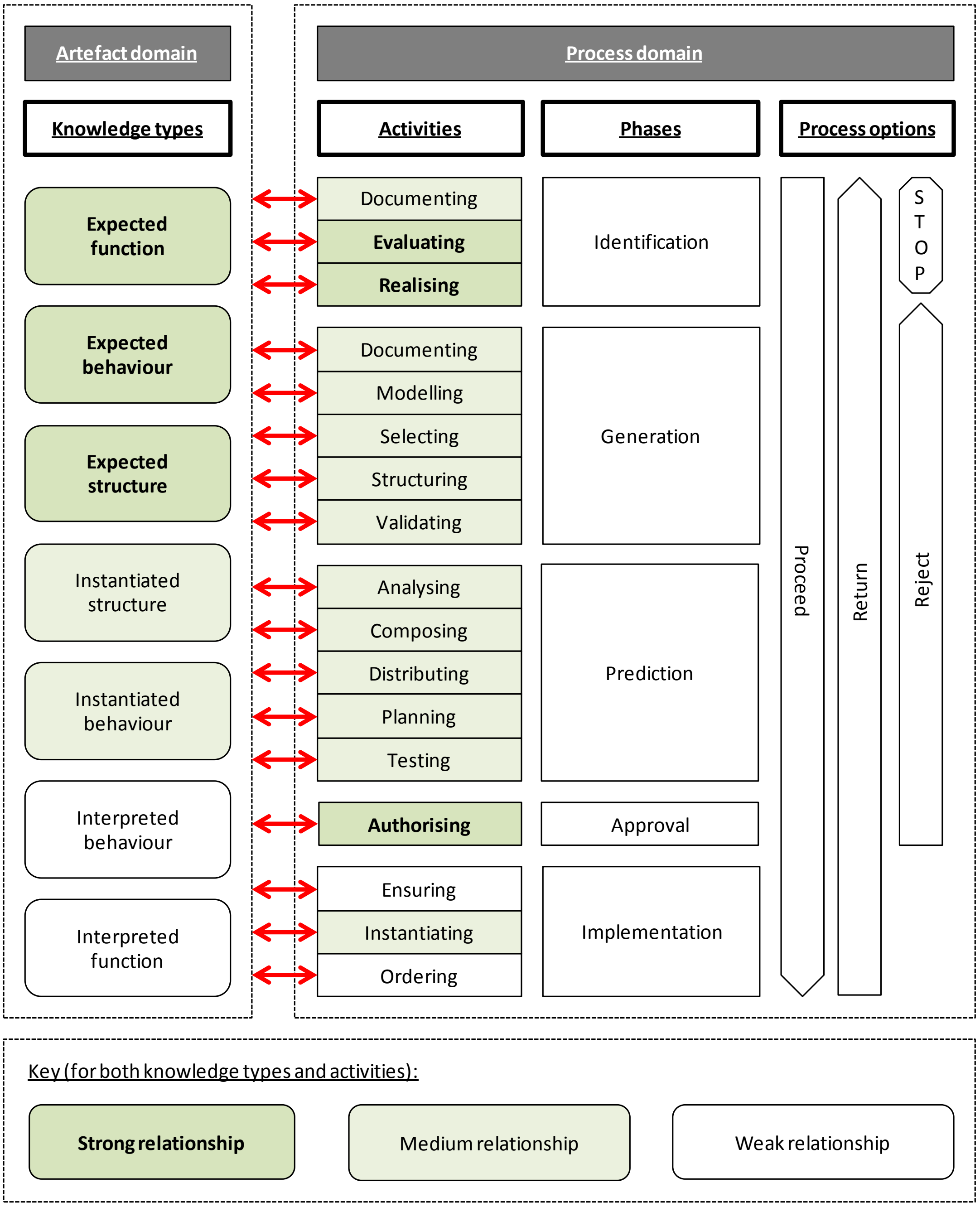


Figure 37 - The engineering change knowledge and process model

In Figure 37 it can be seen that each of the activities that compose the engineering change management process use and create artefact knowledge in some form, demonstrating the significance of this relationship between these. This model also highlights that the most frequently referenced artefact knowledge types are within the expected knowledge domain. Similarly, the activities that show the strongest relationship with artefact knowledge are that of evaluating, realising and authorising. Given this significant relationship, it can be concluded that it is important for engineering change practitioners to possess knowledge of the artefact's expected function, behaviour and structure throughout the engineering change management process. However, during the identification and approval phases, this requirement becomes even more pertinent. As such, particular emphasis should be placed on ensuring that the engineering change practitioners responsible for these phases possess such knowledge or that this knowledge is supported effectively within these phases.

Building upon this model, the research reported on in this thesis has also focussed on variations in the engineering change management process within the product lifecycle. To that end, this thesis has outlined eight characteristics that were found to vary within the product lifecycle: activity clarity, activity enactment frequency, design traceability, formality, goals, implementation likelihood, performance verification and process improvement initiatives. These variations are summarised in Figure 38 with the section of the thesis in which they are discussed being presented in brackets. As such, whilst from an activity perspective the process for managing engineering changes are fundamentally similar within the product lifecycle; eight additional characteristics of this process have been found to vary.

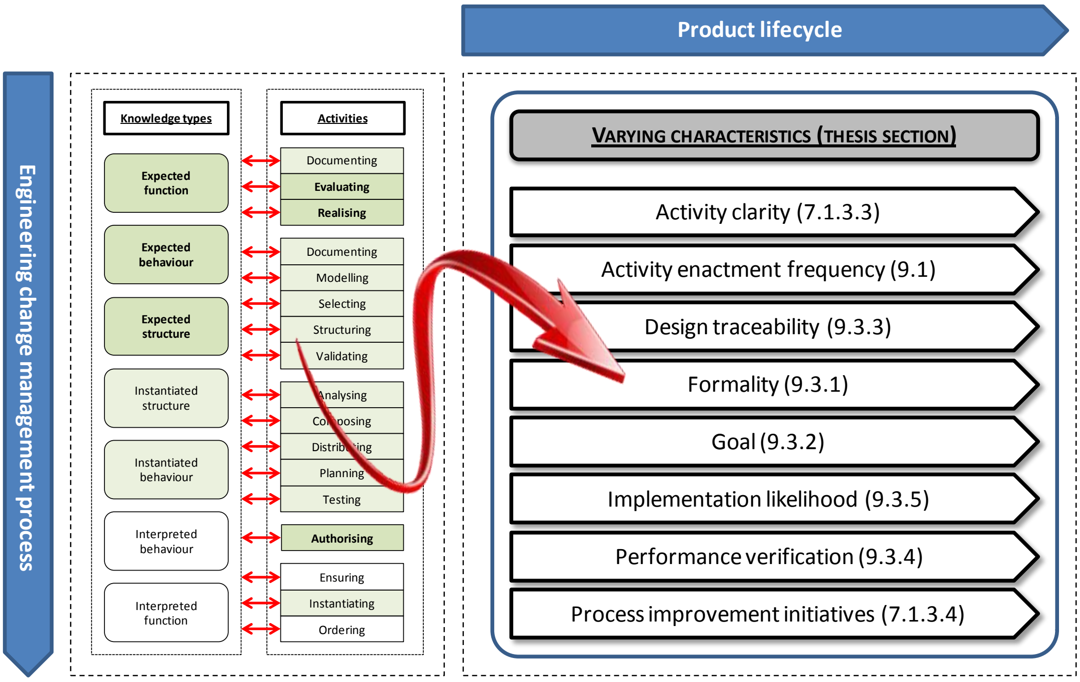


Figure 38 – Engineering change process lifecycle variations

9.5 Chapter summary

This chapter was prepared to present a triangulation of the findings from the various data sources. As such, the chapter commenced with the presentation of the enactment of engineering change management process activities during different stages of the product lifecycle. Based on a correlation between the case study and the survey, only seven of the seventeen activities were found to be enacted during each stage of the product lifecycle. Nevertheless, a number of findings from the case study and survey were found to correlate and were summarised in section 9.1.

Shifting attention to the usage and creation of artefact knowledge during the activities that compose the engineering change management process, correlations between the data sources were also presented. From this, a range of relationships have been identified between two of the three data sources; however, a clear correlation between all three is less apparent. Nevertheless, none of the forty weak relationships reported in the survey were found to couple with any of the relationships identified from literature or the case study demonstrating a degree of correlation.

The chapter then proceeded to present a discussion of the insights that have emerged from the case study and survey. In total, five insights were presented focussing on the formality of the engineering change management process; goal of the engineering change management process; design traceability; verification of solution performance and likelihood of implementation. Where appropriate, any influence that the stage of the product lifecycle had upon these was discussed.

Finally, integrating the findings reported on in this thesis into a concise view, two process models were presented. As such, the first focused on depicting the links between the engineering change management process and artefact knowledge, highlighting most significant relationships. The second proceeded to present the characteristics of the engineering change management process that varied within the product lifecycle, bringing together both avenues of research presented in this thesis.

Based on the findings reported above, the following chapter discusses the validity and reliability of these findings in light of the limitations associated with the research strategy and methodology.

Chapter 10 - DISCUSSION

The aim of this chapter is to both discuss the work that is contained within this thesis and offer an answer to the research questions. As such, this chapter has been separated into eight sections. In section 10.1, the main findings from this research work are presented. Aligning with the two research questions presented in chapter 4, the primary findings and knowledge contributions associated with answering these research questions are presented. Following this, in section 10.2, secondary contributions that have emerged through the research process are presented. In section 10.3 the validity and reliability of the findings are discussed, before the strengths and weakness of the research strategy and research methodology (sections 10.4 and 10.5 respectively) are presented. Lessons learnt from the research process and future work are then covered in sections 10.6 and 10.7, before the chapter is summarised in section 10.8.

10.1 Main findings and contributions

The main findings and contributions contained within this thesis are presented in the following four subsections. In section 10.1.1 a discussion of engineering change management process variations within the product lifecycle is presented. Following this in section 10.1.2, a discussion of the artefact knowledge that the activities use and create during the enactment of the activities that compose the engineering change management process is presented. Based on these findings, in section 10.1.3 recommendations for future engineering change management practice are offered before, in section 10.1.4,, an overview of the primary contributions that are contained within this thesis is presented.

10.1.1 Engineering change management process variations within the product lifecycle

Based on a literature review, case study and survey this thesis has challenged the paradigm that engineering change is limited to exist solely within the later stages of detailed design and production. Extending the currently limited definition for this type of change to permit existence within all phases between the conceptual and in-service stages of the product lifecycle, this thesis has demonstrated that engineering change can and does occur throughout the product lifecycle. Similarly, as it has been demonstrated that engineering changes can exist within these stages, it was also found that processes for the management of these changes exist within these stages too. Focussing on the engineering change management process, significant similarities were evident in the processes throughout the product lifecycle. However, the research reported on in this thesis has demonstrated that the enactment of activities that compose the engineering change management process vary at different stages of the product lifecycle. From this, insights into the enactment frequency, process formality, process goals, design traceability, verification of solution performance, activity clarity, process improvement initiatives and implementation likelihood have emerged.

Focussing on the activities that were enacted within the product lifecycle, a total of seventeen activities were found to compose the engineering change management process: five more than were identified from literature. Of these seventeen activities, the enactment frequency of these was found to vary throughout the product lifecycle. As such, certain activities were more prevalent in certain product lifecycle stages. This indicates that as the product is further developed, the engineering change management process is tailored to meet the requirements of the specific lifecycle stage. For example, the act of ordering was more prevalent in the latter stages of product development than in the early stages. Whilst the engineering change management process was known to vary from case to case, until now empirical evidence had not been presented to support the claim that the product lifecycle had any influence upon the enactment of the activities that compose this process.

Moreover, during the case study it was identified that the engineering change management process was a process that was tailored to achieve specific goals. From this, three goals were found to exist: ensuring the accuracy of impact assessment, development of optimum technical solution and speed of implementation. Subsequent analysis demonstrated that whilst these goals were not mutually exclusive, the most important goal throughout the product lifecycle was ensuring the accuracy of the impact assessment. However, a correlation with the product lifecycle stage was evident as fewer individuals were found to consider this as the most important goal during the conceptual design and in-service stages than the detailed design and production stages. To date little has been reported on in regard to the goals of the engineering change management process and the variations of these goals at different stages of the product lifecycle.

Further, the formality of the engineering change management process was also investigated. Based on an insight offered by Rouibah and Caskey (2003) the engineering change management process was described to be more formal during the latter stages of product development. The findings from this research broadly reflect this observation, as a formal engineering change management process was found to always exist within the detailed design and production stages of the product lifecycle. By comparison, only a proportion of engineering change management processes during the conceptual design and in-service stages had formal process. Further, across all four lifecycle stages, it was reported that not all changes were managed through the formal engineering change management process. Whilst comparatively fewer engineering changes followed this process in the conceptual design and in-service stages than the detailed design and production stages, it was reported that even within the detailed design and production stages, not all engineering change were processed through the formal engineering change management process.

Based on the enactment frequency of certain activities, three further insights into the engineering change management process were evident. Firstly, it was found that the enactment frequently of recording activities such as documenting within the identification and generation phases varied throughout the product lifecycle. Given that these activities are enacted to record the reason for the change and the proposed solution, this demonstrates that an increased emphasis was placed upon maintaining the traceability of the development of an engineered artefact within the design stages of a product lifecycle. Secondly, throughout the lifecycle it was found that generated solutions were not frequently verified prior to implementation. As such, the impact associated with an engineering change could vary from what was estimated from the act of analysis. However, from a lifecycle perspective, this verification was found to be more common during the detailed design and in-service stages. Finally, it was found that the likelihood of implementation varied at different stages of the product lifecycle. As such, it was more likely for an engineering change to be implemented during the latter stages of the product lifecycle.

The activity clarity and process improvement initiatives were also found to vary within the product lifecycle. Within the conceptual design stage in particular, as the processes were less formal and the teams smaller, it was not obvious to define the boundaries between different activities. Single individuals could enact multiple activities without clear distinction between these. This is in comparison with the detailed design and production stages in which, due to an increased formality, the differentiation between activities was more obvious. However, within the in-service stage, the clarity between the activities was found to reduce, reflecting the conceptual design stage. Further, different improvement initiatives were identified from the case study. These ranged from maintaining small teams within the conceptual design and in-service stages, to implementing changes prior to approval in the detailed design and production stages.

To phrase these findings in terms of the first research question, it is evident that the activities that compose the engineering change management process can be enacted within any stage of the product lifecycle. However, the enactment frequency of the activities that compose the engineering change management process vary from stage to stage. In addition, the lifecycle also has an influence upon: the formality and goals of the engineering change management process; the likelihood that a generated solution has its potential performance verified or implemented; the clarity of the activities within the process; the process improvement initiatives used and whether design traceability is maintained. As stated previously, little was known in regard to the engineering change management process at different stages of the product lifecycle. This research has therefore contributed to knowledge by characterising the variations in the engineering change management process within the product lifecycle.

10.1.2 Artefact knowledge usage and creation

To establish the types of artefact knowledge are used and created through the enactment of activities that compose the engineering change management process, a case study was executed. Aggregating the findings from three cases, eleven activities were found to use artefact knowledge, whilst five activities were found to create artefact knowledge, creating a total of twenty six relationships. Cross referencing the findings from the case study against the literature review demonstrated six relationships that correlated between these two data sources and twenty seven that did not correlate.

In addition to the case study, a survey of the wider engineering community was executed. In contrast to the findings from the case study, the results of the survey indicated that each type of artefact knowledge was both used and created through the enactment of the activities within the engineering change management process. However, it was found that the percentage of respondents who considered that a specific relationship existed between artefact knowledge and an activity varied between 11% and 81%. Using the second standard deviation to establish the most statistically significant relationships, nine strong relationships and forty weak relationships were identified.

Triangulating the results from the case study, literature review and survey highlighted that of the forty weak relationships identified from the survey, none of these relationships were identified in either the case study or literature. Conversely, of the nine strong relationships, five correlated with those identified from the case study. However, none of the strong relationships identified from the survey correlated with those identified from literature. An overview of the triangulation of these results can be seen in section 9.2. This summarises the types of artefact knowledge that are used and created during the engineering change management process.

Based on the triangulated findings from this research, it can be concluded that each type of artefact knowledge can be used and created during the enactment of each of the activities that compose the engineering change management process. Nevertheless, the usage of artefact knowledge is most prevalent during the identification and approval phases. This demonstrates that engineering change practitioners most frequently reference the function and behaviour during these phases, aligning the proposed change with the requirements of the project. This safeguard means that only a limited number of engineering changes should ever compromise the design intent in the project. However, the comparatively lesser usage of artefact knowledge during the generation and prediction phase poses a risk for the timely authorisation of engineering changes. As artefact knowledge plays a lesser role during these phases it is possible that solutions may be developed that could have the potential to not meet the requirements. In such a situation, this could be picked up during the approval phase and the solution returned to the generation stage, causing additional rework. This is of particular risk if the solution has already been implemented as the solution would have to be removed as well causing further rework and slowing down the whole engineering change management process.

In addition, it can also be concluded that different engineering change practitioners use and create different types of artefact knowledge when enacting the same activities. Due to the interlinked nature of the engineering change management process, if an engineering change practitioner is unaware of what they should create as a result of an activity, then this may compromise the flow of knowledge between the practitioners in the process. In addition, without clear definitions of what is required for a specific stage, then the same knowledge types may be generated by different individuals. For example, if the individual responsible for structuring a new solution is generating interpreted behavioural knowledge and another individual who is responsible for analysing the solution is also generating interpreted behavioural knowledge then this would increase the overall design effort and result in a slower process. Likewise, if two different individuals believe that one another is responsible for generating a specific type of artefact knowledge, then this may not be covered within the existing project.

Based on the research reported in this thesis, a clear relationship between artefact knowledge and the engineering change management process has been demonstrated. Previous work has hinted towards a relationship; however, this work is the first to formalise the relationship with such clarity. As such, this formalisation can be considered to be a contribution to knowledge.

10.1.3 Recommendations for engineering change management practice

Based upon the research reported in this thesis, a number of recommendations can be made for improving engineering change management practice. In the following section, six recommendations are discussed and summarised.

First, this thesis has challenged the paradigm that engineering changes only occur towards the end of the detailed design and production stages. This paradigm led to the assumption that engineering change should only be managed within the detailed design and production stages of the product lifecycle. However, this research has demonstrated that engineering changes can and do occur within the conceptual design and in-service stages as well. Based on this, it is recommended that as engineering changes exist throughout the product lifecycle, so should processes for their management.

Whilst it is recommended that engineering change management processes should exist throughout the product lifecycle, care must be taken to ensure that the adopted processes are proportional to the scale of the engineering changes. It is clear from this research that complex processes can detrimentally impact the length of time between identification and implementation, causing process inefficiencies. Therefore to optimise the efficiency of engineering change management throughout the product lifecycle, only the largest scale engineering changes should require the rigour of formal engineering change management. For example, small scale and relatively insignificant modifications to components within the conceptual design stage would not be required to proceed through the rigour of a full scale engineering change management process. Conversely, large scale modifications that had the potential to impact upon the success of achieving the project’s requirements should be treated with the upmost rigour. In such a situation, all engineering changes (as defined in section 2.2.2) do not require to be formally managed in the same manner. Instead, corresponding with the impact of the change, the activities that are required to be enacted during the engineering change management process should reflect this. Therefore, prior to commencement of an engineering project, the scale and corresponding process should be defined and communicated with the engineering team.

Second, this thesis has presented evidence for in the implementation of engineering changes prior to the authorisation of these being granted. This was evident in CS2, where it was suggested that the individual responsible for the implementation of an engineering change prior to authorisation being granted could be influenced by the time taken for an engineering change to proceed through the engineering change management process (on average 126 days (Rowell et al., 2009)). This had both positive and negative impacts on the project: positive as it enabled the artefact to be modified when the need to change was fresh in the designer’s head, but negative as it could increase the chance of rework being needed to remove the modification that had been implemented. To build on the positives and mitigate the negatives associated with this practice, it is recommended that effort is expended to reduce the time taken between the identification and approval phases of the engineering change management process, whilst ensuring that every engineering change is formally approved prior to implementation. As such, to achieve this, a distinct emphasis must be placed on breaking down the barriers that inhibit the timely approval of engineering changes whilst maintaining the necessity for a modification to be appropriately approved.

Third, this thesis has shown that the engineering change management process is driven by three distinct goals: development of an optimum technical solution, accuracy of the impact assessment and speed of implementation. These goals have not been found to be mutually exclusive; instead certain individuals place a greater emphasis on certain goals within the same lifecycle stage. Of these, throughout the product lifecycle, the general consensus was that establishing the impact of the changes as accurately as possible was the primary goal. However, assessing the impact of an ineffective solution would lead to unneeded effort as the solution would have to change again. Further, if the emphasis is on accurately establishing the impact of the change, this decouples this act from the development of the technical solution leading to a position in which those responsible for developing the technical solution believe that it is the responsibility of those later in the engineering change management process to establish the impact. This could encourage those responsible for developing a solution to take a narrow perspective rather than adopting a more holistic view. As such, it is recommended that individuals responsible for the technical development of an engineering artefact direct their team to focus on the development of an optimum technical solution as this inherently encapsulates aspects of impact assessment at the time of the solution development.

Fourth, this research has highlighted that formal engineering change management is more prevalent after the conceptual design stage. Indeed engineering change management processes did not always exist in these earlier lifecycle stages with some individuals stating that they believed that this could stifle innovation. Whilst implementing a formal mechanism for managing engineering change would inevitably lead to a less dynamic design process, it could also provide greater clarity, traceability and configuration accuracy for the development of the engineering artefact. Applying a pragmatic approach to the activities that are required to be executed, reflecting the scale of the engineering change, an engineering change management process should be implemented at the start of the project. However, in the early stages, only the largest scale engineering changes would be required to be managed in the most formal manner. Nevertheless, as the project progresses, this should be tailored to incorporate smaller scale engineering changes until all modifications are formally managed through the full rigour of the engineering change management process at the end of the detailed design stage.

Fifth, as covered in section 10.1.2 it has been demonstrated that different individuals use and create different types of artefact knowledge during the execution of the same activities. This has been outlined as a potential influencing factor that could lead to a slower design process or one in which the engineering change practitioners incorrectly assume that others in the process are generating certain knowledge types. To overcome the problems associated with this, clear guidance should be provided at the start of the project that defines the inputs and outputs for each of the activities and highlights the relationships between the activities. This should be widely communicated to ensure that engineering change practitioners realise their role in achieving an efficient and effective process.

Finally, it has been highlighted from the survey that individuals use artefact knowledge most frequently within the identification and approval phases. As such, a lesser proportion use artefact knowledge within the generation, prediction and implementation phases. To reduce the rework that is required following the rejection of a solution from the approval phase, then it should be ensured that those responsible for generating solutions or analysing the impacts of those solutions should possess sufficient artefact knowledge to reduce the likelihood that these changes are rejected. One solution to this would be to recommend that each individual within the project possesses a comprehensive knowledge of the function, behaviour and structure of the engineered artefact. However, in reality this would be unrealistic as the volume knowledge that an individual would have to possess would prohibit this for all but the most simple of engineered artefacts. To overcome this limitation, a more appropriate mechanism for supporting artefact knowledge during the engineering change management process is required.

As the majority of engineering change management processes are supported by textual documents (Huang et al. 2002), these documents could be developed to better support each type of artefact knowledge. At present, these documents typically consist of brief descriptions of what changes are required to the structure of the engineered artefact and why these changes are necessary. As the engineering change management process progresses, this document is used as a basis for the generation, prediction, approval and ultimately the implementation phases. However, if this document only contains structural information then this does not provide the practitioner responsible for the predicting or approving the engineering change with behavioural or functional support. In such a situation, the practitioner responsible for the impact assessment may not possess a comprehensive understanding of the impact of the changes upon the artefact’s behaviour or function. This could then lead to a position in which the approver also misses these implications and the engineering change that is instantiated into the engineered artefact leads to a situation in which the artefact does not meets its functional or behavioural requirements.

To overcome such a situation, it is recommended that behavioural and functional knowledge is supported by including the functional and non-functional requirements of the relevant parts, systems or components of the engineered artefact that could be impacted by the engineering change on the relevant engineering change documentation. This would then enable engineering change practitioners to not only rely on their knowledge of the function and behaviour of the engineered artefact as this would be supported by documentation of these requirements as well. This explicit definition would then enable the engineering change practitioners to make better decisions on whether to implement an engineering change or not.

In summary, based on the research reported in this thesis, six recommendations for future engineering change management practice are offered. An overview of these recommendations is presented in Table 47.

Table 47 - Recommendations for future engineering change management practice

Reference	Recommendation
Rec-1	Instead of a single engineering change management process for all engineering changes, create multiple processes with the activities that are required to be executed during this process reflecting the scale of the engineering changes that are to be processed.
Rec-2	Ensure each engineering change is formally approved and break down the barriers to this approval taking place in a timely manner.
Rec-3	Place more emphasis on the development of an optimum technical solution rather than the speed of implementation or the accuracy of the impact assessment.
Rec-4	Commence formal engineering change management as early within the product lifecycle as possible; however, ensure that the process and scale of the changes that are managed through this process are proportional to the lifecycle stage.
Rec-5	Provide clear guidance at the start of the project that defines the inputs and outputs for each of the activities and highlights the relationships between the activities.
Rec-6	Ensure all engineering change documentation supports functional and behavioural knowledge by including the functional and non-functional requirements of the equipment that could be impacted as a result of the engineering change being implemented.

10.1.4 Primary contribution summary

Summarising the discussions in the previous sections, three offerings are proposed that form the primary contributions contained within this thesis. An overview of these contributions is presented in Table 48 including the location in the thesis that provides the clearest summary of these contributions and the corresponding location in the thesis in which the knowledge gap is outlined.

Table 48 - Overview of primary contribution to knowledge

Contribution reference	**Primary contribution**	**Summary presentation**	**Knowledge gap outlined**
PC-1	• A characterisation of the engineering change management process that highlights eight variations within the product lifecycle	Figure 38, page 195	Section 2.6, page 36
PC-2	• A formalisation of the relationships between artefact knowledge and engineering change management process activities	Figure 37, page 194	Section 3.3, page 63
PC-3	• Six recommendations for improving future engineering change management practice	Table 47, page 206	Section 4.3, page 68

10.2 Secondary contributions and research insights

During the execution of the work undertaken to offer the primary contributions reported on in the previous sections, further findings have emerged in the form of secondary contributions and additional research insights. For clarity, in the context of this thesis, a secondary contribution is an aspect of the findings that has emerged as the result of research work whereas a research insight has come from the literature and has not been tested in the course of the research work. In total, three secondary contributions are offered and one research insight. These are discussed in the following paragraphs.

Firstly, to proceed towards an answer to the first research question, an assumption was initially taken. In chapter 2, this thesis presented an argument that engineering changes do not occur, as previously reported, solely during the latter stages of product development. Instead it was argued that they occur throughout the product lifecycle. Offering a synthesised definition of engineering change, the subsequent research validated the assumption that engineering changes can occur throughout the product lifecycle, by demonstrating that processes for the management of engineering change also exist within these stages. This leads to a position in which future research work in the field of engineering change could be extended to encompass both conceptual design and in-service stages of the product lifecycle. This definition is presented and justified in section 2.2.3.

Secondly, to establish what was currently known in regard to the activities that compose the engineering change management process, the thesis proceeded to outline the activities that compose this process based on current literature. To achieve this, the activities were synthesised into five groupings that covered the entire engineering change management process: identification, generation, prediction, approval and implementation. Offering this as a mechanism of decomposing the process into discrete phases subsequently enabled the complexity of this process to be reduced and the activities that compose the engineering change management process associated with these phases. This model was then tested during the case study and survey. Based on this test it was evident that whilst a number of activities composed the engineering change management process and that the enactment of these activities varied from case to case, in all cases at least one activity from each phase of the engineering change management process was established. As such, it can be concluded that whilst the activities that compose the engineering change management process can vary at different stages of the product lifecycle, the five phase model of engineering change can be used to provide an overview of this process throughout. This model is presented in section 2.3.1.

Thirdly, through establishing the relationship between the stage of the product lifecycle and the activities that compose the engineering change management process an investigation into the activities that compose this process was executed. Based on literature, twelve activities were identified and described in chapter 2. Subsequently, the existence of these activities was tested through the case study and survey. Based on the findings from these methods, the number of activities that compose the engineering change management process was extended to seventeen. Of these, the acts of evaluating, validating, distributing and ordering were not found within literature, whilst the acts of structuring and modelling were found to be a decomposition of the act of solution development. As such a total of seventeen activities were found to compose the engineering change management process, with this thesis contributing by offering a taxonomy of these activities. This taxonomy is presented progressively throughout this thesis; however, the most concise view of this can be seen in Table 43.

Finally, exploring the relationship between artefact knowledge and the engineering change management process, parallels between the nomenclatures used to describe the different types of artefact knowledge and that used in systems engineering became evident. To date, no research has been found that explicitly linked this nomenclature. Based on a review of pertinent literature, it was found that there was a clear relationship between these. As such, this thesis has contributed to knowledge my offering a mapping between artefact knowledge and systems engineering nomenclature. This can be found in section 3.1.5.

These secondary contributions are summarised in Table 49.

Table 49 - Summary of secondary contributions

Contribution reference	**Secondary contribution / research insight**	**Summary presentation**	**Knowledge gap outlined**
SC-1	• A synthesised definition for engineering change that is not constrained to specific lifecycle stages	Section 2.2.3, page 18	Section 2.2, page 9
SC-2	• A phased model of the engineering change management process that is adhered to within all stages of the product lifecycle between conceptual design and in-service	Section 2.3.1, page 20	Section 2.3.1, page 20
SC-3	• A taxonomy of engineering change management process activities that includes four activities not reported in literature and proposes a decomposition of another	Table 43, page 181	Section 2.6, page 36
RI-1	• A mapping between artefact knowledge and systems engineering nomenclature	Section 3.1.5, page 47	Section 3.1.5, page 47

10.3 Validity of the main findings

The concept of validity in terms of research findings has been discussed by a number of authors (Remenyi, Williams et al. 1998, Easterby-Smith, Thorpe et al. 2002, Voss, Tsikriktsis et al. 2002, Yin 2003). Of these, Yin (2003) reports that the validity of a research project can be tested through an exploration of three topics: construct validity, internal validity and external validity. Construct validity refers to the extent to which the concepts that were meant to be measured have actually been measured, internal validity refers to the degree by which the research has been successful in eliminating confounding variables and external validity refers to the degree by which the findings can generalised to the wider population. Encompassing these topics, Easterby-Smith et al. (2002) report that validity varies according to the research philosophy that is adopted by the researcher. As such, they report that validity from a post-positivist philosophy is concerned with establishing whether the researcher has gained comprehensive access to the knowledge and meaning of the informants.

Considering construct validity, this research work aimed to establish the activities that are enacted during the engineering change management process at different stages of the product lifecycle and the artefact knowledge that is used and created through the enactment of these activities. As such, three constructs can be considered: engineering change management process activities, artefact knowledge and product lifecycle stages. To ensure that each of these variables has been measured in a valid manner, descriptions of these variables were created prior to the execution of the research work, based upon published literature and are presented in chapters 2 and 3. However, the constructs in the form that are reported in literature were not always found to be part of the industrial vocabulary (e.g. instantiated behaviour). As such, these terms had to be translated. Therefore, whilst significant effort went into ensuring that these translations accurately represented the constructs that they covered, through subsequent interpretation, particularly in the survey, the meaning of these terms may have been modified.

Moving onto the internal validity, a number of confounding variables were identified from the literature review, specifically: market, production quantity, organisation and type of product. Through the definition and application of case selection criteria, effort was expended to ensure that these variables were controlled. Further, as this research project focused on engineering change, effort was also expended to ensure that only engineering changes were considered. To achieve this, a synthesised definition for engineering change was offered and this definition was adhered to throughout the research work. In addition, as part of this research work focused on activity enactment throughout the product lifecycle, definitions for the different stages of the product lifecycle were developed and adhered to. However, whilst these constructs have been identified, ensuring that they are consistently applied has not been as straight forward. For example, whilst definitions for engineering change were offered to the interviewees it could not be ensured that the responses to the questions drew upon the interviewee’s knowledge of this phenomenon only. Further, during the survey the respondents were asked to indicate what stage of the product lifecycle that the project they were working on was currently within, it was not possible to ensure that the respondents could accurately apply the provided criteria. As such, whilst mitigation exercises such as providing descriptions of product lifecycle stages and selecting companies based upon defined criteria have been applied, the interpretation of these descriptions by humans means that control of the confounding variables could not have been achieved comprehensively.

Focussing on the external validity, this is a concept that is related to whether the results can be generalised. Focussing on case study research, Voss et al. (2002) question whether findings from this research strategy can be abstracted to a wider context. Reflecting this observation, the external validity of this research work has been increased through the execution of a survey within the wider engineering community as well as the execution of the case study. However, again through adopting a post-positivist philosophy the researcher accepts that each research method is inherently exposed to the influence of random error (Taylor 1997) and as such no one source of evidence can be considered to be infallible. Therefore, the discrepancies in the results from the case study and survey were to be expected and were in line with the adoption of a post-positivist philosophy. Nevertheless, integrating the findings from both the case study and survey has improved the generality of the research findings.

Another aspect of external validity is also whether the findings themselves can be transferred not only to other cases, but to other examples of engineering change within the same case. To illustrate this, some feedback was returned through the survey that it was difficult to report specifically whether certain activities were enacted or artefact knowledge used and created accurately as every engineering change was different. As such, it is not possible to suggest that every engineering change undergoes the same management process, but that across a sample of engineering changes the output will tend to what has been identified from this research.

Overarching these three tests of validity, the consideration of whether the researcher has gained full and accurate access to the knowledge and meaning of the informants is reported as being important when adopting a post-positivist philosophy (Easterby-Smith, Thorpe et al. 2002). During the case study the researcher was provided with full access to individuals within the three cases. This was complimented by the responses that were provided by the interviewees that were perceived to be uninhibited. However, ensuring that full and accurate access to knowledge has been obtained through the survey is more difficult to establish. For example, in some instances the questionnaires would be returned with a pattern of responses that made the researcher question whether full consideration or understanding of the questions had been obtained.

In summary, it is recognised that weaknesses exist within the research methodology; however, strategies have been put in place throughout the research to increase the validity of the output (e.g. triangulation through case study and survey, provision of definitions of key constructs). Nevertheless, the very nature of case study and survey research introduce biases that are beyond the control of the researcher, leading to a position in which different results could well be achieved by different researchers. Fundamentally though, the contributions and recommendations for engineering change management practice that have been offered as a direct result of the research presented in this thesis represent grounded guidelines for engineering change management processes. In such a situation, whilst the specific findings from the research may vary in different circumstances, the guidance that has been developed as a result is considered to be valid.

For clarity, an overview of the strengths and weaknesses of the validity of the main findings is presented in Table 50.

Table 50 - Summary table of the validity and reliability of the main findings

Point		Strengths		Weaknesses
Construct validity	✔	Constructs based on published work and as such grounded in existing theory.	✕	Through translation and interpretation the communicated constructs may have deviated from their exact definitions.
Internal validity	✔	Key confounding variables have been identified a priori and actions put in place to control these.	✕	Application of the bounding variables was out with the control of the researcher.
External validity	✔	Case study findings triangulated with those from the survey.	✕	Survey did not cover the entire engineering community and as such may not represent the entire population.

10.4 Research strategy

Within this research project, two research strategies as described by Yin (2003) have been used: case study and a survey. Presenting a discussion on the strengths and weaknesses of the research strategies, the following section has been separated into two parts. As such, section 10.4.1 discusses the strengths and weaknesses associated with the case study whilst section 10.4.2 discusses the strengths and weaknesses associated with the survey.

10.4.1 Case study

Case study research has been much discussed in academic texts. From this multiple strategies for executing case study research have been presented (Eisenhardt 1989, Dyer and Wilkins 1991, Miles and Huberman 1994, Yin 1994, Voss, Tsikriktsis et al. 2002), fundamentally representing variations on the same theme. Of these different variations, this study can be considered to reflect the strategy presented by Eisenhardt (1989) most closely. Adopting this strategy, a study of multiple cases has been executed enabling comparisons between these cases to be made. However, as Dyer and Wilkins (1991) report, multiple cases limit the depth that the researcher can achieve on any particular case resulting in a less coherent, credible and memorable output. In support of case study research, Voss et al. (2002) report that it can have a very high impact and is a powerful research strategy. In addition, Meredith (1998) cites three strengths of case study research put forward by Bebensat et al. (1987): the phenomenon can be studied in its natural setting; full understanding of the nature and complexity of the complete phenomenon can be achieved, and it lends itself well to exploratory investigations where the variables are still unknown and phenomenon is not well understood. However, Yin (1999) reports that although the case study is a distinctive form of empirical enquiry, many research investigators have a disdain for the strategy. In particular, four weaknesses are reported: lack of rigour; little basis for scientific generalisation; lengthy periods of time are required, and the output is often large, unreadable documents that are overly complex (Eisenhardt, 1989).

Valid application of case study strategy details that an appropriate number of cases need to be executed to ensure the validity of the output. Whilst Eisenhardt (1989) describes that there is no optimum number of cases, it is generally considered that a balance between the number of cases and the depth of the analysis needs to be established. Within this research work, three cases have been studied, representing different stages of the product lifecycle. Whilst this number is below the minimum recommended by Eisenhardt (1989), it is in line with the observations on the number of cases commonly reported upon by Voss et al. (2002).

Whilst there are a number of data collection techniques available to the case study researcher, Maguire (2010) argues that interviews are generally the primary source of data collection. This observation is reflected within this piece of work, as semi-structured interviews form the basis of the formal data collection process. As such, this research project has been based upon a total of nineteen semi-structured interviews, of which sixteen of these represent the core data collected to answer the research questions representing 367 minutes and 6 seconds of total recorded interview length. The other three interviews formed the pilot study, providing the interviewer with valuable experience of how to conduct interviews, how to phrase questions appropriately and how much information to provide prior to the interviewee. However, whilst nineteen interviews were executed that contribute to this research, this study could have benefitted from an increased number of interviews to provide further perspectives on the engineering change management process resulting in a more statistically significant output.

In the case study it was evident that the interviewees found it difficult to define exactly what they used and created during the enactment of activities. This resulted in the interviewees sometimes defaulting to answers such as, “through technical and personal experience", providing the researcher with little reportable insight. To improve the recalling process, the interviewer asked the interviewee to consider a specific engineering change so that they could more readily recall the knowledge that they used and created; however, even when asked to do this the answers were not always forthcoming. In this case it is believed that as the interviewees were put on the spot and asked to recall what they considered to be used and created, the researcher was relying on the interviewee's memory to answer the question without providing any prompts. Due to the fallibility of human memory, certain pieces of information could have been forgotten or the questions misinterpreted.

To increase the traceability of the results and enable post-processing of the interview output, the interviews were recorded and transcribed as a verbatim account of the event. Whilst recording an interview can have an effect on the interviewee's response (Voss, Tsikriktsis et al. 2002), this was deemed the most appropriate method of capturing the data. Following the transcription process, the documents were analysed and coded using a procedure described by Strauss and Corbin (1990). As such, having a verbatim account of the interviews has facilitated the traceability of the research output. However, this process took a significant period of time (it was estimated that five minutes of verbal interchange resulted in one hour of transcribing, followed by another hour of analysis), was laborious and could be partially avoided through the use of computer packages such as NVivo and Clementine.

In summary, whilst increasing either the number of cases or the number of interviewees within each of the cases could have led to a statistically significant insight into process by which engineering change were processed within each of the cases, developing a statistically significant list of engineering change management process activities was not the primary aim of this case study. Instead a balance was struck between the number of cases and the number of interviewees, focussing on the specific research questions. Further, as Pikosz and Malmqvist (1998) reports, engineering change management process activities can be similar at higher levels of abstraction, these tend to be more tailored to specific organisational requirements at lower levels. Therefore, it was envisaged that the benefit of conducting a greater number of interviews or analysing other cases would not have outweighed the disadvantages associated with the high costs of organisation, execution, transcription and analysis of further interviews and additional cases. In such an instance, it is considered that whilst additional cases may provide an increased validity, it would not affect the contributions or recommendations contained within this thesis.

Summarising the strengths and weaknesses of the case study research strategy, the main points are presented below:

Table 51 - Summary table of case study strengths and weaknesses

Point		Strengths		Weaknesses
Case study strategy	✔	Adopted case study strategy proposed by Eisenhardt (1989) enabled comparisons to be made between different cases.	×	Case study research is inherently subjective and as such suffers from bias and results that cannot be generalised.
Number of cases	✔	Number of cases enabled insights to be taken from multiple stages of the product lifecycle and is in line with the number of cases reported by Voss et al. (2002).	×	Three cases is below the number recommended by Eisenhardt (1989).
Pilot study	✔	Enabled the researcher to gain valuable experience of how to perform interviews and how to phrase the questions.	×	A larger number of interviewees could have been interviewed.
Data collection	✔	Sixteen semi-structured interviews representing over six hours of recorded interviews.	×	Could have benefitted from an increased number of interviews to gain a more statistically significant output.
Post processing	✔	Transcription of interviewee data created a verbatim account of the interview, facilitating traceability.	×	Laborious and time consuming process that could have been partially avoided through the use of qualitative computer analysis packages such as NVivo.

10.4.2 Survey

Surveys have been reported as benefitting from low administration costs and high speed of proliferation, with the advent of the internet enabling global-reach and timeliness of response (Evans and Mathur 2005). However, surveys have also been criticised by a number of authors, of which one of the most pertinent criticisms is that of respondent apathy that can emerge as inaccurate results, low response rates and ultimately incorrect conclusions being drawn (Janes 2001). These insights were reflected in the survey that was executed in this study; with the wider access to individuals being coupled with a lower than expected response rate. This could be explained by the lack of personal touch, with the respondents not thinking that their input would be valuable. In addition, when asking individuals to complete the surveys, it was frequently asked “what will I get in return?” This was difficult to quantify as it was decided to not offer an incentive to complete the questionnaire: instead, the researcher offered a copy of the results to the participating organisations.

The main data collection mechanism associated with a survey is that of the questionnaire. A questionnaire contains a documented list of questions that individuals answer in a structured manner. This questionnaire can be delivered verbally or presented as a document to the respondent to complete. Whilst Yu and Cooper (1983) suggest that the response rate of documented surveys can be about half as effective as surveys which are executed verbally, it was decided to execute a documented survey in an attempt to obtain a greater proliferation and more representative insight from industry as a whole, at a lower administrational cost. Prior to this proliferation to the wider engineering community, the questionnaire went through a pilot study with three engineering change practitioners. This enabled the structure, terminology and analysis technique to be tested and optimised. Whilst it was considered that this contributed to the readability of the questionnaire, some respondents required further help to understand the questions. Furthermore, on a few occasions the questionnaire was criticised for not capturing the diversity and complexity of engineering change management or that the respondents found it difficult to fit the engineering change management processes executed in their projects into the more generic approach documented in the questionnaire.

To improve the ease of analysis, the questions were provided with a number of possible answers in a multiple choice format, enabling the responses to be analysed quantitatively. This permitted a numerical comparison between different activities across the product lifecycle that were reported to be enacted during the engineering change management process. Furthermore, whilst the questionnaire contained a number of multiple choice questions, the possible answers to these were either dichotomous or represented as a multiple point scale. In relation to the dichotomous question format, this simplified the analysis process but was also criticised as the respondents found it difficult to provide a clear response, indicating a sliding scale may have been more appropriate.

To ensure that the questionnaire was delivered to the most appropriate individuals a set of selection criteria was set out. Using the same selection criteria for the survey as the case study, a total of twenty nine companies were approached. In addition to the case selection criteria, candidate selection criteria were also supplied to the coordinating individuals within the organisations. This was prepared to help the coordinator identify the best individuals to send the questionnaires to. However, this relied upon the coordinator’s knowledge of the individuals within the project and what their roles were. In total, 294 questionnaires were sent out of which 85 were returned (28.9%) from 15 companies (51.7%) of which six were rejected due to an insufficiency of information (7%), leaving 79 questionnaires to form the basis of the analysis. These questionnaires were not spread evenly across each of the phases of the product lifecycle, with an increased number of responses being obtained from the detailed design stage in particular. Furthermore, whilst twenty nine companies were contacted, this represents a low distribution when considering the entire engineering community.

In quantitative analysis, the accuracy of the results is an important consideration and is closely related to the number of responses (Bartlett, Kotrlik et al. 2001). There is a range of anecdotal evidence available that states between 20 and 30 responses are required. However, an empirical source of this anecdotal evidence has not been found. Instead, an empirical source for the number of responses required was found in a publication by Bartlett et al. (2001), who relates the number of responses to the error rate in the findings. Based on the calculation method for continuous data described by Bartlett et al. (2001), and applying the recommended values for the selected alpha value (t=1.65), standard deviation estimate (s=0.5) and acceptable error in the mean (3%) a minimum of 3,303 respondents is calculated as being required. Subsequently, accepting a 20% response rate would mean that over 16,000 questionnaires would have to be proliferated. This significant disparity between the number of questionnaires required using the method presented by Bartlett et al. (2001) and the number of those collected in the survey can be thought to be a weaknesses in the statistical certainty of the output.

Whilst a significantly lower quantity of responses was used in this study than was recommended, this quantity is considered to be valid for a number of reasons. Firstly, Bartlett et al. (2001) denotes that in organisational research, researchers frequently have to conclude with sample sizes that can be significantly below the recommended number. Due to the significant difficulty in gaining access to individuals within applicable cases, the researcher was not able to achieve this number. The cold calling of organisations was found to be of little impact, with organisations frequently refusing to take part. In fact, only through the facilitation of a third party were any completed questionnaires returned from organisations in which the researcher did not have a personal contact. Secondly, the calculation method presented by Bartlett et al. (2001) is based upon the survey being the sole source of evidence into a specific phenomenon. By comparison, less work has been done to determine the sample size required for research methodologies conducted under the adoption of post-positivism in which triangulation of different data sources is offered as the key aspect of ensuring research validity. Thirdly, the calculation method described by Bartlett et al. (2001) asks the researcher to provide estimates about the nature of the data. These estimates have a significant influence on the number of responses required and given that there is little information provided to support the estimation of these, it is not clear whether the estimates of the nature of the data in the engineering change field are appropriate or not. Finally, in the field only a handful of papers have been produced that use a survey methodology, e.g. (Huang and Mak 1999, Huang, Yee et al. 2003). Of these the error in the returned sample size has not been calculated and similar problems in the response rate cited (in the survey presented by Huang and Mak (1999), only a 5% response rate was achieved, with just 100 of the 2,000 companies approached returning completed questionnaires).

Given the problems with calculating and attaining a sample size that is sufficient for statistical certainty of the output, this survey cannot be considered to be representative of the entire population of engineering change practitioners. Nevertheless, it has provided evidence through which some inferences can be made.

Summarising the strengths and weaknesses of the survey, the main points are presented below:

Table 52 - Summary table of survey strengths and weaknesses

Point	Strengths		Weaknesses	
Survey strategy	✔	Enabled insights from a number of different sources to be obtained quickly and cheaply.	×	A significant amount of time was spent on identifying and contacting individuals to ensure an adequate level of response.
Pilot study	✔	Enabled the structure and terminology within the questionnaire to be optimised.	×	A larger number of respondents could have provided further optimisation.
Questionnaire format	✔	Multiple choice format enabled rapid completion of questionnaire.	×	Questionnaire criticised for not capturing complexity of engineering change management process.
Dichotomous question format	✔	Simplified the analysis process.	×	Respondents found it difficult to provide a clear response, indicating a sliding scale may have been more appropriate.
Respondent contact	✔	Defined list of inclusion criteria used for selecting individuals to complete questionnaire.	×	Relied on coordinator within a company to identify relevant individuals.
Distribution	✔	294 questionnaires sent out to named individuals and 29 companies contacted.	×	Low distribution when considering entire engineering industry.
Response level	✔	79 completed questionnaires (26.8% response rate) received from 15 companies (51.7% response rate).	×	Responses not spread evenly across each stage of the product lifecycle.
Error	✔	Lack of error estimation in line with existing studies in the field.	×	Response rate insufficient to enable generalised conclusions to be drawn about entire population.

10.5 Research methodology

In this thesis post-positivism was adopted as the research philosophy that has guided the application of an appropriate research methodology. This adoption was based on the link between engineering change management process and the human beings who drive this process and as Stone (2002) suggests, it has been guided by the nature of the research question. This adoption enabled the usage of human centric research strategies, based upon interviewing and surveying engineering practitioners to provide different sources of evidence. However, a post-positivist must recognise that each source of evidence contains error and that the biases and interpretations of the researcher cannot be ignored (Popper 1959). In this case the goal of a post-positivist research is not to provide a single objective reality, but through considering that all theory is revisable, it is to provide a more enduring reality that is backed up by multiple error laden sources of evidence (Easterby-Smith, Thorpe et al. 2002).

One of the first and most fundamental decisions the researcher was presented within during this research project was whether to execute a cross sectional or longitudinal study. Based on the reasons described in chapter 5 a cross sectional approach was decided as being the most appropriate; however, this decision had a number of implications for the research work. Fundamentally, the decision to use a cross sectional approach was based upon the desire to enquire into the current state of engineering change management within a contemporary industrial context. Recognising that industrial projects generally ran for a number of years, a longitudinal study was deemed to have not been appropriate within the available time period. Nevertheless, executing a cross sectional study has exposed the research work to other variables (e.g. different interviewees, organisational cultures) that may have been omitted through the use of a longitudinal study. This could have meant that uncontrolled variables that may have an influence upon the results could have crept into the research findings.

Using a cross sectional approach to the research has meant that extra importance was placed upon accurately identifying the stage of the product lifecycle that the engineering artefact being developed was currently within. Whilst guidelines for this were presented in chapter 2, it was found that the boundaries between the stages were somewhat blurred. In addition, due to variation in system maturation across the engineering artefact and the use of concurrent engineering within the cases, to place an entire case within a single stage can be inaccurate. This was first identified in the case study when CS2 was seen to span both the detailed design and production phase. In addition, feedback from the survey was received in which the respondents found it difficult to determine what stage of the product lifecycle their project was currently within. Whilst guidance was provided in these instances and was based upon existing product lifecycle theory, the accuracy of the results was constrained by the respondents interpretation and understanding of this information.

A further point for discussion in this study was the methodology by which the researcher went about identifying the activities associated with the engineering change management process and linking artefact to these activities. Fundamentally, this research relied on two types of knowledge procedural and declarative to provide an insight into the research question. Whilst debate still exists as to the exact nature of these knowledge types, declarative knowledge has been referred to as relating to knowledge of facts and events, whereas procedural knowledge has been referred to as relating to abilities, skills and other procedures (Eichenbaum and Cohen 2001). Reflecting this difference, Ullman (2001) reports that declarative and procedural knowledge draw upon different parts of the brain and as such rely on these different parts of the brain to recall. In a further publication Ullman (2005) describes procedural knowledge as an “implicit memory system” because both the knowledge itself and the learning of the knowledge are generally not available to conscious access. As such, knowledge of the activities that are enacted within the engineering change management processes can be considered to be declarative knowledge. However, the artefact knowledge that is used and created by these activities can be considered to be procedural. This could explain why the interviewees and survey respondents found it more difficult to describe what knowledge they used and created during the engineering change management process than to describe the activities that they executed during the engineering change management process.

Taking a balanced view on the strengths and weaknesses associated with the research methodology, the methodology is deemed to be suitable for offering the contributions described above. Adopting a positivist philosophy would have placed more emphasis on statistical significance of each data source and whilst it would have produced more valid survey results, the depth associated with the qualitative nature of the case study would have been lost. Further, a longitudinal approach to the collection of data may well have decreased the influence of confounding variables; however, given the time restrictions this was considered to be out with the permitted time frame for doctoral research.

Summarising the strengths and weaknesses of the research methodology, the main points are presented in Table 53:

Table 53 - Summary table of research methodology strengths and weaknesses

Point		Strengths		Weaknesses
Post-positivist philosophy	✔	Permitted the use of human centric research methods that use both qualitative and quantitative data.	×	Research output cannot be considered to represent a single objective reality.
Cross sectional study	✔	Permitted enquiry into this phenomenon within the time constraints of the project.	×	Has led to the introduction of other variables that may inadvertently influence the findings.
Accuracy of product life cycle phase classification	✔	Definitions for the product lifecycle stages have been defined and are based upon product lifecycle theory.	×	Engineering artefacts were found to exist in different product lifecycle stages simultaneously.
Declarative and procedural knowledge	✔	Declarative knowledge used to establish activities performed within the engineering change management process deemed as a reliable source of knowledge of events and facts.	×	Procedural knowledge used to link artefact knowledge to the activities resulting in questions over the accuracy of the relationships.

10.6 Lessons learnt

Reflecting upon the research project two lessons have been learnt that would affect the way the researcher would approach this research question if the project was to be executed again. As such, the following section provides a brief overview of these lessons.

Completing research within an organisational domain and applying human centric research methods has caused a number of complications to the acquisition of data throughout this project. In the case study, establishing appropriate cases and organising the interviewees was difficult and required months worth of discussion and deliberation. Further, executing the survey was also difficult for two main reasons. Firstly, due to the affiliation with the sponsoring company, other organisations seemed hesitant to permit access to individuals to participate in the study. Meetings had to be set up in advance of the proliferation of questionnaires and in one instance a non-disclosure agreement had to be signed, delaying the process significantly. Secondly, as personal contacts in relevant organisations diminished, cold calling of relevant organisations was executed. This strategy was found to be unsuccessful as the request for access to individuals to participate in the study was frequently rejected. In this case, reliance was placed upon the personal contacts and the input from a specific third party. These were by far a more successful mechanism of obtaining responses. As such, the lesson that has been learnt was to build as many personal contacts in relevant companies as possible, prior to the execution of the research, so the data collection is less time consuming.

Reflecting upon the survey, a number of lessons have also been learnt. In particular, as response rate is critical to the success of a survey strategy, significant effort should be expended by the researcher to maximise the return. This is particularly important as when asking engineering practitioners to complete the survey they have to manage to find the time to complete these over and above their day jobs. Finding time to fill in these questionnaires can therefore be difficult and as such a significant effort is required to encourage these individuals. Reflecting this, a shift in administration strategy from document based to verbal based should see a significant increase in response rate (Yu and Cooper 1983). Furthermore, incentivising responses could be considered to increase the response rate along with shortening the questionnaire itself (Kiesler and Sproull 1986). Considering the limitations associated with the survey, it could be suggested that these could overcome by adopting a different research method, e.g. focus groups, protocol analysis. However, each research method has a range of limitations, introducing and exacerbating different research issues. In such an environment, the researcher should implement the most appropriate methodology initially, but strive to triangulate these findings with as many different, yet relevant methods as the research programme permits.

10.7 Future work

This study has provided a foundation for further work within the field of engineering change management processes. As such, eight potential future projects are offered, within three main groupings: further methodological triangulation, directly related research avenues and postulations on future engineering change management research.

10.7.1 Further methodological triangulation

Recognising that a post-positivist philosophy relies upon the triangulation of a number of different methods, future research could focus on providing further triangulation through either the execution of additional research methods or a shift from a cross sectional study to a longitudinal study.

- *Execution of additional research methods*

Through the adoption of a post-positivist philosophy the researcher accepts that there is an intrinsic error in each source of evidence. To mitigate the impact of this, multiple sources of evidence are used to triangulate the results. In this research work, two research methods were used to triangulate the results: a case study and a survey. This has provided two sources of evidence that contribute to answering the research questions. However, through the use of further research methods, the error in the conclusions that are drawn could be reduced. In particular, protocol analysis should be considered as Kim et al. (2011) cite Ericsson and Simon (1993) suggesting that protocol analysis has been recently used as the most likely method "to bring out the somewhat mysterious cognitive activities of designers". As such, future work should focus on the adoption of different research methods to further triangulate the results and provide more general conclusions.

- *Longitudinal rather than cross-sectional study*

The research that is presented in this thesis was restricted by time-constraints leading to three cases being reported that focussed on different phases of the product lifecycle. However, each of the cases contained project variations that may be influencing the results. To eliminate these influences a longitudinal rather than cross-sectional study should be executed, with the same individual being interviewed at different points in the process. This would help to reduce the influence that different project constraints had upon the results. In addition, a longitudinal approach could also be adopted for the survey asking individuals to detail how they perceived the activities to vary across the product lifecycle.

10.7.2 Directly related research avenues

Increasing an existing body of knowledge can subsequently open up new research questions at the fringes of the findings. Through the execution of this research work, three directly related research avenues have emerged:

- *Development of future engineering change support systems*

This research has highlighted both the activities that are enacted at different stages of the product lifecycle and the artefact knowledge that is used and created through the enactment of these activities. Based on this knowledge, future engineering change support systems could be developed reflecting the activities that are enacted and the artefact knowledge that is used and created, offering more comprehensive support to engineering change activities.

- *Prescription of artefact knowledge usage and creation*

This research has demonstrated a significant relationship between artefact knowledge and the engineering change management process. From this it has been found that a proportion of engineering change practitioners use and create functional, behavioural and structural knowledge through the enactment of the activities that compose the engineering change management process. However, this research has not been able to establish whether the activities can be enacted without this knowledge. As such, future research should focus on identifying the key types of artefact knowledge that are critical to the enactment of specific activities.

- *Goal identification and influences*

This research has demonstrated that the engineering change management process is driven by a range of goals. Citing three goals, this research has demonstrated that a correlation between the product lifecycle and the goal of the engineering change management process currently exists. However, only three goals were established within this research project and it is not currently known whether other goals exist. Furthermore, whilst a correlation between the product lifecycle stage and the goal of the engineering change management process has been established, it is not known whether this is a causal link or not. As such, further work is required to establish what other influencers there are on these goals and whether these are casual or not.

10.7.3 Postulations on future engineering change management research

Through this research process, potential future research projects in the field of engineering change have been postulated. Rather than being directly related to the findings from the specific research project reported on in this thesis, three potential projects have come through postulations of future avenues of engineering change management research that could contribute to increasing the effectiveness of engineering change management.

- *Knowledge usage and creation beyond artefact knowledge*

This piece has work has focussed on the relationship between the activities within the engineering change management process and how they relate to artefact knowledge. As such, it has not considered the relationship between these activities and other non-product domain knowledge types, such as financial and time based metrics. An extension to this piece of work could therefore be considered based on other non-artefact knowledge types. The generated output could then be used to inform the development of future engineering change support systems, creating new systems that deliver support to both artefact and non-artefact knowledge types simultaneously.

- *Initiation point identification for implementation of formal engineering change management processes*

Based on the findings of this research it can be concluded that at some point during the product lifecycle a formal engineering change management process is implemented. At this point, a structured and prescribed set of activities replaces the ad hoc tasks associated with the processing of engineering changes. Whilst this research has illustrated the existence of this, it has not extended to establish the exact point when a formal method of managing engineering changes is implemented, nor when it should be implemented. As such, further research is required to identify what the triggers and influencing factors are for the implementation of a formal engineering change management process and when this should be implemented to provide the optimal project performance.

- *A sociotechnical approach to engineering change management process optimisation*

Due to the inextricable link between engineering change and human beings, the engineering change management process can be considered to be a sociotechnical system (Biazzo 2002). Currently, much effort has been placed on the development of technical systems for managing engineering change. However, comparatively less effort has been placed on the social side of engineering change management. As such, future work should focus on developing the social aspects of engineering change management in an attempt to co-optimise both the social and technical aspects of the engineering change management process.

10.8 Chapter summary

This chapter was prepared to summarise the contributions contained within this thesis and phrase the findings in such a manner as to answer the research questions posed. Summarising the findings from the study of engineering change management process activities, it was evident that the enactment frequency of these activities varied throughout the product lifecycle. This provided an insight that the likelihood of a generated solution being implemented or undergoing performance verification varied throughout the product lifecycle. Likewise, it was demonstrated that the lifecycle had an influence upon the formality and goal of the engineering change management process and the likelihood that a solution would be implemented. Further, that the activity clarity and process improvement initiatives varied throughout the product lifecycle. In addition, the relationship between artefact knowledge and the engineering change management process was discussed. As such, the significant relationship between artefact knowledge and the identification and approval phase of the engineering change management process outlined. Based on these findings, a total of six recommendations for future engineering change management practice were presented.

The subsequent sections of the chapter then acted to discuss the strengths and weaknesses of the research strategy and methodology, outlining the limitations on the validity and reliability of these caused by the adoption of certain techniques. In addition, two of the key lessons learnt through conducting this research project offered. Finally, eight future research projects were presented focusing on obtaining further methodological triangulation of the existing output, directly related research avenues and postulations of future engineering change management research.

Chapter 11 - RESEARCH EXPLOITATION

In the previous chapter the main findings have been discussed and recommendations for engineering change management offered. In an effort to overcome a number of issues with current engineering change management practice within the sponsoring company, a number of these findings and recommendations were implemented within specific projects. Acting as a summary, the following section provides an overview of how the findings and recommendations have influenced the sponsoring company, providing three specific examples. As such, the following chapter commences with an overview of the issues that the company were looking to overcome. Following this, it proceeds to outlining how the findings and recommendations helped to overcome these issues and what the impact of implementing these was for the specific case.

11.1 Engineering change management issues

Within the sponsoring company, the management of engineering change had been identified as an area that could benefit from the development and implementation of best practice, to improve current processes. A number of site wide initiatives had been executed to improve the management of engineering change; however, a number of issues still remained. In particular, four primary issues were experienced that were based upon deficiencies arising in specific engineering projects. These issues focussed on: inclusion of appropriate activities within the engineering change management process, content of an engineering change request document, establishing the point at which to implement a formal engineering change management process and linking engineering change to project progress estimates.

In the following sections of this chapter, three cases are described that outline how the findings and recommendations reported in this thesis have been applied within the sponsoring company to overcome these issues. In each example, a brief contextualisation of each project is provided before a description of how the researcher proposed tackling these issues is presented. For clarity, the issues that were addressed are presented in Figure 39, linking these to the section of the chapter in which the solution to these issues is offered.

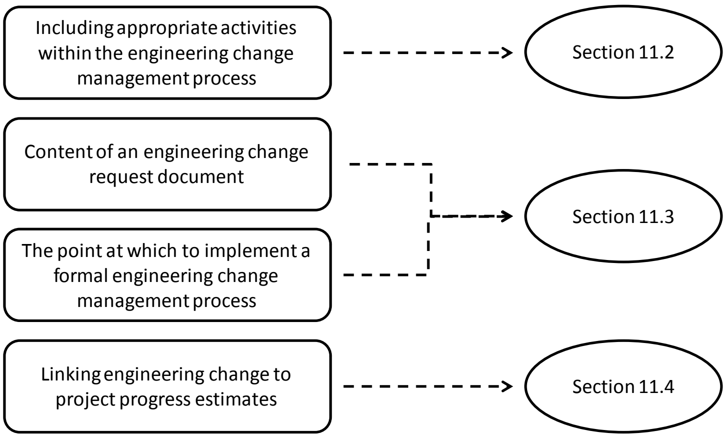


Figure 39 - Engineering change management issues and corresponding chapter sections

11.2 Engineering change management process capture and development

Following the completion of the research work presented in this thesis, a senior manager from Babcock who had been recently been promoted to run the change management team on the QEC project (CS2, presented in chapter 5) requested support for capturing and developing the process for the management of engineering changes. Following a management reshuffle, the tacit knowledge of the process had been lost and existing process maps were considered to be obsolete. In lieu of these, there was a perception that the process was not being executed consistently across the team. A documented process was requested to provide a shared understanding of what activities were executed, who was responsible for executing these and what recommendations could be offered for improving this process.

To commence, the process that had been captured during the case study was interrogated to establish the similarities between the current process and that which was conducted at the time of the case study. After initial investigation, it was determined that the process had developed since the time of the initial investigation and as such, the findings from the case study were not immediately applicable. As such, a workshop was organised with key individuals from the engineering change management process to establish the activities that were conducted and determine the interdependencies between these. Using the five phase model of the engineering change management process (secondary contribution SC-2), this offered a framework to proceed through the process and enable the practitioners to systematically identify the activities that were executed. It also provided a mechanism for defining the activities in a standardised form so that activities that were defined differently by different individuals, but were essentially the same could be referred to in the correct manner. Once the capture had taken place, the activity taxonomy was then used (secondary contribution SC-3) to determine whether additional activities should be considered with the benefits and limitations of implementing certain activities discussed.

As a result of this work, the developed map was used to facilitate understanding between project team members, highlighting how the activities they enacted were placed within the overall process. This enabled an improved consistency of approach across the project. It also enabled specific activities that were deemed to be the most complex or risky to be focussed on. From this, desktop instructions were developed to provide clarity over what should be done at a detailed activity level.

11.3 Implementation of an engineering change management process

Based on the research that had been conducted, a request was received from an engineering manager to set up an engineering change management process on a ship design project in one of Babcock's UK shipyards. The manager had raised concerns over the configuration of the ship and wanted to make sure that engineering changes were controlled appropriately. For this, the manager requested support in two areas: deciding at what stage of the design project to implement an engineering change management process and what information the engineering change documentation should contain.

Based on existing theory, the implementation of an engineering change management process could only be recommended following the detailed design stage. However, from the recommendations outlined in section 10.1.3, it was suggested that an engineering change management process be implemented as soon as possible, even though certain sections of the ship had not completed the detailed design stage. It was advised that this process should be proportionate to the stage of the product lifecycle, with a formal and documented engineering change management process being required for all changes to the structure of the engineered artefact within specific zones, once that zone had successfully completed a detailed design review (primary contribution PC-3: recommendation Rec-4). However, prior to these zones proceeding through the detailed design stage, the principal structural elements should also be placed under formal engineering change control. This meant that any changes to the configuration of the engineering artefact were to be captured, documented and formally approved prior to the change being instantiated following the completion of a detailed design review. In addition, any principal structural elements should be processed in this manner also.

As a result of this implementation, the configuration control of the design was improved. Modifications to existing parts were permitted, but had to be justified and traceable to documented design rationale, leading to a position in which only changes that had to be made were permitted. It also provided the design team with an understanding of when the design was to be frozen meaning that changes that were not approved were not implemented without an understanding of the impact that the change had on the design. Implementing this process early in the design process also enabled the design team to understand what they could and couldn’t change as the design developed.

In addition, the engineering manager requested the development of a documented engineering change management process to communicate and control engineering changes. From this research, the risks associated with an inefficient process have been highlighted. As such, effort was expended to develop an engineering change request document template that minimised the length of time to complete, breaking down barriers to the timely completion of this (primary contribution PC-3: recommendation Rec-2). In addition, by focussing the content on the key required information in terms of function, behaviour and structure, engineering change practitioners were able to support their knowledge of the engineered artefact leading to improved decision making throughout the engineering change management process (primary contribution PC-2 & PC-3: recommendation Rec-6).

11.4 Development of design maturity measurement method

It has been previously reported that engineering changes are inevitable in engineering projects following the detailed design and production stages (Huang, Yee et al. 2001). This finding has been emphasised by this research and, through studying different stages of the product lifecycle as described in RQ 1, extended to demonstrate that engineering changes also exist within the conceptual design and in-service stages (secondary contribution SC-1). Accepting the premise that the design of an engineering artefact will change throughout its development, the researcher led a project to integrate the likelihood of engineering change into the progress of the project during the conceptual and detailed design stages. Using the term design maturity and decomposing it into a function of design completion (the degree to which the current state of the engineering artefact reflected the required state) and stability confidence (how likely is it that the current state of the engineering artefact will change) a new measure that integrated the chance of engineering change into the design process was established. This was subsequently implemented into the development of an offshore patrol vessel that was, at the time of implementation, currently within the detailed design stage.

Based on research executed to answer RQ 2, it was establish that functional, behavioural and structural knowledge are all strongly linked with the engineering change management process. Therefore, the implementation commenced by decomposing the ship into its structural elements and linking these to their corresponding functional and behavioural requirements. Linking the structural elements together in this manner then meant that if the design was to change, then the functional and behavioural requirements could readily established, supporting the knowledge required for engineering change management process. The design completion and stability confidence for each of these structural elements were then estimated and the product of these estimates was used to define the design maturity of each structural element. For a more global representation of design maturity, the product of the design maturities of each of the structural elements was then calculated against a set of predefined criteria to provide an indication of the design maturity at different stages of the product lifecycle.

Based on this measurement technique, a number of benefits were brought about. Firstly, this technique was used as a prequalification assessment mechanism for design reviews, to determine whether the design was mature enough to proceed to the reviews. This eliminated the execution of reviews in which the design development was insufficient, resulting in a reduced number of hours spent on unproductive reviews. In addition, it enabled the engineering manager to identify immature architectural elements within the engineered artefact. Based on this knowledge, the engineering manager could then prioritise design resource to focus on areas that demonstrated significant immaturities, to ensure that the design maturity was uniform across all systems within the engineered artefact. Finally, it provided senior management with a clear and concise view of project progress that reflected the progress made on current state of the design and how likely the current state was to change. This enabled the senior management with the basis for determining whether additional resources were required to be provided on the project.

A detailed description of the proposed design maturity process and a case study of its implementation can be found in the paper presented by Rowell and Rodgers (2012).

11.5 Chapter summary

This chapter aimed to outline how the findings and recommendations contained within this thesis had been exploited by the sponsoring company. To that end, this chapter commenced by outlining four issues that related to engineering change management that had been identified by the sponsoring company. Taking each issue in turn, the context that brought about the identification of the issue was outlined and the solutions to overcome these presented. In total, three cases were described that covered the four issues raised and the corresponding contributions that were used within each of the cases discussed. To summarise the link between the company issues and the corresponding contributions, Figure 40 is presented.

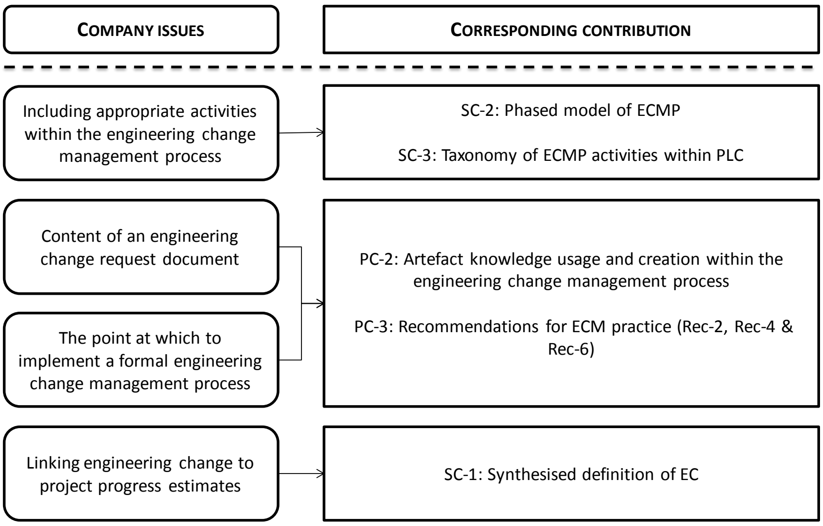


Figure 40 - Link between company issues and thesis contributions

Chapter 12 - CONCLUSION

The primary aim of the research reported in this thesis was to characterise the variations in the engineering change management process within the product lifecycle and explore the relationship between this process and artefact knowledge. From this, recommendations for future engineering change management practice were sought, translating the findings from this research into practical advice for engineering change management practitioners. As such, chapters 6, 7 and 8 present the findings from a case study of three engineering projects and a survey of seventy nine engineering change practitioners. Subsequent triangulation is then presented in chapter 9, highlighting the similarities and differences between these research methods and presenting models of engineering change management.

The contribution of the research presented in this thesis is made up of a number of elements. As an overall summary of the work, Figure 41 highlights these elements and the relationships that exist between these. Aligning with these elements, the rest of the chapter summarises these and offers conclusion to this thesis.

12.1 PC-1: Engineering change management process variations within the product lifecycle

A review of literature confirms that significant research effort has been expended to describe the nature of engineering change management in industry. However, limited by the paradigm that engineering changes are constrained to the latter stages of the product lifecycle, a significant proportion of this work has focussed on the detailed design and production stages. Offering an argument that engineering change can and does exist throughout the product lifecycle, this thesis proposed a new perspective on engineering change, opening the possibility for research into engineering change within the early design and through-life service stages of the product lifecycle. Building upon this increased scope, a significant proportion of the research reported in this thesis was executed to establish the variations in the engineering change management process within the product lifecycle, focussing primarily on the activities that composed this process.

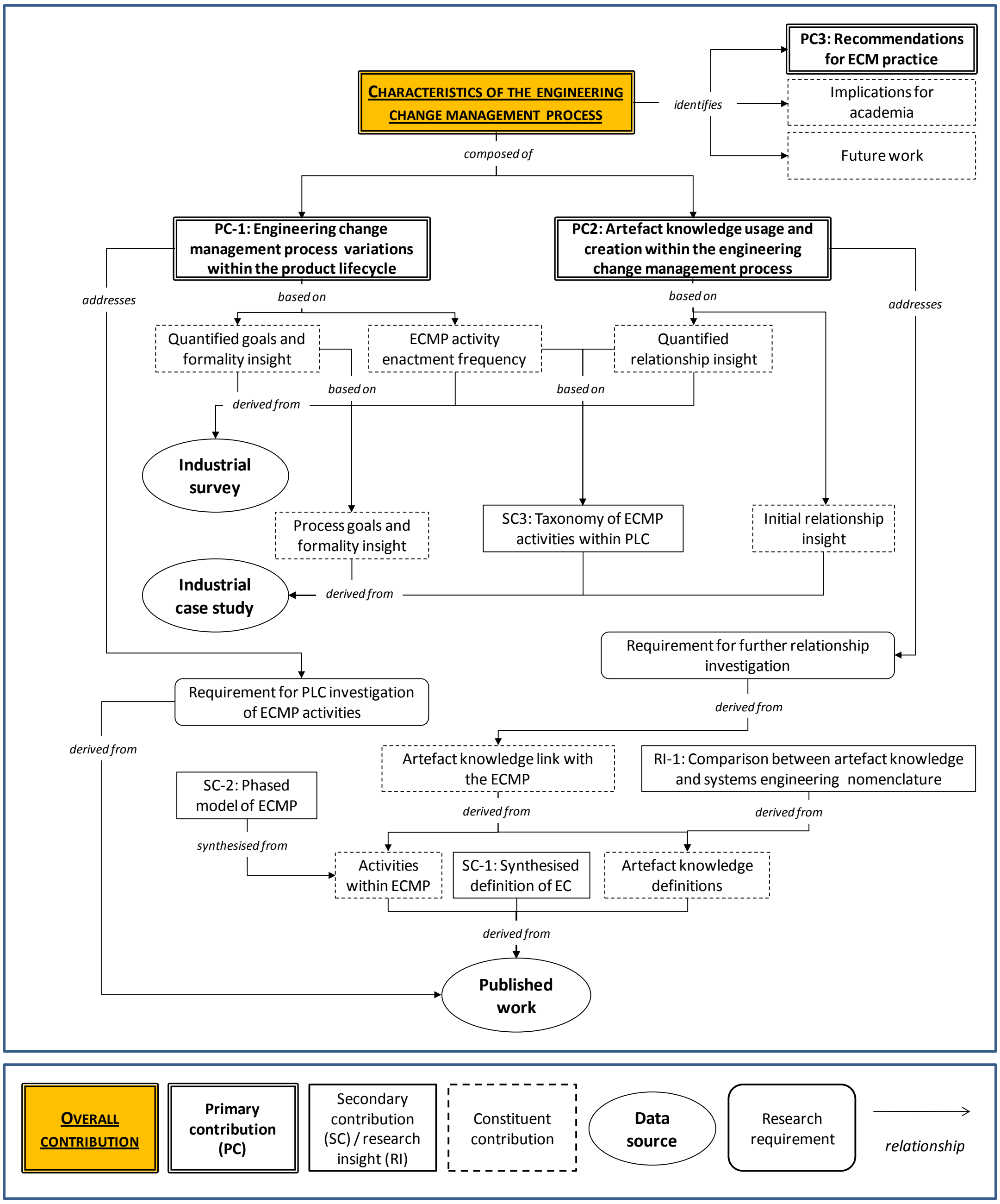


Figure 41 - Contribution map

Through a case study and survey, a total of seventeen distinct activities were identified as composing the engineering change management process. Coupling these activities with the product lifecycle stage subsequently demonstrated that all the activities that compose the engineering change management process could be enacted throughout; however, variations in their enactment were evident in certain stages. In particular, the frequency in which the activities were enacted was found to vary at different lifecycle stages. Exploring the variation in enactment frequency led to a number of insights into engineering change management. Firstly, it was demonstrated that an engineering change was more likely to be implemented during the latter stages of the product lifecycle than within the early stages. Secondly, that it was more likely that the performance of a proposed solution would be verified prior to implementation during detailed design and in-service stages. Thirdly, that a greater emphasis was placed on maintaining the traceability of the development of an engineered artefact through the engineering change management process during the conceptual and detailed design stages.

In addition, emerging from the case study four other characteristics were found to vary throughout the product lifecycle. First, the formality of the process was found to vary. Previous research had informed that engineering change management processes were more formal after the detailed design stage. The work reported in this thesis extended this insight, demonstrating that whilst this was the case for the detailed design and production stages, less formal processes existed within the conceptual design and in-service stages. The lifecycle stage was also found to have an influence on the goal of the process. Whilst the primary goal throughout the product lifecycle was to provide the most accurate impact assessments, this goal was found to be most important during the detailed design and production stages. The activity clarity was also found to vary, with activities within the conceptual design and in-service stages being less distinct than those in the detailed design and production stages. Finally, the initiatives that had been put in place to improve the performance of the engineering change management process were found to vary. These varied from keeping the design teams small to maintain local control over the changes within the conceptual design and in-service stages, to implementing changes prior to approval to speed the process up within the detailed design and production stages.

Based on these findings it is evident that the activities that compose the engineering change management process are similar within the product lifecycle. This highlights that the same process could be adopted in each stage of the product lifecycle was some success. However, merely applying the same process ignores some of the nuances that occur throughout the product lifecycle. As such, the eight characteristics of the engineering change management process that have been found to vary are important as they provide engineering change practitioners with a more holistic understanding of the differences between these processes at different stages of the product lifecycle.

12.2 PC-2: Artefact knowledge usage and creation within the engineering change management process

As discussed previously, significant research effort has been expended to describe the nature of engineering change management. This research effort has enabled the activities that compose this process to be established and influences upon these processes described. By comparison, relatively less research work has been put into determining the inputs and outputs of these activities, with significantly less work focussing on formalising the relationship between the knowledge of the individual and enactment of these activities. This creates a position in which the information sources that are used and created have been described; however, little is known about the knowledge that the engineering change practitioners use to enact these activities and create as a result of this enactment. In such a case, crucial inputs to these activities and outputs from these activities have been omitted or assumed.

Exploring the relevant literature, a link between artefact knowledge and the engineering change management process became apparent. In a range of previous papers in the field, artefact knowledge had been assumed to be a prerequisite for the management of engineering change. This, often tacit assumption led to the emergence a research question in regard to the types of artefact knowledge that are used to enact the activities that compose the engineering change management process and those created through this enactment.

Through triangulation of the findings from the case study, survey and literature review, this thesis offers a formalisation of the relationship between artefact knowledge and engineering change management process. From this it is evident that artefact knowledge is used and created throughout the engineering change management process. However, it is most frequently used and created within the identification and approval phases. Furthermore, the most frequently used and created types of artefact knowledge were that of expected function, expected behaviour and expected structure. This finding acts to demonstrate the importance of engineering change practitioners possessing artefact knowledge within the engineering change management process. Furthermore, it stresses the need for this knowledge within the identification and approval phases in particular.

This finding also has an implication for the future development of engineering change support systems. From literature, it was evident that the majority of these systems focus solely on supporting structural knowledge. However, this research has stressed the need for functional and behavioural knowledge within the engineering change management process as well. As such, this thesis forms the basis for the argument that future engineering change support system development should move beyond solely structural knowledge modelling, incorporating behavioural and functional knowledge as well.

12.3 PC-3: Recommendations for engineering change management practice

Reflecting the nature of the research questions presented in section 4.4 and based on the findings from this research, a total of six recommendations to improve the future engineering change management practice were offered. The basis and justification for these recommendations are presented in sections 10.1.3. Nevertheless, four recommendations that are offered based upon enquiry into RQ 1 are offered:

1. Instead of a single engineering change management process for all engineering changes, create multiple processes with the activities that are required to be executed during this process reflecting the scale of the engineering changes that are to be processed.

2. Ensure each engineering change is formally approved and break down the barriers to this approval taking place in a timely manner.

3. Place a greater emphasis on the development of an optimum technical solution rather than the speed of implementation or the accuracy of the impact assessment.

4. Commence formal engineering change management as early within the product lifecycle as possible; however, ensure that the process and scale of the changes that are managed through this process are proportional to the lifecycle stage.

In addition to these, two recommendations are offered based on enquiry into RQ 2:

5. Provide clear guidance at the start of the project that defines the inputs and outputs for each of the activities and highlights the relationships between the activities.

6. Ensure all engineering change documentation supports functional and behavioural knowledge by including the functional and non-functional requirements of the

equipment that could be impacted as a result of the engineering change being implemented.

12.4 Secondary knowledge contributions and research insights

Whilst the research reported within this thesis has been primarily executed to answer two research questions, through striving to answer these, a number of interrelated contributions to knowledge have emerged. Within this section, three secondary contributions are presented along with an additional research insight. Alongside a description of these contributions and insight, the implications for both academia and industry are also reported.

12.4.1 SC-1: Synthesised definition for engineering change

In chapter 2, it was reported that multiple different published definitions of engineering change exist within engineering change literature. Decomposing these definitions into the subject of the engineering change and the constraints that are placed upon the definitions, a discussion was presented, highlighting the consistencies and inconsistencies between these definitions. Through a synthesis of this discussion a definition of engineering change has been offered that captured the core elements of the published definitions. As such, engineering change was defined as: a modification to one or more of an artefact’s structural parameters, of which the state of the structural parameter, prior to the modification and during the current development project, had been agreed to be fixed. Incorporating recent research the fundamental shift presented in this definition is the concept that engineering changes can and do exist throughout the product lifecycle, rather than solely within the latter stages of product development. Furthermore, it argues that engineering changes are not limited to modifying documents or drawings; instead, an engineering change must modify a defined parameter, in whatever form the defined parameter is recorded in.

Given the multiple definitions of engineering change and the number of articles that have been published which adhere to these different definitions, clear comparisons between these articles was not possible. Offering a synthesised definition of engineering change that is grounded in those published enables these papers to be compared and contrasted more appropriately. Furthermore, future research that adheres to the presented definition would enable comparisons to be made between different research projects with an improved degree of accuracy. From a practical perspective, currently industry operates on a tacit understanding of what constitutes an engineering change. This emerges as a lack of distinction between engineering changes, other types of changes and standard product development activities. Offering a standardised definition for engineering change enables industry to better understand what engineering change is and as such, what should be managed through the engineering change management process.

12.4.2 SC-2: Phase model of the engineering change management process

In chapter 2, a range of published engineering change management processes have been presented. These processes have been demonstrated to consist of a number of activities. Grouping these activities together revealed five fundamental phases to the engineering change management process, namely identification, generation, prediction, approval and implementation. Subsequently, through the case study and survey, this model was found to be representative of all engineering change management processes analysed. This demonstrates the validity of the five phase model of engineering change as a generic representation of the engineering change management process.

Given the range and varying complexity of engineering change management process models reported in literature, the phase model presents a simplified view that encompasses a number of potentially project specific activities. This high level model therefore enables the researcher to classify which activities are enacted within each product lifecycle stage, modelling the process with a greater degree of accuracy. Further, engineering change management processes in industry can be complex involving the enactment of a range of engineering change activities. Applying the five phase framework, the activities that compose the engineering change management process can be grouped within these phases providing a simplified view of the process.

12.4.3 SC-3: Taxonomy of engineering change management process activities

Based on a review of literature a total of twelve activities were reported to compose the engineering change management process. This thesis has extended the number of activities within this process by five, demonstrating that the engineering change management process composes seventeen activities: documenting (identification), evaluating, realising, documenting (generation), modelling, structuring, validating, analysing, composing, distributing, planning, testing, authorising, ensuring, instantiating and ordering. Of these, the acts of evaluating, validating, distributing and ordering were found to be new activities whilst the acts of structuring and modelling were found to compose the act of solution generation.

Presenting a synthesis of the activities that were reported in literature, the case study and the survey has led to the development of an engineering change management process activity taxonomy. This taxonomy provides a means of rationalising the specific activities enacted in different engineering change management processes. Of these discrete activities, chapter 3 has demonstrated that engineering change support system development is currently focused on the acts of analysis and implementation. Recognising other activities within the engineering change management process, future research work is required to develop support systems for these activities. In addition, given that a significant number of engineering projects that have formal processes for the management of engineering change, at some point this process needs to be designed before it can be implemented. Offering a list of activities that are enacted in different engineering change management processes enables the process architect to consider the inclusion of specific activities within their process. Furthermore, it provides a benchmark against which existing engineering change management processes can be assessed.

12.4.4 RI-1: Comparison between artefact knowledge and systems engineering nomenclature

Through exploration of the relationship between artefact knowledge and the engineering change management process, similarities between artefact knowledge and system engineering nomenclature became apparent. Acting as a secondary contribution, this thesis has compared this nomenclature used in artefact knowledge and systems engineering literature and presented a mapping of the different terms used (see section 3.1.5). This has relevance for both industry and academia as it relates work that covers artefact knowledge to that in systems engineering. As such, comparisons between these fields can now be made with greater clarity.

12.5 Strengths and weaknesses of the research

Summarising the discussion of strengths and weaknesses of the main findings, research method and research methodology this validity and reliability of the findings have been discussed (see section chapter 10). Adopting a post-positivist philosophical stance, the researcher has accepted the premise that all knowledge is fallible and all theory revisable. Reflecting this, methodological triangulation has been at the heart of the research process. Using data from published work, a case study of three separate projects and a survey of seventy nine engineering practitioners, and triangulating the results has meant that the bias involved in answering the research questions has been reduced, but not eliminated. In addition, whilst this work has used the input from a range of engineering practitioners, the results may provide an insight into what the reality of the wider engineering community but the sample size could not be considered to be wholly representative this population.

Continuing the theme of triangulation, literature also recommends that multiple investigators are used. Processing the same data, different interpretations of this may occur that through discussion could provide further clarity. However, during this research project, investigator triangulation has not been implemented. Instead only the author of this thesis has been involved with the interpretation of the data. This is of particular relevance when synthesising published work and encoding the interview transcripts. During these stages multiple different perspectives of the same process are offered, containing a range of different terminology. To increase the reliability of the study, a data collection protocol was developed and described. As such, whilst investigator triangulation has not been achieved, it is envisaged that if another researcher was to follow this protocol then the same, or very similar, output would be achieved.

12.6 Future work

Reflecting upon the strengths and weaknesses of the work contained in this thesis and the contributions that have been presented, this study calls for further research in a number of areas. Grouping these areas together, three main categories of future research have been established: further methodological triangulation; directly related research avenues and postulations on future engineering change management research.

12.6.1 Further methodological triangulation

First, recognising that a post-positivist philosophy relies upon the triangulation of a number of different methods, future research could focus on providing further triangulation through either the execution of additional research methods or a shift from a cross sectional study to a longitudinal one. To this end, two further research activities are considered:

- Execution of additional research methods
- Repetition of study adopting a longitudinal rather than cross sectional approach

12.6.2 Directly related research avenues

In addition, recognising the contributions contained within this thesis and the implications that this has for academia, potential future research work could also be focused on the following areas:

- Development of future engineering change support systems
- Prescription of artefact knowledge usage and creation
- Goal identification and influences

12.6.3 Postulations on future engineering change management research

Finally, considering the wider field of engineering change literature that has been reviewed throughout this research work, three further areas of research work are also considered as avenues for future work:

- Knowledge usage and creation beyond the product domain
- Initiation point identification for implementation of formal engineering change management processes
- A sociotechnical approach to engineering change management optimisation

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APPENDIX A – INTERVIEW TRANSCRIPTS

Due to the size of the interview transcripts it has been decided to omit these from the appendix. However, these transcripts are available upon request.

APPENDIX B – SURVEY QUESTIONNAIRE

University of Strathclyde
Engineering

THE ENGINEERING CHANGE MANAGEMENT PROCESS: VARIATIONS ACROSS PRODUCT LIFECYCLE

The engineering change management process can be considered to be a series of interrelated activities that facilitate modification to a product. This study seeks to establish how this process changes during the various lifecycle stages that a product goes through. As such, this questionnaire focuses on the activities that are performed and the knowledge that is drawn upon and created during the engineering change management process.

You have been selected to complete this survey based upon your experience within the engineering industry and exposure to the change process.

Thank you very much for your assistance!

Willie Rowell
Engineering Doctorate (EngD) student

william.rowell@strath.ac.uk
07716 357 459

M106, James Weir Building, University of Strathclyde,
75 Montrose Street, Glasgow, G1 1XJ, UK

Your information

Job title: ____

Engineering experience (years): ______________________________

Project lifecycle stage: conceptual design / detailed design / production / in-service

General engineering change management questions

Do you have a formal method for processing engineering changes within your project?

Yes / No

If so, are all engineering changes processed in this manner?

Yes / No

Engineering change management goals

The engineering change management process can be considered to be driven by a number of process goals. Based on your own experience, please could you rank these from most important to least important (1 being most important and 3 being least important)?

Process goal	Rank
Accuracy of impact assessment (to establish the effects of the change as accurately and comprehensively as possible)	
Development of optimum technical solution (to create the best technical solution that overcomes the need to change)	
Speed of implementation (get through the engineering change management process as fast as possible)	
Other (please state)	

Activities associated with the engineering change management process

From your experience, please indicate by ticking the relevant boxes how frequently the activities listed below are performed for each engineering change that occurs within the project that you current work (please leave blank if you are unsure of the answer).

Phase	**Activity**	**How frequently are these activities performed for each engineering change that occurs?**				
		Never (0%)	**Occasionally** (1 – 33%)	**Sometimes** (34 – 66%)	**Frequently** (67 – 99%)	**Always** (100%)
Identification	1. Recognising a problem / opportunity					
	2. Evaluation of the existing design					
	3. Creation of a text based description of the problem / opportunity					
	Other (please state)					
Generation	4. Creation of a solution to overcome the problem / opportunity					
	5. Creation of a text based description of the new solution					
	6. Creation of drawings or sketches of the new solution					
	7. Selection of one of the solutions from a number of possible solutions					
	8. Validating that the problem / opportunity actually exists					
	Other (please state)					
Prediction	9. Identifying and informing impacted individuals					
	10. Predicting the effects of implementing the new solution					
	11. Collating the impacts associated with the change					
	12. Planning the associated tasks that are required to implement the new solution					
	13. Prototyping / trialling the new solution					
	Other (please state)					
Approval	14. Choosing whether to authorise the change or not					
	Other (please state)					
Implementation	15. Checking that the implementation is proceeding					
	16. Implementing the new solution					
	17. Procurement of the relevant equipment and material to enable implementation					
	Other (please state)					

Identification phase

Please indicate by ticking the relevant boxes: **1.** What type of information do you require / use to perform these activities? and, **2.** What information do you modify / create as a result of the activities? Examples of the possible sources of this information are presented for convenience.

- If you indicated in the previous part of the questionnaire that the activities are either never performed or that you were unsure whether the activities are performed then please disregard the corresponding activity in this part.

Activities **Information**	1. Recognising a problem / opportunity		2. Evaluation of the existing design		3. Creation of a text based description of the problem / opportunity	
	Require / use to perform activity	Modify / create as a result of activity	Require / use to perform activity	Modify / create as a result of activity	Require / use to perform activity	Modify / create as a result of activity
The purpose of the product (e.g. functional requirements)						
How the purpose is expected to be achieved (e.g. system requirements, design parameters, design intent)						
The expected form, dimensions or materials for the product (e.g. change request documents, design decisions)						
The current form, dimensions or materials of the product (e.g. 3D models, 2D drawings)						
The current performance characteristics of the product (e.g. system specification)						
The emergent behaviour of the product in certain conditions (e.g. operational constraints)						
The functions that the product achieves (e.g. compliancy matrix)						
Other (please describe)						

Generation phase

Please indicate by ticking the relevant boxes: **1.** What type of information do you require / use to perform these activities? and, **2.** What information do you modify / create as a result of the activities? Examples of the possible sources of this information are presented for convenience.

- If you indicated in the previous part of the questionnaire that the activities are either never performed or that you were unsure whether the activities are performed then please disregard the corresponding activity in this part.

Activities / **Information**	4. Creation of a solution to overcome the problem / opportunity		5. Creation of a text based description of the new solution		6. Creation of drawings or sketches of the new solution		7. Selection of one of the solutions from a number of possible solutions		8. Validating that the problem / opportunity actually exists	
	Require / use to perform activity	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**
The purpose of the product (e.g. functional requirements)										
How the purpose is expected to be achieved (e.g. system requirements, design parameters, design intent)										
The expected form, dimensions or materials for the product (e.g. change request documents, design decisions)										
The current form, dimensions or materials of the product (e.g. 3D models, 2D drawings)										
The current performance characteristics of the product (e.g. system specification)										
The emergent behaviour of the product in certain conditions (e.g. operational constraints)										
The functions that the product achieves (e.g. compliancy matrix)										
Other (please describe)										

Prediction phase

Please indicate by ticking the relevant boxes: **1.** What type of information do you require / use to perform these activities? and, **2.** What information do you modify / create as a result of the activities? Examples of the possible sources of this information are presented for convenience.

- If you indicated in the previous part of the questionnaire that the activities are either never performed or that you were unsure whether the activities are performed then please disregard the corresponding activity in this part.

Activities **Information**	9. Identifying and informing impacted individuals		10. Predicting the effects of implementing the new solution		11. Collating the impacts associated with the change		12. Planning the associated tasks that are required to implement the new solution		13. Prototyping / trailing the new solution	
	Require / use to perform activity	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**	**Require / use to perform activity**	**Modify / create as a result of activity**
The purpose of the product (e.g. functional requirements)										
How the purpose is expected to be achieved (e.g. system requirements, design parameters, design intent)										
The expected form, dimensions or materials for the product (e.g. change request documents, design decisions)										
The current form, dimensions or materials of the product (e.g. 3D models, 2D drawings)										
The current performance characteristics of the product (e.g. system specification)										
The emergent behaviour of the product in certain conditions (e.g. operational constraints)										
The functions that the product achieves (e.g. compliancy matrix)										
Other (please describe)										

Approval phase

Please indicate by ticking the relevant boxes: **1.** What type of information do you require / use to perform these activities? and, **2.** What information do you modify / create as a result of the activities? Examples of the possible sources of this information are presented for convenience.

- If you indicated in the previous part of the questionnaire that the activities are either never performed or that you were unsure whether the activities are performed then please disregard the corresponding activity in this part.

Activities / **Information**	14. Choosing whether to authorise the change or not	
	Require / use to perform activity	Modify / create as a result of activity
The purpose of the product (e.g. functional requirements)		
How the purpose is expected to be achieved (e.g. system requirements, design parameters, design intent)		
The expected form, dimensions or materials for the product (e.g. change request documents, design decisions)		
The current form, dimensions or materials of the product (e.g. 3D models, 2D drawings)		
The current performance characteristics of the product (e.g. system specification)		
The emergent behaviour of the product in certain conditions (e.g. operational constraints)		
The functions that the product achieves (e.g. compliancy matrix)		
Other (please describe)		

Implementation phase

Please indicate by ticking the relevant boxes: **1.** What type of information do you require / use to perform these activities? and, **2.** What information do you modify / create as a result of the activities? Examples of the possible sources of this information are presented for convenience.

- If you indicated in the previous part of the questionnaire that the activities are either never performed or that you were unsure whether the activities are performed then please disregard the corresponding activity in this part.

Activities **Information**	15. Checking that the implementation is proceeding		16. Implementing the new solution		17. Procurement of the relevant equipment and material to enable implementation	
	Require / use to perform activity	Modify / create as a result of activity	Require / use to perform activity	Modify / create as a result of activity	Require / use to perform activity	Modify / create as a result of activity
The purpose of the product (e.g. functional requirements)						
How the purpose is expected to be achieved (e.g. system requirements, design parameters, design intent)						
The expected form, dimensions or materials for the product (e.g. change request documents, design decisions)						
The current form, dimensions or materials of the product (e.g. 3D models, 2D drawings)						
The current performance characteristics of the product (e.g. system specification)						
The emergent behaviour of the product in certain conditions (e.g. operational constraints)						
The functions that the product achieves (e.g. compliancy matrix)						
Other (please describe)						

APPENDIX C – SURVEY DATA

In the following appendix, the activity enactment frequency for each of the activities that compose the engineering change management process and the artefact knowledge usage and creation through the enactment of these activities is displayed based upon the results from the survey.

Documenting (identification)

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	71.4%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	4	22%	0.5	0.11	
	67% - 100%	13	72%	0.835	0.60	
Detailed design	-	0	0%	0	0.00	74.8%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	7	26%	0.5	0.13	
	67% - 100%	20	74%	0.835	0.62	
Production	-	0	0%	0	0.00	55.9%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	8	47%	0.5	0.24	
	67% - 100%	6	35%	0.835	0.29	
In-service	-	2	11%	0	0.00	55.6%
	0% - 33%	4	22%	0.165	0.04	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	10	56%	0.835	0.46	
Across product lifecycle	-	3	4%	0	0.00	65.7%
	0% - 33%	7	9%	0.165	0.01	
	34% - 66%	21	26%	0.5	0.13	
	67% - 100%	49	61%	0.835	0.51	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	10	59%	6	35%	10	40%	5	20%	15	88%	0	0%	9	64%	7	50%	44	60%	18	25%
	No	7	41%	11	65%	15	60%	20	80%	2	12%	17	100%	5	36%	7	50%	29	40%	55	75%
Expected behaviour	Yes	8	47%	6	35%	12	48%	4	16%	13	76%	6	35%	10	71%	6	43%	43	59%	22	30%
	No	9	53%	11	65%	13	52%	21	84%	4	24%	11	65%	4	29%	8	57%	30	41%	51	70%
Expected structure	Yes	7	41%	6	35%	14	56%	6	24%	13	76%	3	18%	6	43%	5	36%	40	55%	20	27%
	No	10	59%	11	65%	11	44%	19	76%	4	24%	14	82%	8	57%	9	64%	33	45%	53	73%
Instantiated structure	Yes	10	59%	7	41%	11	44%	3	12%	12	71%	5	29%	5	36%	1	7%	38	52%	16	22%
	No	7	41%	10	59%	14	56%	22	88%	5	29%	12	71%	9	64%	13	93%	35	48%	57	78%
Instantiated behaviour	Yes	12	71%	5	29%	13	52%	4	16%	10	59%	3	18%	7	50%	4	29%	42	58%	16	22%
	No	5	29%	12	71%	12	48%	21	84%	7	41%	14	82%	7	50%	10	71%	31	42%	57	78%
Interpreted behaviour	Yes	9	53%	4	24%	10	40%	3	12%	8	47%	2	12%	6	43%	6	43%	33	45%	15	21%
	No	8	47%	13	76%	15	60%	22	88%	9	53%	15	88%	8	57%	8	57%	40	55%	58	79%
Interpreted function	Yes	10	59%	9	53%	11	44%	3	12%	8	47%	1	6%	4	29%	5	36%	33	45%	18	25%
	No	7	41%	8	47%	14	56%	22	88%	9	53%	16	94%	10	71%	9	64%	40	55%	55	75%

Evaluating

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	73.3%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	15	83%	0.835	0.70	
Detailed design	-	1	4%	0	0.00	63.0%
	0% - 33%	5	19%	0.165	0.03	
	34% - 66%	4	15%	0.5	0.07	
	67% - 100%	17	63%	0.835	0.53	
Production	-	0	0%	0	0.00	61.8%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	9	53%	0.835	0.44	
In-service	-	0	0%	0	0.00	65.8%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	2	3%	0	0.00	65.7%
	0% - 33%	12	15%	0.165	0.03	
	34% - 66%	13	16%	0.5	0.08	
	67% - 100%	52	66%	0.835	0.55	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	15	88%	4	24%	19	79%	5	21%	15	88%	2	12%	11	65%	8	47%	60	80%	19	25%
	No	2	12%	13	76%	5	21%	19	79%	2	12%	15	88%	6	35%	9	53%	15	20%	56	75%
Expected behaviour	Yes	12	71%	6	35%	18	75%	6	25%	16	94%	6	35%	11	65%	8	47%	57	76%	26	35%
	No	5	29%	11	65%	6	25%	18	75%	1	6%	11	65%	6	35%	9	53%	18	24%	49	65%
Expected structure	Yes	6	35%	7	41%	16	67%	7	29%	14	82%	6	35%	9	53%	8	47%	45	60%	28	37%
	No	11	65%	10	59%	8	33%	17	71%	3	18%	11	65%	8	47%	9	53%	30	40%	47	63%
Instantiated structure	Yes	11	65%	6	35%	19	79%	8	33%	14	82%	7	41%	10	59%	6	35%	54	72%	27	36%
	No	6	35%	11	65%	5	21%	16	67%	3	18%	10	59%	7	41%	11	65%	21	28%	48	64%
Instantiated behaviour	Yes	13	76%	2	12%	16	67%	4	17%	12	71%	4	24%	12	71%	9	53%	53	71%	19	25%
	No	4	24%	15	88%	8	33%	20	83%	5	29%	13	76%	5	29%	8	47%	22	29%	56	75%
Interpreted behaviour	Yes	11	65%	5	29%	13	54%	10	42%	9	53%	3	18%	11	65%	11	65%	44	59%	29	39%
	No	6	35%	12	71%	11	46%	14	58%	8	47%	14	82%	6	35%	6	35%	31	41%	46	61%
Interpreted function	Yes	9	53%	6	35%	12	50%	8	33%	11	65%	1	6%	7	41%	6	35%	39	52%	21	28%
	No	8	47%	11	65%	12	50%	16	67%	6	35%	16	94%	10	59%	11	65%	36	48%	54	72%

Realising

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	73.3%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	3	17%	0.5	0.08	
	67% - 100%	14	78%	0.835	0.65	
Detailed design	-	0	0%	0	0.00	76.1%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	6	22%	0.5	0.11	
	67% - 100%	21	78%	0.835	0.65	
Production	-	0	0%	0	0.00	67.7%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	11	65%	0.835	0.54	
In-service	-	0	0%	0	0.00	79.6%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	2	12%	0.5	0.06	
	67% - 100%	15	88%	0.835	0.74	
Across product lifecycle	-	1	1%	0	0.00	74.4%
	0% - 33%	2	3%	0.165	0.00	
	34% - 66%	15	19%	0.5	0.09	
	67% - 100%	61	77%	0.835	0.64	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	17	100%	5	29%	19	76%	14	56%	13	76%	2	12%	12	71%	10	59%	61	80%	31	41%
	No	0	0%	12	71%	6	24%	11	44%	4	24%	15	88%	5	29%	7	41%	15	20%	45	59%
Expected behaviour	Yes	12	71%	6	35%	15	60%	13	52%	13	76%	8	47%	12	71%	6	35%	52	68%	33	43%
	No	5	29%	11	65%	10	40%	12	48%	4	24%	9	53%	5	29%	11	65%	24	32%	43	57%
Expected structure	Yes	12	71%	6	35%	17	68%	12	48%	15	88%	5	29%	10	59%	9	53%	54	71%	32	42%
	No	5	29%	11	65%	8	32%	13	52%	2	12%	12	71%	7	41%	8	47%	22	29%	44	58%
Instantiated structure	Yes	12	71%	8	47%	16	64%	11	44%	12	71%	9	53%	8	47%	8	47%	48	63%	36	47%
	No	5	29%	9	53%	9	36%	14	56%	5	29%	8	47%	9	53%	9	53%	28	37%	40	53%
Instantiated behaviour	Yes	14	82%	7	41%	12	48%	10	40%	8	47%	3	18%	13	76%	4	24%	47	62%	24	32%
	No	3	18%	10	59%	13	52%	15	60%	9	53%	14	82%	4	24%	13	76%	29	38%	52	68%
Interpreted behaviour	Yes	12	71%	6	35%	10	40%	11	44%	9	53%	3	18%	9	53%	8	47%	40	53%	28	37%
	No	5	29%	11	65%	15	60%	14	56%	8	47%	14	82%	8	47%	9	53%	36	47%	48	63%
Interpreted function	Yes	12	71%	6	35%	9	36%	10	40%	6	35%	0	0%	5	29%	8	47%	32	42%	24	32%
	No	5	29%	11	65%	16	64%	15	60%	11	65%	17	100%	12	71%	9	53%	44	58%	52	68%

Documenting (generation)

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	71.4%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	4	22%	0.5	0.11	
	67% - 100%	13	72%	0.835	0.60	
Detailed design	-	0	0%	0	0.00	64.9%
	0% - 33%	3	11%	0.165	0.02	
	34% - 66%	9	33%	0.5	0.17	
	67% - 100%	15	56%	0.835	0.46	
Production	-	0	0%	0	0.00	67.7%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	8	47%	0.5	0.24	
	67% - 100%	9	53%	0.835	0.44	
In-service	-	0	0%	0	0.00	67.7%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	1	1%	0	0.00	67.6%
	0% - 33%	5	6%	0.165	0.01	
	34% - 66%	25	32%	0.5	0.16	
	67% - 100%	48	61%	0.835	0.51	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	10	59%	4	24%	10	42%	5	21%	9	53%	3	18%	4	24%	6	35%	33	44%	18	24%
	No	7	41%	13	76%	14	58%	19	79%	8	47%	14	82%	13	76%	11	65%	42	56%	57	76%
Expected behaviour	Yes	7	41%	10	59%	10	42%	10	42%	12	71%	8	47%	8	47%	9	53%	37	49%	37	49%
	No	10	59%	7	41%	14	58%	14	58%	5	29%	9	53%	9	53%	8	47%	38	51%	38	51%
Expected structure	Yes	5	29%	7	41%	8	33%	15	63%	12	71%	6	35%	6	35%	8	47%	31	41%	36	48%
	No	12	71%	10	59%	16	67%	9	38%	5	29%	11	65%	11	65%	9	53%	44	59%	39	52%
Instantiated structure	Yes	10	59%	6	35%	8	33%	10	42%	12	71%	6	35%	2	12%	3	18%	32	43%	25	33%
	No	7	41%	11	65%	16	67%	14	58%	5	29%	11	65%	15	88%	14	82%	43	57%	50	67%
Instantiated behaviour	Yes	7	41%	4	24%	10	42%	6	25%	11	65%	4	24%	5	29%	6	35%	33	44%	20	27%
	No	10	59%	13	76%	14	58%	18	75%	6	35%	13	76%	12	71%	11	65%	42	56%	55	73%
Interpreted behaviour	Yes	6	35%	5	29%	8	33%	8	33%	7	41%	4	24%	4	24%	7	41%	25	33%	24	32%
	No	11	65%	12	71%	16	67%	16	67%	10	59%	13	76%	13	76%	10	59%	50	67%	51	68%
Interpreted function	Yes	6	35%	5	29%	7	29%	9	38%	11	65%	2	12%	4	24%	5	29%	28	37%	21	28%
	No	11	65%	12	71%	17	71%	15	63%	6	35%	15	88%	13	76%	12	71%	47	63%	54	72%

Structuring

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	2	11%	0	0.00	70.5%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	0	0%	0.5	0.00	
	67% - 100%	15	83%	0.835	0.70	
Detailed design	-	0	0%	0	0.00	78.5%
	0% - 33%	1	4%	0.165	0.01	
	34% - 66%	2	7%	0.5	0.04	
	67% - 100%	24	89%	0.835	0.74	
Production	-	0	0%	0	0.00	77.6%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	15	88%	0.835	0.74	
In-service	-	0	0%	0	0.00	79.6%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	2	12%	0.5	0.06	
	67% - 100%	15	88%	0.835	0.74	
Across product lifecycle	-	2	3%	0	0.00	76.7%
	0% - 33%	3	4%	0.165	0.01	
	34% - 66%	5	6%	0.5	0.03	
	67% - 100%	69	87%	0.835	0.73	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	14	88%	3	19%	16	64%	7	28%	13	76%	3	18%	8	47%	7	41%	51	68%	20	27%
	No	2	13%	13	81%	9	36%	18	72%	4	24%	14	82%	9	53%	10	59%	24	32%	55	73%
Expected behaviour	Yes	9	56%	9	56%	17	68%	6	24%	13	76%	9	53%	10	59%	4	24%	49	65%	28	37%
	No	7	44%	7	44%	8	32%	19	76%	4	24%	8	47%	7	41%	13	76%	26	35%	47	63%
Expected structure	Yes	7	44%	10	63%	10	40%	16	64%	12	71%	6	35%	5	29%	4	24%	34	45%	36	48%
	No	9	56%	6	38%	15	60%	9	36%	5	29%	11	65%	12	71%	13	76%	41	55%	39	52%
Instantiated structure	Yes	11	69%	8	50%	10	40%	16	64%	14	82%	8	47%	5	29%	5	29%	40	53%	37	49%
	No	5	31%	8	50%	15	60%	9	36%	3	18%	9	53%	12	71%	12	71%	35	47%	38	51%
Instantiated behaviour	Yes	8	50%	8	50%	15	60%	8	32%	11	65%	5	29%	9	53%	6	35%	43	57%	27	36%
	No	8	50%	8	50%	10	40%	17	68%	6	35%	12	71%	8	47%	11	65%	32	43%	48	64%
Interpreted behaviour	Yes	7	44%	9	56%	12	48%	12	48%	9	53%	3	18%	8	47%	7	41%	36	48%	31	41%
	No	9	56%	7	44%	13	52%	13	52%	8	47%	14	82%	9	53%	10	59%	39	52%	44	59%
Interpreted function	Yes	6	38%	9	56%	10	40%	11	44%	11	65%	2	12%	7	41%	5	29%	34	45%	27	36%
	No	10	63%	7	44%	15	60%	14	56%	6	35%	15	88%	10	59%	12	71%	41	55%	48	64%

Modelling

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	67.7%
	0% - 33%	2	11%	0.165	0.02	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	13	72%	0.835	0.60	
Detailed design	-	0	0%	0	0.00	69.9%
	0% - 33%	2	7%	0.165	0.01	
	34% - 66%	7	26%	0.5	0.13	
	67% - 100%	18	67%	0.835	0.56	
Production	-	0	0%	0	0.00	73.6%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	13	76%	0.835	0.64	
In-service	-	0	0%	0	0.00	67.7%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	1	1%	0	0.00	69.7%
	0% - 33%	7	9%	0.165	0.01	
	34% - 66%	16	20%	0.5	0.10	
	67% - 100%	55	70%	0.835	0.58	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	10	59%	5	29%	9	36%	4	16%	10	59%	4	24%	3	19%	4	25%	32	43%	17	23%
	No	7	41%	12	71%	16	64%	21	84%	7	41%	13	76%	13	81%	12	75%	43	57%	58	77%
Expected behaviour	Yes	8	47%	10	59%	10	40%	6	24%	13	76%	8	47%	5	31%	4	25%	36	48%	28	37%
	No	9	53%	7	41%	15	60%	19	76%	4	24%	9	53%	11	69%	12	75%	39	52%	47	63%
Expected structure	Yes	6	35%	9	53%	14	56%	12	48%	12	71%	6	35%	8	50%	7	44%	40	53%	34	45%
	No	11	65%	8	47%	11	44%	13	52%	5	29%	11	65%	8	50%	9	56%	35	47%	41	55%
Instantiated structure	Yes	11	65%	6	35%	10	40%	18	72%	13	76%	12	71%	10	63%	8	50%	44	59%	44	59%
	No	6	35%	11	65%	15	60%	7	28%	4	24%	5	29%	6	38%	8	50%	31	41%	31	41%
Instantiated behaviour	Yes	9	53%	6	35%	8	32%	5	20%	10	59%	5	29%	3	19%	4	25%	30	40%	20	27%
	No	8	47%	11	65%	17	68%	20	80%	7	41%	12	71%	13	81%	12	75%	45	60%	55	73%
Interpreted behaviour	Yes	6	35%	6	35%	6	24%	6	24%	5	29%	4	24%	2	13%	5	31%	19	25%	21	28%
	No	11	65%	11	65%	19	76%	19	76%	12	71%	13	76%	14	88%	11	69%	56	75%	54	72%
Interpreted function	Yes	6	35%	7	41%	9	36%	5	20%	7	41%	4	24%	3	19%	3	19%	25	33%	19	25%
	No	11	65%	10	59%	16	64%	20	80%	10	59%	13	76%	13	81%	13	81%	50	67%	56	75%

Selecting

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	75.1%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	15	83%	0.835	0.70	
Detailed design	-	2	7%	0	0.00	55.0%
	0% - 33%	7	26%	0.165	0.04	
	34% - 66%	4	15%	0.5	0.07	
	67% - 100%	14	52%	0.835	0.43	
Production	-	0	0%	0	0.00	65.8%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	10	59%	0.835	0.49	
In-service	-	1	6%	0	0.00	58.9%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	9	53%	0.835	0.44	
Across product lifecycle	-	4	5%	0	0.00	62.7%
	0% - 33%	12	15%	0.165	0.03	
	34% - 66%	15	19%	0.5	0.09	
	67% - 100%	48	61%	0.835	0.51	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	12	71%	3	18%	15	65%	2	9%	14	82%	0	0%	5	33%	3	20%	46	64%	8	11%
	No	5	29%	14	82%	8	35%	21	91%	3	18%	17	100%	10	67%	12	80%	26	36%	64	89%
Expected behaviour	Yes	10	59%	4	24%	17	74%	2	9%	12	71%	5	29%	5	33%	1	7%	44	61%	12	17%
	No	7	41%	13	76%	6	26%	21	91%	5	29%	12	71%	10	67%	14	93%	28	39%	60	83%
Expected structure	Yes	8	47%	5	29%	12	52%	7	30%	13	76%	5	29%	5	33%	3	20%	38	53%	20	28%
	No	9	53%	12	71%	11	48%	16	70%	4	24%	12	71%	10	67%	12	80%	34	47%	52	72%
Instantiated structure	Yes	11	65%	4	24%	13	57%	6	26%	12	71%	5	29%	3	20%	2	13%	39	54%	17	24%
	No	6	35%	13	76%	10	43%	17	74%	5	29%	12	71%	12	80%	13	87%	33	46%	55	76%
Instantiated behaviour	Yes	10	59%	5	29%	14	61%	2	9%	11	65%	3	18%	5	33%	2	13%	40	56%	12	17%
	No	7	41%	12	71%	9	39%	21	91%	6	35%	14	82%	10	67%	13	87%	32	44%	60	83%
Interpreted behaviour	Yes	8	47%	5	29%	14	61%	3	13%	10	59%	0	0%	5	33%	2	13%	37	51%	10	14%
	No	9	53%	12	71%	9	39%	20	87%	7	41%	17	100%	10	67%	13	87%	35	49%	62	86%
Interpreted function	Yes	9	53%	5	29%	14	61%	4	17%	11	65%	0	0%	6	40%	2	13%	40	56%	11	15%
	No	8	47%	12	71%	9	39%	19	83%	6	35%	17	100%	9	60%	13	87%	32	44%	61	85%

Validating

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	2	11%	0	0.00	59.3%
	0% - 33%	3	17%	0.165	0.03	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	11	61%	0.835	0.51	
Detailed design	-	1	4%	0	0.00	61.8%
	0% - 33%	5	19%	0.165	0.03	
	34% - 66%	5	19%	0.5	0.09	
	67% - 100%	16	59%	0.835	0.49	
Production	-	0	0%	0	0.00	61.8%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	9	53%	0.835	0.44	
In-service	-	0	0%	0	0.00	69.7%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	3	4%	0	0.00	62.9%
	0% - 33%	12	15%	0.165	0.03	
	34% - 66%	17	22%	0.5	0.11	
	67% - 100%	47	59%	0.835	0.50	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	10	63%	4	25%	13	59%	2	9%	11	65%	1	6%	7	41%	2	12%	41	57%	9	13%
	No	6	38%	12	75%	9	41%	20	91%	6	35%	16	94%	10	59%	15	88%	31	43%	63	88%
Expected behaviour	Yes	10	63%	4	25%	13	59%	3	14%	13	76%	5	29%	3	18%	3	18%	39	54%	15	21%
	No	6	38%	12	75%	9	41%	19	86%	4	24%	12	71%	14	82%	14	82%	33	46%	57	79%
Expected structure	Yes	8	50%	5	31%	9	41%	6	27%	13	76%	3	18%	2	12%	0	0%	32	44%	14	19%
	No	8	50%	11	69%	13	59%	16	73%	4	24%	14	82%	15	88%	17	100%	40	56%	58	81%
Instantiated structure	Yes	10	63%	4	25%	10	45%	7	32%	11	65%	5	29%	3	18%	1	6%	34	47%	17	24%
	No	6	38%	12	75%	12	55%	15	68%	6	35%	12	71%	14	82%	16	94%	38	53%	55	76%
Instantiated behaviour	Yes	10	63%	4	25%	12	55%	4	18%	11	65%	3	18%	5	29%	2	12%	38	53%	13	18%
	No	6	38%	12	75%	10	45%	18	82%	6	35%	14	82%	12	71%	15	88%	34	47%	59	82%
Interpreted behaviour	Yes	8	50%	4	25%	11	50%	5	23%	10	59%	1	6%	5	29%	2	12%	34	47%	12	17%
	No	8	50%	12	75%	11	50%	17	77%	7	41%	16	94%	12	71%	15	88%	38	53%	60	83%
Interpreted function	Yes	6	38%	4	25%	11	50%	6	27%	12	71%	1	6%	6	35%	4	24%	35	49%	15	21%
	No	10	63%	12	75%	11	50%	16	73%	5	29%	16	94%	11	65%	13	76%	37	51%	57	79%

Analysing

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	67.7%
	0% - 33%	3	17%	0.165	0.03	
	34% - 66%	0	0%	0.5	0.00	
	67% - 100%	14	78%	0.835	0.65	
Detailed design	-	1	4%	0	0.00	63.0%
	0% - 33%	5	19%	0.165	0.03	
	34% - 66%	4	15%	0.5	0.07	
	67% - 100%	17	63%	0.835	0.53	
Production	-	0	0%	0	0.00	71.7%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	2	12%	0.5	0.06	
	67% - 100%	13	76%	0.835	0.64	
In-service	-	0	0%	0	0.00	65.8%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	2	3%	0	0.00	66.5%
	0% - 33%	13	16%	0.165	0.03	
	34% - 66%	9	11%	0.5	0.06	
	67% - 100%	55	70%	0.835	0.58	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	9	53%	3	18%	13	57%	4	17%	15	88%	4	24%	9	56%	9	56%	46	63%	20	27%
	No	8	47%	14	82%	10	43%	19	83%	2	12%	13	76%	7	44%	7	44%	27	37%	53	73%
Expected behaviour	Yes	9	53%	4	24%	12	52%	6	26%	12	71%	8	47%	5	31%	7	44%	38	52%	25	34%
	No	8	47%	13	76%	11	48%	17	74%	5	29%	9	53%	11	69%	9	56%	35	48%	48	66%
Expected structure	Yes	8	47%	9	53%	8	35%	5	22%	11	65%	4	24%	7	44%	5	31%	34	47%	23	32%
	No	9	53%	8	47%	15	65%	18	78%	6	35%	13	76%	9	56%	11	69%	39	53%	50	68%
Instantiated structure	Yes	7	41%	8	47%	7	30%	6	26%	11	65%	6	35%	7	44%	6	38%	32	44%	26	36%
	No	10	59%	9	53%	16	70%	17	74%	6	35%	11	65%	9	56%	10	63%	41	56%	47	64%
Instantiated behaviour	Yes	5	29%	7	41%	12	52%	6	26%	12	71%	4	24%	3	19%	7	44%	32	44%	24	33%
	No	12	71%	10	59%	11	48%	17	74%	5	29%	13	76%	13	81%	9	56%	41	56%	49	67%
Interpreted behaviour	Yes	6	35%	6	35%	10	43%	8	35%	10	59%	5	29%	4	25%	6	38%	30	41%	25	34%
	No	11	65%	11	65%	13	57%	15	65%	7	41%	12	71%	12	75%	10	63%	43	59%	48	66%
Interpreted function	Yes	5	29%	6	35%	10	43%	7	30%	11	65%	3	18%	6	38%	7	44%	32	44%	23	32%
	No	12	71%	11	65%	13	57%	16	70%	6	35%	14	82%	10	63%	9	56%	41	56%	50	68%

Composing

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	58.4%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	9	50%	0.5	0.25	
	67% - 100%	7	39%	0.835	0.32	
Detailed design	-	1	4%	0	0.00	55.6%
	0% - 33%	8	30%	0.165	0.05	
	34% - 66%	4	15%	0.5	0.07	
	67% - 100%	14	52%	0.835	0.43	
Production	-	0	0%	0	0.00	65.8%
	0% - 33%	2	12%	0.165	0.02	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	10	59%	0.835	0.49	
In-service	-	0	0%	0	0.00	57.9%
	0% - 33%	4	24%	0.165	0.04	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	8	47%	0.835	0.39	
Across product lifecycle	-	2	3%	0	0.00	58.9%
	0% - 33%	15	19%	0.165	0.03	
	34% - 66%	23	29%	0.5	0.15	
	67% - 100%	39	49%	0.835	0.41	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	9	53%	2	12%	8	42%	4	21%	10	59%	5	29%	6	38%	3	19%	33	48%	14	20%
	No	8	47%	15	88%	11	58%	15	79%	7	41%	12	71%	10	63%	13	81%	36	52%	55	80%
Expected behaviour	Yes	6	35%	2	12%	7	37%	5	26%	9	53%	6	35%	4	25%	1	6%	26	38%	14	20%
	No	11	65%	15	88%	12	63%	14	74%	8	47%	11	65%	12	75%	15	94%	43	62%	55	80%
Expected structure	Yes	6	35%	5	29%	12	63%	7	37%	12	71%	6	35%	6	38%	3	19%	36	52%	21	30%
	No	11	65%	12	71%	7	37%	12	63%	5	29%	11	65%	10	63%	13	81%	33	48%	48	70%
Instantiated structure	Yes	9	53%	4	24%	10	53%	7	37%	12	71%	8	47%	5	31%	4	25%	36	52%	23	33%
	No	8	47%	13	76%	9	47%	12	63%	5	29%	9	53%	11	69%	12	75%	33	48%	46	67%
Instantiated behaviour	Yes	9	53%	5	29%	10	53%	5	26%	9	53%	5	29%	6	38%	5	31%	34	49%	20	29%
	No	8	47%	12	71%	9	47%	14	74%	8	47%	12	71%	10	63%	11	69%	35	51%	49	71%
Interpreted behaviour	Yes	8	47%	7	41%	8	42%	8	42%	8	47%	6	35%	6	38%	6	38%	30	43%	27	39%
	No	9	53%	10	59%	11	58%	11	58%	9	53%	11	65%	10	63%	10	63%	39	57%	42	61%
Interpreted function	Yes	5	29%	7	41%	12	63%	7	37%	10	59%	7	41%	6	38%	8	50%	33	48%	29	42%
	No	12	71%	10	59%	7	37%	12	63%	7	41%	10	59%	10	63%	8	50%	36	52%	40	58%

Distributing

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	71.4%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	14	78%	0.835	0.65	
Detailed design	-	0	0%	0	0.00	62.4%
	0% - 33%	7	26%	0.165	0.04	
	34% - 66%	3	11%	0.5	0.06	
	67% - 100%	17	63%	0.835	0.53	
Production	-	0	0%	0	0.00	71.7%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	12	71%	0.835	0.59	
In-service	-	0	0%	0	0.00	65.8%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	11	65%	0.835	0.54	
Across product lifecycle	-	1	1%	0	0.00	67.2%
	0% - 33%	12	15%	0.165	0.03	
	34% - 66%	12	15%	0.5	0.08	
	67% - 100%	54	68%	0.835	0.57	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	10	63%	2	13%	8	36%	1	5%	9	56%	2	13%	4	24%	8	47%	31	44%	13	18%
	No	6	38%	14	88%	14	64%	21	95%	7	44%	14	88%	13	76%	9	53%	40	56%	58	82%
Expected behaviour	Yes	7	44%	5	31%	8	36%	4	18%	11	69%	6	38%	7	41%	5	29%	33	46%	20	28%
	No	9	56%	11	69%	14	64%	18	82%	5	31%	10	63%	10	59%	12	71%	38	54%	51	72%
Expected structure	Yes	7	44%	5	31%	10	45%	9	41%	10	63%	4	25%	6	35%	5	29%	33	46%	23	32%
	No	9	56%	11	69%	12	55%	13	59%	6	38%	12	75%	11	65%	12	71%	38	54%	48	68%
Instantiated structure	Yes	9	56%	4	25%	7	32%	9	41%	9	56%	5	31%	4	24%	2	12%	29	41%	20	28%
	No	7	44%	12	75%	15	68%	13	59%	7	44%	11	69%	13	76%	15	88%	42	59%	51	72%
Instantiated behaviour	Yes	9	56%	6	38%	6	27%	4	18%	10	63%	4	25%	3	18%	4	24%	28	39%	18	25%
	No	7	44%	10	63%	16	73%	18	82%	6	38%	12	75%	14	82%	13	76%	43	61%	53	75%
Interpreted behaviour	Yes	5	31%	5	31%	7	32%	4	18%	8	50%	2	13%	3	18%	3	18%	23	32%	14	20%
	No	11	69%	11	69%	15	68%	18	82%	8	50%	14	88%	14	82%	14	82%	48	68%	57	80%
Interpreted function	Yes	6	38%	7	44%	7	32%	3	14%	9	56%	2	13%	3	18%	6	35%	25	35%	18	25%
	No	10	63%	9	56%	15	68%	19	86%	7	44%	14	88%	14	82%	11	65%	46	65%	53	75%

Planning

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	1	6%	0	0.00	62.1%
	0% - 33%	2	11%	0.165	0.02	
	34% - 66%	5	28%	0.5	0.14	
	67% - 100%	10	56%	0.835	0.46	
Detailed design	-	1	4%	0	0.00	60.6%
	0% - 33%	7	26%	0.165	0.04	
	34% - 66%	2	7%	0.5	0.04	
	67% - 100%	17	63%	0.835	0.53	
Production	-	1	6%	0	0.00	54.9%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	6	35%	0.5	0.18	
	67% - 100%	7	41%	0.835	0.34	
In-service	-	0	0%	0	0.00	67.7%
	0% - 33%	3	18%	0.165	0.03	
	34% - 66%	2	12%	0.5	0.06	
	67% - 100%	12	71%	0.835	0.59	
Across product lifecycle	-	3	4%	0	0.00	61.2%
	0% - 33%	15	19%	0.165	0.03	
	34% - 66%	15	19%	0.5	0.09	
	67% - 100%	46	58%	0.835	0.49	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	7	44%	2	13%	10	45%	4	18%	8	53%	3	20%	5	31%	4	25%	30	43%	13	19%
	No	9	56%	14	88%	12	55%	18	82%	7	47%	12	80%	11	69%	12	75%	39	57%	56	81%
Expected behaviour	Yes	7	44%	4	25%	12	55%	7	32%	9	60%	8	53%	6	38%	4	25%	34	49%	23	33%
	No	9	56%	12	75%	10	45%	15	68%	6	40%	7	47%	10	63%	12	75%	35	51%	46	67%
Expected structure	Yes	7	44%	3	19%	12	55%	8	36%	9	60%	6	40%	11	69%	5	31%	39	57%	22	32%
	No	9	56%	13	81%	10	45%	14	64%	6	40%	9	60%	5	31%	11	69%	30	43%	47	68%
Instantiated structure	Yes	8	50%	4	25%	10	45%	5	23%	11	73%	7	47%	7	44%	2	13%	36	52%	18	26%
	No	8	50%	12	75%	12	55%	17	77%	4	27%	8	53%	9	56%	14	88%	33	48%	51	74%
Instantiated behaviour	Yes	8	50%	4	25%	7	32%	2	9%	9	60%	4	27%	3	19%	2	13%	27	39%	12	17%
	No	8	50%	12	75%	15	68%	20	91%	6	40%	11	73%	13	81%	14	88%	42	61%	57	83%
Interpreted behaviour	Yes	5	31%	4	25%	6	27%	5	23%	8	53%	4	27%	3	19%	1	6%	22	32%	14	20%
	No	11	69%	12	75%	16	73%	17	77%	7	47%	11	73%	13	81%	15	94%	47	68%	55	80%
Interpreted function	Yes	5	31%	6	38%	7	32%	5	23%	5	33%	3	20%	2	13%	2	13%	19	28%	16	23%
	No	11	69%	10	63%	15	68%	17	77%	10	67%	12	80%	14	88%	14	88%	50	72%	53	77%

Testing

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	2	11%	0	0.00	25.8%
	0% - 33%	10	56%	0.165	0.09	
	34% - 66%	6	33%	0.5	0.17	
	67% - 100%	0	0%	0.835	0.00	
Detailed design	-	1	4%	0	0.00	40.7%
	0% - 33%	10	37%	0.165	0.06	
	34% - 66%	12	44%	0.5	0.22	
	67% - 100%	4	15%	0.835	0.12	
Production	-	1	6%	0	0.00	27.4%
	0% - 33%	11	65%	0.165	0.11	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	1	6%	0.835	0.05	
In-service	-	1	6%	0	0.00	39.2%
	0% - 33%	7	41%	0.165	0.07	
	34% - 66%	6	35%	0.5	0.18	
	67% - 100%	3	18%	0.835	0.15	
Across product lifecycle	-	5	6%	0	0.00	34.1%
	0% - 33%	38	48%	0.165	0.08	
	34% - 66%	28	35%	0.5	0.18	
	67% - 100%	8	10%	0.835	0.08	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	4	40%	1	10%	10	45%	3	14%	9	69%	5	38%	5	33%	8	53%	28	47%	17	28%
	No	6	60%	9	90%	12	55%	19	86%	4	31%	8	62%	10	67%	7	47%	32	53%	43	72%
Expected behaviour	Yes	4	40%	2	20%	12	55%	6	27%	9	69%	8	62%	5	33%	4	27%	30	50%	20	33%
	No	6	60%	8	80%	10	45%	16	73%	4	31%	5	38%	10	67%	11	73%	30	50%	40	67%
Expected structure	Yes	2	20%	3	30%	9	41%	5	23%	8	62%	5	38%	4	27%	3	20%	23	38%	16	27%
	No	8	80%	7	70%	13	59%	17	77%	5	38%	8	62%	11	73%	12	80%	37	62%	44	73%
Instantiated structure	Yes	5	50%	3	30%	10	45%	6	27%	10	77%	6	46%	3	20%	1	7%	28	47%	16	27%
	No	5	50%	7	70%	12	55%	16	73%	3	23%	7	54%	12	80%	14	93%	32	53%	44	73%
Instantiated behaviour	Yes	6	60%	3	30%	11	50%	3	14%	8	62%	4	31%	3	20%	5	33%	28	47%	15	25%
	No	4	40%	7	70%	11	50%	19	86%	5	38%	9	69%	12	80%	10	67%	32	53%	45	75%
Interpreted behaviour	Yes	2	20%	3	30%	9	41%	5	23%	8	62%	4	31%	5	33%	5	33%	24	40%	17	28%
	No	8	80%	7	70%	13	59%	17	77%	5	38%	9	69%	10	67%	10	67%	36	60%	43	72%
Interpreted function	Yes	2	20%	4	40%	11	50%	4	18%	7	54%	5	38%	5	33%	6	40%	25	42%	19	32%
	No	8	80%	6	60%	11	50%	18	82%	6	46%	8	62%	10	67%	9	60%	35	58%	41	68%

Authorising

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	2	11%	0	0.00	66.8%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	2	11%	0.5	0.06	
	67% - 100%	13	72%	0.835	0.60	
Detailed design	-	1	4%	0	0.00	65.5%
	0% - 33%	5	19%	0.165	0.03	
	34% - 66%	2	7%	0.5	0.04	
	67% - 100%	19	70%	0.835	0.59	
Production	-	1	6%	0	0.00	60.9%
	0% - 33%	4	24%	0.165	0.04	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	11	65%	0.835	0.54	
In-service	-	0	0%	0	0.00	81.5%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	16	94%	0.835	0.79	
Across product lifecycle	-	4	5%	0	0.00	68.2%
	0% - 33%	10	13%	0.165	0.02	
	34% - 66%	6	8%	0.5	0.04	
	67% - 100%	59	75%	0.835	0.62	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	12	80%	5	33%	16	70%	3	13%	12	80%	6	40%	10	59%	5	29%	50	71%	19	27%
	No	3	20%	10	67%	7	30%	20	87%	3	20%	9	60%	7	41%	12	71%	20	29%	51	73%
Expected behaviour	Yes	11	73%	8	53%	17	74%	5	22%	12	80%	8	53%	8	47%	6	35%	48	69%	27	39%
	No	4	27%	7	47%	6	26%	18	78%	3	20%	7	47%	9	53%	11	65%	22	31%	43	61%
Expected structure	Yes	9	60%	8	53%	17	74%	9	39%	11	73%	8	53%	10	59%	6	35%	47	67%	31	44%
	No	6	40%	7	47%	6	26%	14	61%	4	27%	7	47%	7	41%	11	65%	23	33%	39	56%
Instantiated structure	Yes	9	60%	5	33%	14	61%	6	26%	12	80%	6	40%	8	47%	3	18%	43	61%	20	29%
	No	6	40%	10	67%	9	39%	17	74%	3	20%	9	60%	9	53%	14	82%	27	39%	50	71%
Instantiated behaviour	Yes	10	67%	8	53%	15	65%	8	35%	12	80%	6	40%	7	41%	5	29%	44	63%	27	39%
	No	5	33%	7	47%	8	35%	15	65%	3	20%	9	60%	10	59%	12	71%	26	37%	43	61%
Interpreted behaviour	Yes	9	60%	9	60%	17	74%	4	17%	11	73%	7	47%	8	47%	5	29%	45	64%	25	36%
	No	6	40%	6	40%	6	26%	19	83%	4	27%	8	53%	9	53%	12	71%	25	36%	45	64%
Interpreted function	Yes	10	67%	9	60%	13	57%	6	26%	10	67%	6	40%	6	35%	6	35%	39	56%	27	39%
	No	5	33%	6	40%	10	43%	17	74%	5	33%	9	60%	11	65%	11	65%	31	44%	43	61%

Ensuring

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	4	22%	0	0.00	48.2%
	0% - 33%	4	22%	0.165	0.04	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	9	50%	0.835	0.42	
Detailed design	-	1	4%	0	0.00	63.0%
	0% - 33%	3	11%	0.165	0.02	
	34% - 66%	8	30%	0.5	0.15	
	67% - 100%	15	56%	0.835	0.46	
Production	-	0	0%	0	0.00	61.8%
	0% - 33%	4	24%	0.165	0.04	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	10	59%	0.835	0.49	
In-service	-	0	0%	0	0.00	71.7%
	0% - 33%	1	6%	0.165	0.01	
	34% - 66%	4	24%	0.5	0.12	
	67% - 100%	12	71%	0.835	0.59	
Across product lifecycle	-	5	6%	0	0.00	61.3%
	0% - 33%	12	15%	0.165	0.03	
	34% - 66%	16	20%	0.5	0.10	
	67% - 100%	46	58%	0.835	0.49	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	3	21%	4	29%	5	22%	2	9%	7	41%	2	12%	2	12%	3	18%	17	24%	11	15%
	No	11	79%	10	71%	18	78%	21	91%	10	59%	15	88%	15	88%	14	82%	54	76%	60	85%
Expected behaviour	Yes	6	43%	3	21%	4	17%	3	13%	9	53%	6	35%	3	18%	2	12%	22	31%	14	20%
	No	8	57%	11	79%	19	83%	20	87%	8	47%	11	65%	14	82%	15	88%	49	69%	57	80%
Expected structure	Yes	8	57%	4	29%	7	30%	5	22%	9	53%	4	24%	3	18%	3	18%	27	38%	16	23%
	No	6	43%	10	71%	16	70%	18	78%	8	47%	13	76%	14	82%	14	82%	44	62%	55	77%
Instantiated structure	Yes	8	57%	4	29%	5	22%	3	13%	10	59%	6	35%	1	6%	2	12%	24	34%	15	21%
	No	6	43%	10	71%	18	78%	20	87%	7	41%	11	65%	16	94%	15	88%	47	66%	56	79%
Instantiated behaviour	Yes	6	43%	4	29%	4	17%	4	17%	9	53%	4	24%	3	18%	2	12%	22	31%	14	20%
	No	8	57%	10	71%	19	83%	19	83%	8	47%	13	76%	14	82%	15	88%	49	69%	57	80%
Interpreted behaviour	Yes	5	36%	3	21%	7	30%	1	4%	8	47%	4	24%	3	18%	5	29%	23	32%	13	18%
	No	9	64%	11	79%	16	70%	22	96%	9	53%	13	76%	14	82%	12	71%	48	68%	58	82%
Interpreted function	Yes	5	36%	5	36%	7	30%	5	22%	6	35%	2	12%	4	24%	4	24%	22	31%	16	23%
	No	9	64%	9	64%	16	70%	18	78%	11	65%	15	88%	13	76%	13	76%	49	69%	55	77%

Instantiating

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	4	22%	0	0.00	59.4%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	3	17%	0.5	0.08	
	67% - 100%	11	61%	0.835	0.51	
Detailed design	-	1	4%	0	0.00	70.5%
	0% - 33%	1	4%	0.165	0.01	
	34% - 66%	6	22%	0.5	0.11	
	67% - 100%	19	70%	0.835	0.59	
Production	-	1	6%	0	0.00	68.7%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	5	29%	0.5	0.15	
	67% - 100%	11	65%	0.835	0.54	
In-service	-	0	0%	0	0.00	77.6%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	3	18%	0.5	0.09	
	67% - 100%	14	82%	0.835	0.69	
Across product lifecycle	-	6	8%	0	0.00	69.1%
	0% - 33%	1	1%	0.165	0.00	
	34% - 66%	17	22%	0.5	0.11	
	67% - 100%	55	70%	0.835	0.58	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	7	50%	4	29%	6	24%	6	24%	9	56%	3	19%	4	24%	2	12%	26	36%	15	21%
	No	7	50%	10	71%	19	76%	19	76%	7	44%	13	81%	13	76%	15	88%	46	64%	57	79%
Expected behaviour	Yes	7	50%	4	29%	8	32%	8	32%	9	56%	6	38%	4	24%	2	12%	28	39%	20	28%
	No	7	50%	10	71%	17	68%	17	68%	7	44%	10	63%	13	76%	15	88%	44	61%	52	72%
Expected structure	Yes	9	64%	5	36%	8	32%	10	40%	11	69%	5	31%	6	35%	6	35%	34	47%	26	36%
	No	5	36%	9	64%	17	68%	15	60%	5	31%	11	69%	11	65%	11	65%	38	53%	46	64%
Instantiated structure	Yes	8	57%	9	64%	9	36%	10	40%	12	75%	9	56%	4	24%	6	35%	33	46%	34	47%
	No	6	43%	5	36%	16	64%	15	60%	4	25%	7	44%	13	76%	11	65%	39	54%	38	53%
Instantiated behaviour	Yes	8	57%	4	29%	8	32%	9	36%	11	69%	6	38%	1	6%	4	24%	28	39%	23	32%
	No	6	43%	10	71%	17	68%	16	64%	5	31%	10	63%	16	94%	13	76%	44	61%	49	68%
Interpreted behaviour	Yes	6	43%	5	36%	6	24%	7	28%	8	50%	5	31%	1	6%	2	12%	21	29%	19	26%
	No	8	57%	9	64%	19	76%	18	72%	8	50%	11	69%	16	94%	15	88%	51	71%	53	74%
Interpreted function	Yes	6	43%	4	29%	8	32%	7	28%	9	56%	6	38%	3	18%	4	24%	26	36%	21	29%
	No	8	57%	10	71%	17	68%	18	72%	7	44%	10	63%	14	82%	13	76%	46	64%	51	71%

Ordering

Activity enactment frequency

Product lifecycle stage	Frequency banding	Number of respondents	Percentage of respondents	Weighting factor	Distribution	Mean frequency
Conceptual design	-	0	0%	0	0.00	45.8%
	0% - 33%	8	50%	0.165	0.08	
	34% - 66%	2	13%	0.5	0.06	
	67% - 100%	6	38%	0.835	0.31	
Detailed design	-	0	0%	0	0.00	63.0%
	0% - 33%	5	28%	0.165	0.05	
	34% - 66%	1	6%	0.5	0.03	
	67% - 100%	12	67%	0.835	0.56	
Production	-	0	0%	0	0.00	65.2%
	0% - 33%	1	9%	0.165	0.02	
	34% - 66%	4	36%	0.5	0.18	
	67% - 100%	6	55%	0.835	0.46	
In-service	-	0	0%	0	0.00	77.9%
	0% - 33%	0	0%	0.165	0.00	
	34% - 66%	2	17%	0.5	0.08	
	67% - 100%	10	83%	0.835	0.70	
Across product lifecycle	-	0	0%	0	0.00	61.8%
	0% - 33%	14	25%	0.165	0.04	
	34% - 66%	9	16%	0.5	0.08	
	67% - 100%	34	60%	0.835	0.50	

Artefact knowledge usage and creation

Artefact knowldge type	Option	Concept design				Detailed design				Production				In-service				Across PLC			
		Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%	Used	%	Created	%
Expected function	Yes	3	33%	3	33%	4	19%	3	14%	7	44%	3	19%	2	12%	2	12%	16	25%	11	17%
	No	6	67%	6	67%	17	81%	18	86%	9	56%	13	81%	15	88%	15	88%	47	75%	52	83%
Expected behaviour	Yes	3	33%	2	22%	5	24%	6	29%	9	56%	7	44%	4	24%	3	18%	21	33%	18	29%
	No	6	67%	7	78%	16	76%	15	71%	7	44%	9	56%	13	76%	14	82%	42	67%	45	71%
Expected structure	Yes	3	33%	3	33%	5	24%	4	19%	8	50%	3	19%	5	29%	5	29%	21	33%	15	24%
	No	6	67%	6	67%	16	76%	17	81%	8	50%	13	81%	12	71%	12	71%	42	67%	48	76%
Instantiated structure	Yes	6	67%	3	33%	9	43%	5	24%	11	69%	7	44%	4	24%	4	24%	30	48%	19	30%
	No	3	33%	6	67%	12	57%	16	76%	5	31%	9	56%	13	76%	13	76%	33	52%	44	70%
Instantiated behaviour	Yes	3	33%	3	33%	3	14%	4	19%	8	50%	5	31%	2	12%	1	6%	16	25%	13	21%
	No	6	67%	6	67%	18	86%	17	81%	8	50%	11	69%	15	88%	16	94%	47	75%	50	79%
Interpreted behaviour	Yes	3	33%	8	89%	3	14%	2	10%	7	44%	5	31%	1	6%	4	24%	14	22%	19	30%
	No	6	67%	1	11%	18	86%	19	90%	9	56%	11	69%	16	94%	13	76%	49	78%	44	70%
Interpreted function	Yes	3	33%	4	44%	5	24%	2	10%	6	38%	5	31%	2	12%	3	18%	16	25%	14	22%
	No	6	67%	5	56%	16	76%	19	90%	10	63%	11	69%	15	88%	14	82%	47	75%	49	78%