A framework to support the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) products

By

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Abstract

This thesis presents the first ever framework for implementing Product Lifecycle Management (PLM) within high value Engineering to Order (ETO) programmes. It describes the PLM related challenges in large-scale, complex, long-life, no prototype, highly customised, one-off or few of kind ETO products compared to other product types such as Make to Stock (MTS), Make to Order (MTO) or Assemble to Order (ATO). It highlights that the scale, complexity, uncertainty, long-lifecycle, maturity management and an inability to prototype ETO products results in significant challenges necessitating a tailored approach to PLM Implementation.

The framework has been developed using a qualitative methodology based on the thematic analysis of 27 semi-structured interviews, and 1 pilot interview. The participants were senior personnel from 11 ETO organisations in the UK, France, Australia, USA and Canada.

Each of the themes in the framework is described in information, process, people and technology sub-sections within the main section of objectives, challenges and enablers. The themes were developed using a qualitative methodology which enabled the grouping of interview responses allowing the related key points from the interviews to be described. To provide an audit trail to support the truthfulness of the findings, each key point was referenced to the transcribed responses. The results of this preparation supported the development of the findings as each theme and related key points could be easily identified and described.

The validation and evaluation used a questionnaire to ask selected participants from ETO products for their opinion on statements related to the framework. There were 19 evaluation participants who were selected from 7 ETO organisations. The responses to the questionnaire statements and the comments supported the objectives of the questionnaire for quality, structure and versatility with the majority (95%) of the responses either agreeing or strongly agreeing with the statements.

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Nomenclature

Abbreviation	Meaning
AEC	Architectural, Engineering and Construction
ATO	Assemble to Order
ATU	Air Treatment Unit
BIM	Business Information Modelling
BoM	Bill of Material
CAD	Computer Aided Design
CADMID	Concept, Assessment, Demonstration, Manufacture, In-service, Disposal
CAM	Computer Aided Manufacture
CBT	Computer Based Training
CCPM	Collaborative Construction Project Management
CSC	Canadian Surface Combatant
CMM	Capability Maturity Model
COTS	Commercial off the Shelf
DMAIC	Define, Measure, Analyse, Improve and Control
DMEDI	Define, Measure, Explore, Develop, Implement
EA	Enterprise Architecture
EAC	Export Administration Regulations
EBoM	Engineering Bill of Material
EDMS	Electronic Document Management System
ELV	End of Life Vehicle
ERP	Enterprise Resource Planning
ETO	Engineer to Order
FOC	First of Class
GA	General Arrangement
GCS	Global Combat Ship
GFE	Government Furnished Equipment
HCF	Hunter Class Frigate
HOQ	House of Quality
HPSW	High Pressure Sea Water
HVAC	Heating Ventilation and Air Conditioning

iBoM	Integrated Bill of Material
IM&T	Information Management and Technology
IPDE	Integrated Product Development Environment
IPR	Intellectual Property Rights
ITAR	International Traffic in Arms Regulations
KPI	Key Performance Indicators
LBPLM	Logic Based PLM
LFE	Learning From Experience
LHC	Large Hadron Collider
MBoM	Manufacturing Bill of Material
MES	Manufacturing Execution System
MOD	Ministry of Defence
MTO	Made to Order
MTS	Made to Stock
NPD	New Product Development
OEM	Original Equipment Manufacturer
OOTB	Out of the Box
PAR	Participatory Action Research
PBS	Product Breakdown Structure
PDM	Product Data Management
PLM	Product Lifecycle Management
PND	Product Necessary Date
QEC	Queen Elizabeth Class
QFD	Quality Function Deployment
REACH	Registration, Evaluation, and Authorization of Chemicals
RN	Royal Navy
RoHS	Restriction of use of certain Hazardous Substances
SQEP	Suitably Qualified and Experience Personnel
TOGAF	The Open Group Architectural Framework
VPE	Virtual Prototyping Environment

1 Introduction

Organisations collaborate on New Product Development (NPD) to leverage the benefits of expertise across different geographical locations from various sources to enable ‘strategic oriented partnerships’ in order to reduce costs and increase quality [1]. These extended enterprises [2] ‘may be regarded as a collection of independent, heterogeneous companies working closely together in order to produce an integrated product or service in whose commercial success they all have a vested interest’ [3]. The approach is applicable to large-scale, complex long design and build lifecycle engineering products where there are a wide range of stakeholders contributing to the programme over multiple geographical locations. The management of the product information across the various locations and throughout its lifecycle is required to enable the successful development of the product.

Stakeholders in an extended enterprise require immediate and accurate access to the product information. These stakeholders can be described as those who contribute to wealth creation and are potential beneficiaries and risk bearers [4]. If implemented successfully the rewards of the extended enterprise can be significant with even the very survival of the organisation relying on establishing and improving the relationships with the stakeholders [4]. These stakeholders utilise the information management environment as a way of collaborating and exchanging information to support the product’s lifecycle. The automotive company Chrysler estimate that: ‘5,000,000 people and 100,000 organisations are involved in their extended enterprise’ whilst ‘Rolls Royce estimate that 70% of the value of one of their engines is created outside the company’ [3].

The increasing level of collaboration across multi-site extended enterprises requires greater management of product information, which is supported by the concept of Product Lifecycle Management (PLM). PLM assist organisations with the increasing competitiveness in the marketplace across all industries which results in a constant need to increase innovation, product time to market, quality, business measurement, protecting Intellectual Property Rights (IPR) and auditing [5]. Nolan stated that ‘PLM supports these organisational objectives through the management of business processes and associated information, both human and software generated, across the entire product’s lifecycle’ [1]. He went on to describe that to deliver these benefits requires PLM processes and technology such as Product Data Management (PDM), Computer Aided Manufacturing (CAM) and Computer Aided Design (CAD).

CIMData described the evolution of PDM in the late 1980’s and 1990’s to the comprehensive PLM used to manage todays products [6]. CIMData defined PLM as ‘a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information’. They went onto state that PDM was first used to manage CAD files in home grown systems primarily for engineering but evolved to PLM which included multiple business functions to increase quality, reduce cost, increase return on investment, improve innovation, increase quality and improve collaboration. The time evolution of PLM is illustrated in Figure 1.

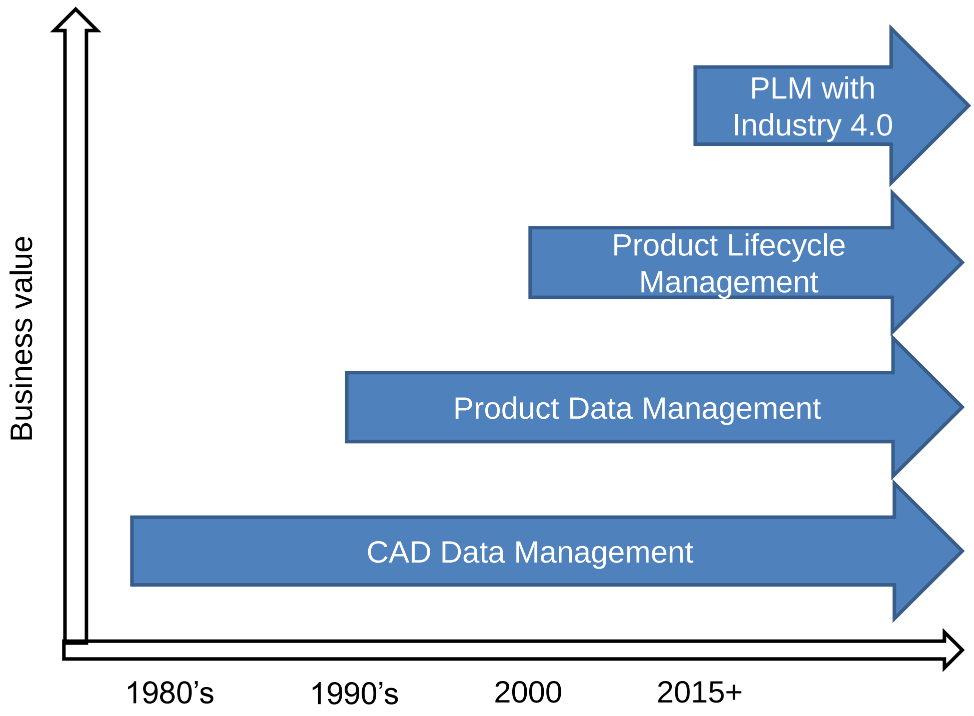


Figure 1 The evolution of PLM

Design collaboration has matured rapidly since the advent of web technologies; so much so that these collaboration tools have functionality surpassing those of the traditional non web-based PDM systems. Emerson stated that 'the advent and widespread adoption of the Internet and web-based tools has had a tremendous impact on development and utilisation of PDM and related systems, and promises an even greater impact in the future'. These technologies are maturing to a level where design is shared and managed by facilitating real-time collaboration with various stakeholders across a networked real-time environment [7].

The technologies bring benefits but they also introduce new challenges to the organisation including balancing creativity with the rules implemented in the system and the difficulties with managing the configuration of the information across multiple geographical locations. Configuration Management (CM) is 'a management discipline used to capture and control data', and is required for the success of an extended enterprise but is challenging for people, process and technology [8]. These technologies have enabled organisations that produce large-scale engineering products to become integrators of systems developed in an extended enterprise by the various stakeholders across multiple geographical locations [1], [9].

PLM is used to support the product development process across various product types. Assemble To Order (ATO) products such as aircraft require PLM to support NPD across an extended enterprise. Boeing have NPD partners in many different geographical locations, including the US, Canada, Japan, UK and France [7]. Airbus also have a large extended enterprise with wings and landing gear designed in the UK, the fuselage design split between Germany and France, the tail fin designed in Spain and the engines designed in either Britain or America [10]. The A380 for example has 4 million parts supplied from 30 countries [11].

PLM is also used to support an extended enterprise in Engineer To Order (ETO) products. These large-scale, complex, few or one off, long design and build lifecycle engineering products include the Type 45 Destroyer and the Queen Elizabeth Class (QEC) Aircraft Carrier which are the new generation of naval ships which have recently entered service for the UK Royal Navy. These ETO products have design and build undertaken across many locations both within the UK and through a global supply chain [12]. Another example of an ETO product designed across an extended enterprise which requires support from PLM is the Type 26 Global Combat Ship (GCS). The Type 26 will progressively replace the Type 23 for the UK Royal Navy providing anti-submarine and general purpose capability. The ships are being designed and built by BAE Systems across a number of locations including Glasgow, Portsmouth and Bristol. The programme began its system design, or assessment phase, in 2010 with the first of eight ships entering service mid 2020's. The Type 26 GCS was identified by the UK Government as a product which could secure export opportunities for UK industry [13].

The GCS has proven successful in the export market with both the Australian and Canadian governments choosing the product as its preferred design for their own naval requirements, resulting in multi-billion pound orders [14]. Due to the success of the GCS, the BAE Systems PLM implementation will be required to support the management of multiple variants of the design across a wider extended enterprise, including Type 26 for the UK, Hunter Class Frigate (HCF) for Australia and the Canadian Surface Combatant (CSC).

Further examples of ETO products include The Large Hadron Collider (LHC) and the Crossrail project. The LHC is provided by CERN, the European organisation for nuclear research. CERN has 21 member states, 6 observer states and more than 80 collaborating countries. The LHC is a huge installation in the border between Switzerland and France which operates particle accelerators in a 27km circular tunnel 100m below ground. It involves millions of high-tech components with a lifecycle measured in decades, and has 80 countries from across the world involved in its design [11].

The Crossrail project is a £15B project to upgrade existing railway networks in London. It involves huge volumes of data which are required to be managed and expects to generate 1 million drawing and model records [11]. These products have close links with their main suppliers, who are regarded as major stakeholders and work closely with the design and build teams.

There have been many contributions to PLM research to determine and describe the benefits, challenges and implementation guidance across multiple industrial contexts and product types. The existing research does not provide guidance for implementing PLM on ETO products. ETO products have specific challenges with PLM implementation compared to other product types such as ATO.

ETO product delivery is complex with many differing elements interacting across the overlapping lifecycle phases, such as concurrent designs of different but integrated systems. This complexity is compounded by levels of uncertainty where design changes have an impact across the programme which are difficult to predict and manage.

The procurement process is also challenging due to each major programme having to be retendered to provide evidence of value for money, resulting in difficulties with maintaining supplier relationships and accessing their information. Also in many cases there are long lead-times for delivery of equipment which is required to be integrated into the product. This delivery may not take place for many years after the contract is placed and the design completed. Some of these equipment items are customised in order to meet the specific requirement of the customer with the information gradually delivered by the supplier.

ETO products are customised to meet the needs of a specific customer. Therefore the design elements such as equipment and system contained within the product can be a mixture of high volume standard COTS products and those customised by a supplier. These suppliers provide product information throughout the lifecycle of the ETO programme which is used to design the integrated systems. Customisation results in a high degree of risk due to their low volume and lack of standardisation which may result in design changes that will impact the product in terms of schedule and cost.

ETO products have a maturing design over many years, throughout this lifecycle there will be changes to the configured design which are required to be managed. This is further compounded by manufacturing beginning before the design is fully mature, resulting in product change affecting not just the design but also potentially causing manufacturing rework. The relationship between the BoM, change, configuration and maturity management is an important factor in ETO products

In other product types manufacturing would not begin until the product is mature. Physical prototypes would be used to test the design and manufacture and product changes would be incorporated before full scale manufacturing begins. A full physical prototype for ETO products would be prohibitively costly and time-consuming due to its scale.

There are also project management challenges which are required to be addressed due to the consistent cost and schedule overruns in ETO products which can reach £billions and have products delivered years late.

1.1 Guidance for PLM implementation on ETO products

The Cambridge dictionary described a framework as 'a system of rules, ideas, or beliefs that is used to plan or decide something' [15]. A framework can provide guidance to organisations on what is required to successfully implement PLM on ETO products. Sections 2 and 3 will show that a framework for PLM implementation is necessary to support the successful NPD for ETO products and that a framework that achieves this does not currently exist within published research. Without a framework, it is posited that ETO NPD organisations cannot not fully understand their PLM objectives, the challenges they will face, the improvements that are necessary, and how they can be enabled to ensure the successful implementation of PLM.

Donoghue et al. conducted a literature review on existing PLM frameworks and stated that 'PLM initiatives range from Information System (IS) change to strategic business transformation, and capabilities to implement PLM successfully are unclear' [16]. They went onto say that 'the challenge for any company is to identify the most relevant model that can be adapted to the context of the business. These models offer a starting point to create a systematic approach and understand the PLM transformation (Current state vs. To-be state)'. They concluded that 'the results show that strategy-driven PLM transformation impacting a company on many levels, and PLM focusing on IS-driven process harmonisation fails due to limited knowledge of the business models, products and services'. Therefore to ensure that a PLM implementation on ETO products is successful requires an understanding of its unique challenges, i.e. the context of the business. There is a gap in knowledge with the implementation of PLM on ETO products which means that the available guidance will not result in PLM which successfully addresses the objectives of an organisation for NPD in an extended enterprise. To address this gap a PLM implementation framework is required for ETO products which overcomes the challenges compared to other product types. It will identify the key objectives for the implementation of PLM on ETO products, the challenges, and the enablers to overcome the challenges and meet the objectives. The framework will structure these objectives, challenges and enablers by those which relate to information, process, people and technology.

This PhD research was initiated in January 2011 to investigate and apply improvements relating to PLM directly onto Type 26 to assist with the successful delivery of the programme and with the securing of export orders. The research has directly influenced the PLM implementation on Type 26 and the programme enabled a case study to be developed which is used to provide an industrial PLM context to the research. This enables an improved understanding of the framework against a real-life application of a PLM implementation.

This thesis will describe the core concepts of PLM as published in the literature. Different product types will be described and the challenges relating to PLM across these products with be discussed. This will demonstrate that ETO products have unique challenges which require a specific approach to PLM implementation that is not available in the published literature. Through a qualitative research approach a framework is developed by conducting and analysing 28 semi-structured interviews with senior stakeholders from global organisations involved in ETO NPD who have an interest in the successful implementation of PLM. The framework was then evaluated and validated using responses to questionnaires distributed to senior stakeholders from global organisations involved in ETO NPD who have an interest in the successful implementation of PLM. These findings are then discussed and related to the Type 26 case study.

1.2 Scope

The scope of the research presented in this thesis focusses on Engineer to Order (ETO) products which can be described as those which include all of the following characteristics:

- High capital value - typically with NPD costs greater than £1B;
- Large-scale - with thousands of stakeholders generating and consuming millions of product information items;
- Complex - with NPD development behaviours that are difficult to manage and understand;
- Long design and build lifecycle - exceeding 10 years;
- Long in-service life - which can be greater than 30 years;
- No physical prototype – the costs of creating a prototype are so great that the processes and design cannot be tested prior to the initiation of manufacturing;
- Highly customised - customised to a single or small group of customers; and,
- Few or one off - the costs and scale are so great only a few are produced.

ETO products have significant challenges and this research will focus solely on those which are related to Product Lifecycle Management (PLM). The boundary of the research is limited to the implementation of PLM on ETO products.

1.2.1 Research question

Donoghue et al. conducted a literature review of existing PLM frameworks which can be used to support a PLM implementation [15]. Those frameworks reviewed included those by Sääksvuori and Immonen [17], Schuh [18], Batenburg et al. [19], Stark [20], and Kärkkäinen [21]. Donoghue et al. concluded that these frameworks while valuable provide only a starting point on a PLM transformation initiative. It is difficult for a single framework to provide a 'one size fits' solution all for an organisation or product type. Each framework has its strengths and weaknesses and can contribute to a successful PLM implementation but they lack detailed guidance to support the specific business need for PLM implementation in ETO products. This supports the need for a PLM framework for a specific business context, for example a framework which addresses the challenges in ETO products. The published research from Donoghue et al. and the literature they used to form their conclusions are reviewed and critiqued in Section 3.

The literature on ETO NPD programmes stated that there are challenges related to PLM implementation which are not common to other product types. These challenges result in current PLM implementation approaches not providing the necessary structure to enable a successful realisation of ETO NPD objectives. Therefore the research question is: how can an ETO programme implement PLM to meet its objectives due to the challenges relating to its unique nature?

The research question can be decomposed into more specific questions, these are:

- What is the nature of PLM in relation to ETO products compared to other product types?
- What are the specific challenges of ETO products which necessitate a different approach to PLM implementation?
- What are the objectives of PLM implementation on ETO products?
- What are the challenges with PLM implementation on ETO products?
- What are the enablers to overcome the challenges of PLM implementation on ETO products in order to meet the objectives?

1.2.2 Research aim

PLM implementation is based on the specific context of the product type. As no PLM implementation strategy exists to overcome the challenges faced by ETO products one must be developed. Therefore to answer the research question, a framework is required to provide the necessary structure for PLM implementation on ETO products. The research aim is to provide a framework to ensure that objectives are met in relation to PLM implementation on ETO products considering the challenges faced due to its unique nature.

1.2.3 Research Objectives

To achieve the research aim, the following objectives were defined:

O1. Capture organisational requirements for a successful PLM implementation which can be used to develop a target PLM environment for ETO products

O2. Capture a PLM environment which meets the requirements of the ETO case study. This will be used to relate the findings to a target environment which can contribute to the understanding of the PLM framework.

O3. Conduct semi-structured interviews to:

- 03a.Confirm, and adapt where necessary, the identified challenges in relation to PLM implementation on ETO products.

- 03b.Contribute to the identification of the key business objectives on ETO products which a PLM implementation will support.

- 03c.Capture key challenges with the successful PLM implementation on ETO products.

- 03d.Capture and describe enablers which can be implemented to ensure PLM meets business objectives on ETO products.

O4. Create a Framework which can be used to successfully implement PLM for ETO products

O5. Validate the findings used to develop the framework and assess the value in relation to how it supports the implementation of PLM on ETO products

O6. Relate the key findings to the PLM target environment in the case study to support the discussion of the findings used to develop the framework with an actual ETO case study.

1.2.4 Significant contribution to knowledge

A framework to support the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) products.

1.2.5 Out of scope

This research is focused on the development of a framework for the implementation of PLM on ETO products which is the gap in knowledge. It does not include the readiness, or maturity, of an organisation for implementing PLM or assessing the success of PLM post implementation. It also does not provide guidance on PLM software selection.

1.2.6 Thesis structure

The structure of this thesis is as follows: -

- Section 2 describes the research problem and relates it to the scope of the research in the context of the aims and objectives described in the introduction.
- Section 3 presents a review of the literature relating to the characteristics and the aims and objectives.
- Section 4 describes the research methodology used to conduct the research.
- Section 5 describes the requirements relating to the implementation of PLM to meet organisational objectives on ETO products; this meets objective O1. It also provides a target environment for an ETO PLM environment which will be used to discuss the findings; this meets objective O2.
- Section 6 describes the research procedures used to capture the research findings.
- Section 7 describes the findings from the analysis of the interviews which are used to develop the framework; this meets objectives O3 and O4.
- Section 8 evaluates and presents the framework developed from the findings in Section 7; this meets objective O4.
- Section 9 discusses the findings and relates them to literature and the case study of the target PLM environment discussed in Section 5**;** this meets objective O6.
- Section 10 describes the main results of the research which concludes the thesis.

The thesis structure is illustrated in Figure 2 below.

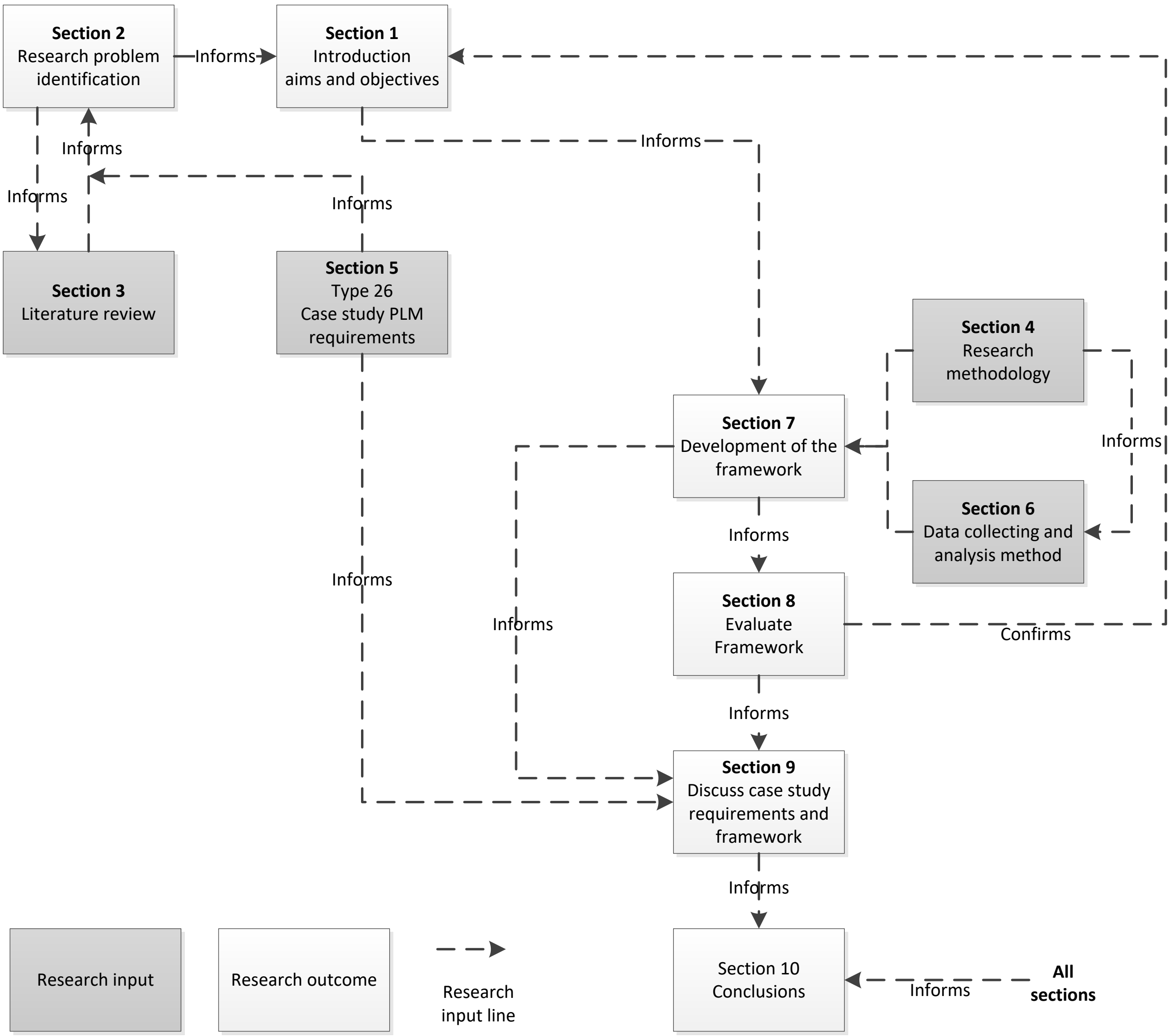


Figure 2 Thesis structure

2 PLM challenges in relation to ETO products

The research aim is to provide a framework to ensure that organisational objectives are met in relation to PLM implementation on ETO products considering the challenges faced due to its unique nature. Addressing this aim requires the development of an appropriate framework to support the PLM implementation. The framework will provide guidance to organisations on what is required to successfully implement PLM on ETO products. This is currently not available for ETO products.

BAE Systems Naval Ships has experienced significant challenges with PLM implementation over several decades and major programmes. These include the Type 45 destroyer and Queen Elizabeth Aircraft Carrier. A key business objective for the next major programme, the Type 26 Global Combat Ship, was to ensure that PLM was implemented to assist with the management of the programme and future business objectives. These objectives included demonstrating to potential future export customers that BAE Systems recognised the importance of PLM and that it would be applied successfully to products secured in the export market. The research described in this thesis supports these objectives by applying academic rigour and industrial application to the field of PLM in ETO products. This will enable the research findings to be applied directly onto Type 26 to realise business improvement, and also create a significant contribution to knowledge which could be applied across other ETO products. To support this objective, a literature review must first be undertaken to establish the nature of the problem and to ensure that no solutions in the form of frameworks already exists. This section describes PLM and its benefits using published literature. Due to the lack of material specifically relating to PLM on ETO products, the literature review was conducted to describe different product types and to use this material to formulate the specific challenges relating to PLM implementation on ETO products.

2.1 PLM Overview

Sääksvuori and Immonen described a key benefit of PLM is that up-to date, relevant and configured information can be accessed easily [17]. This enables tasks such as design or planning to be improved and timescales reduced as the approved information can be presented and reused in a more efficient way. PLM supports the extended enterprise by ensuring not only that information is available to all those who require, it but also at the same time, controls access to only those who have authority to view or update this information. This is of particular concern in defence programmes where secure information management is critical [22]. With large-scale, complex, long-life products such as naval ships, aircraft or submarines, the design and build takes place across multiple locations with multiple stakeholders and will include highly sensitive information in this extended enterprise. This introduces administrative overheads as information access must be carefully analysed, configured, implemented and managed to ensure the organisation is compliant with its security and regulatory obligations. These obligations include strict export control guidelines such as the International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR) which companies operating in the defence sector must adhere to. Those companies who fail audits, or are found to have breached these regulations can be issued with heavy fines or lose their licence to trade in the defence sector [23]. Managing these export obligations is a critical business objective, with PLM being a key enabler for managing sensitive export information [24].

There is also the requirement to manage the Intellectual Property Rights (IPR) of the information contained within the extended enterprise. The increasing levels of collaboration using product data results in sensitive commercial information being managed and shared across multiple partners, who may be competitors out-with the specific project [25]. This can be managed through the enterprise's PLM system thus reducing the threat of IPR falling into the wrong hands [26].

It is important that PLM does not simply ensure that information is available to those who require it and have the necessary rights, but that the information is configured, duplications are reduced and the data is up-to date to ensure that the context and applicability of the design is clear. This must be supported by robust authorisation and approval procedures which are governed by integrated workflows and change management processes in order to maintain the configured product definition. These approval and authorisation procedures are undertaken by the appropriate technical authorities such as systems owners, chief engineer or the customer depending on the level of authorisation required. For example a key system design on an ETO product, such as fire prevention, may require customer (Ministry of Defence) authorisation. However, the design of a low risk system, e.g. fresh water, may only require local system owner approval. The authorisation hierarchy becomes stricter when the configured design is required to be altered through the change management process. Typically this would require authorisation from a chief engineer or delegate as changes late in the design lifecycle may have significant consequences.

These processes are required to ensure that a particular configuration of a product is designed to meet specific customer requirements. As a consequence, the configurations of large-scale, complex, long-life products such as naval ships or aircraft are judiciously managed and each individual element is identified with unique numbering [5].

The information management in the context of PLM is not only to aid the delivery of a configuration chosen by a customer but also to ensure the design, build and in-service support of the product is robust. PLM ensures that during the product's lifecycle, the information is properly structured in support of the active life phase and that any design changes are highlighted and effectively communicated. This aids improved decision making, decreases approval time, decreases rework and ultimately improves quality as relevant information is presented to those who need it when it is required [17]. Without effective PLM, quality issues will emerge throughout the lifecycle of a product which will ultimately result in rework in the design and manufacturing environments [27].

Effective PLM requires robust configuration management processes and technology across the entire project, including the supply chain. There is a high volume of change which affects large-scale, complex, products, resulting in a critical need to capture, understand, communicate and action change concurrently with the design, manufacture and support phases [5]. A full audit history of when changes are introduced, and by whom, are critical to understanding why these decisions were made. This not only contributes to the organisation's knowledge but is also necessary for managing the maturity of the design and to support business measurement for targeting areas for improvement.

These descriptions and benefits can be summed up as PLM being a product-centric business model which is supported by Information Management and Technology (IM&T) across the entirety of a product's lifecycle, involving people, information, processes and organisations in order to achieve a product performance or service goal [28]. Brunsmann and Wilkes describe the main goal of PLM is to support the integration of people, information, process and systems to provide an information backbone to the business [29]. Therefore, 'IT Applications that support PLM have assumed critical importance as companies focus on enhancing the efficiency and effectiveness of their innovation across the enterprise' [10]. This is essential for major defence products given the limited budgets but increasing demand for advanced capability [30].

2.2 The PLM system of systems

PLM system is a series of interconnected applications, or system of systems, which perform various functions throughout the lifecycle of the product across the extended enterprise [28]. These interconnected systems have their own integration challenges resulting in numerous examples in industry where the Commercial-Off-The-Shelf (COTS) products are often highly customised by the organisation to meet their capability needs. This system of systems can be integrated for data integration and exchange, and for reporting purposes through a backbone such as a data warehouse where the information is structured and represented based on the source PLM systems [27]. Figure 3 illustrates the PLM system of systems in the context of the overall scope of PLM. These PLM toolsets were designed to support specific product objectives and typically evolved to improve their functionality to meet these objectives. This has resulted in disparate technologies that were not specifically developed to be integrated in the manner that directly satisfies the organisations objectives. Figure 3 highlights the fragmented nature of the PLM toolsets over the course of a product's lifecycle which leads to expensive integration to align with an enterprise's lifecycle processes [31].

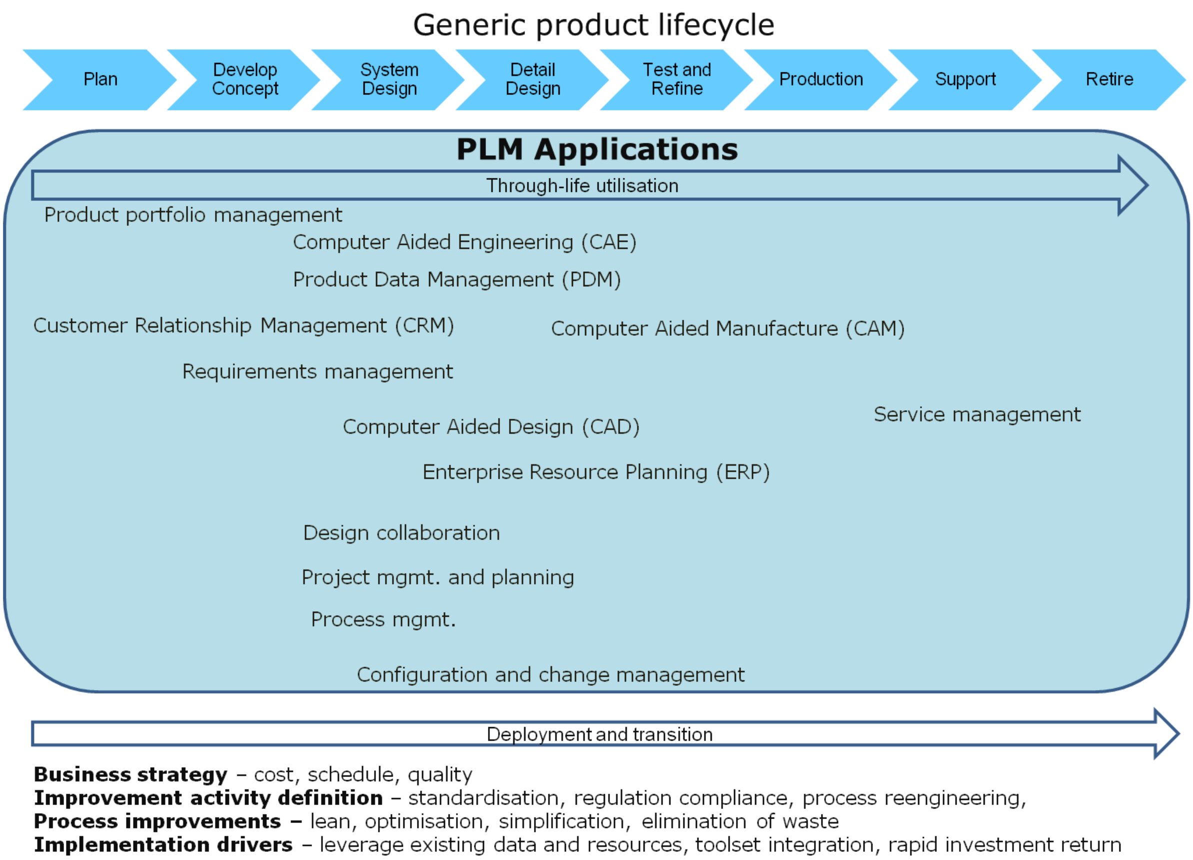


Figure 3 PLM system of systems – adapted from [31]

An important requirement of the PLM system is to capture information and to provide traceability throughout the lifecycle of the product [32] including providing version and audit management of the product information [33]. This information should be meaningful and not just a data dump to ensure that it can be used effectively and support the transformation into knowledge [32]. Capturing this information across the lifecycle of the product in the PLM systems will support design reuse through managing the configuration of the design and its intent [29]. This reuse is supported through the relationships with supporting documentation and workflows, ensuring that when engineers change roles, retire or leave the organisation, the legacy of their work remains within the organisation to be utilised in the future [29]. These structures are necessary not only to ensure the configuration is maintained throughout the lifecycle of the product, but also to ensure that the design is reusable as is it will provide relevance and ease of access for future interrogation [34].

To develop complex products requires a collaboration effort across multiple geographic locations with personnel from multiple disciplines and with a variety of skills [29]. PLM system integration removes the traditional problems of silos of information which has impacted the interchanging, integration and sharing of product information and will enhance collaboration across the extended enterprise [35]. It will also provide an efficient way of retrieving information for business intelligence such as dashboards or reports [27].

The information captured in PLM systems across the extended enterprise must be able to be retrieved and understood, resulting in a need to ensure that capturing, searching and displaying the information is robust and efficient to support the knowledge generation activity [29]. The technology must support organisational knowledge management and learning through the integration of project, process and product knowledge [36]. Organisations are required to support their products through its entire lifecycle which in the case of large-scale, complex, long-life products can be in excess of 30 years [37].

The core of the PLM system is typically the Product Breakdown Structure (PBS) [35], which supports the management and control of the product through object relationships [18] and its associated metadata. The PBS is used to define, capture, manage and configure the Bill of Materials (BoM) and its relationship to supporting information [18]. The BoM reflects the way complex products manage and evolve their product information throughout their lives [38]. The BoM typically consists of objects such as parts and occurrences but has a close relationship to the supporting information such as documents, drawings, 3D models and change objects [18]. Figure 4 shows an example of these object relationships for Shipbuilding where an occurrence of a radar monitor equipment part is related to a radar system in the system design PBS. This enables a representation of the design from the system schematic to be managed in the PDM system. The radar occurrence is also placed in a specific compartment in the physical PBS which is used to create a 3D representation in the CAD model for the ship. The object relationships provide further benefits such as:

- Writing and managing equipment data once but applying many times through occurrences;
- Assisting with traversing though the design;
- Supporting the application of permission constraints for access and updating;
- Enabling improved reporting; and,
- Application of configuration and change control.

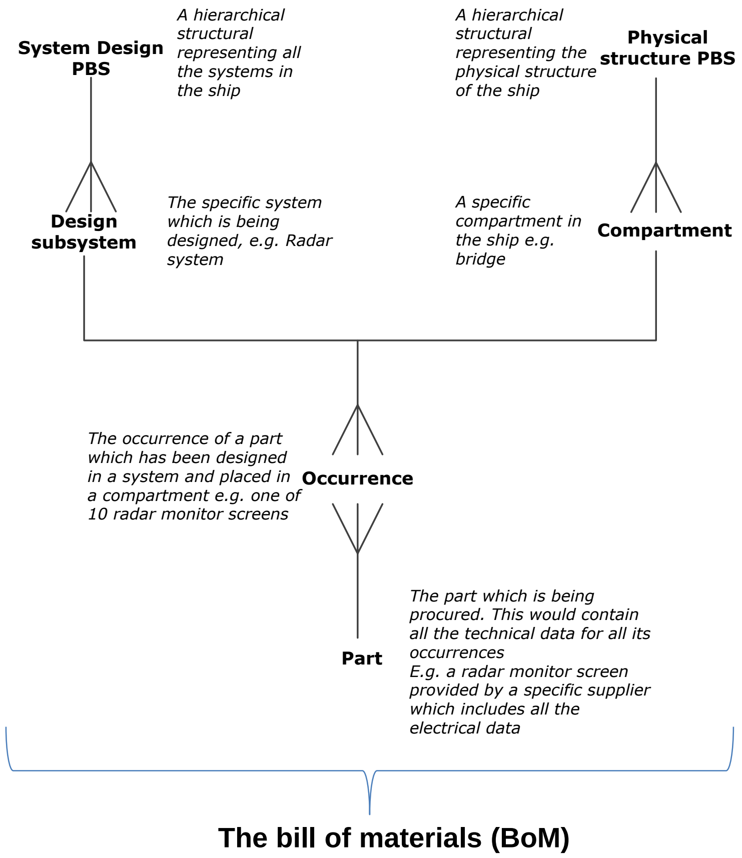


Figure 4 Product object relationships in shipbuilding.

Different Product Breakdown Structures are necessary for the various disciplines in complex products and can be represented and integrated to support an Enterprise BoM [38]. An Enterprise BoM is to support multiple stakeholders who require different levels of information in the BoM at different phases in the product's lifecycle. These include the:

- Engineering BoM – to manage the design of the product and generate the engineering BoM which is the basis for all other BoMs;
- Manufacturing planning BoM – to manage the planning for delivery, manufacture and installation of the engineering BoM into the physical product;
- Manufacturing BoM – to manage the build of the physical product; and,
- Maintainable BoM – to provide the in-service support information for the product.

The Enterprise BoM supports the information needs of multiple stakeholders through the integration of multiple BoM structures, required to support the business throughout the lifecycle of the product as shown. Figure 5 shows the BoM for breakdown of an equipment part at various points in the lifecycle phase including engineering, manufacturing planning and in-service support. The engineering BoM reflects the product as-designed by engineering. The manufacturing BoM represents the product as it is required to be shipped, assembled or manufactured. The maintainable BoM represents the product as it is required to be maintained.

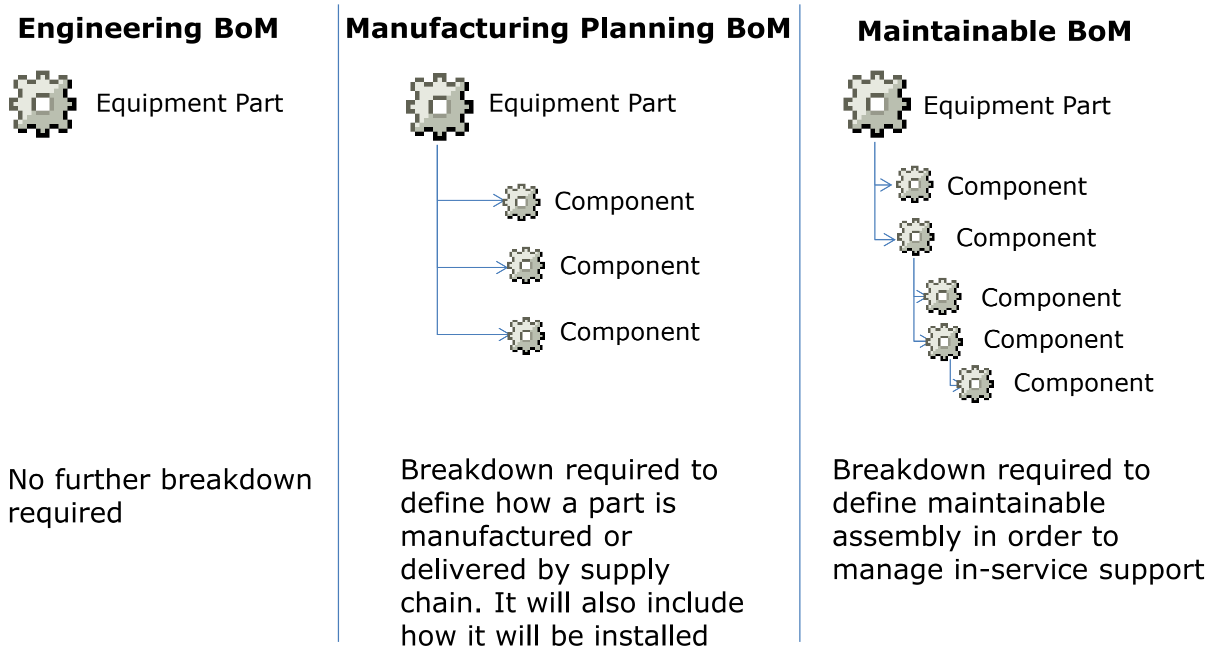


Figure 5 Example of the same equipment part broken down at different points in the lifecycle.

The enterprise BoM should be considered as the master BoM across all the enterprise's systems [38] in order to avoid any disparate sources which may contain out of date or inaccurate information. The various needs of the stakeholders across the lifecycle of the project should ideally be met by an Integrated Product Development Environment (IPDE) [39] with the PLM technology at its core [30]. The aim of an IPDE is to provide the information to support the product development processes in an integrated environment.

The management of the process and information objects is not only to support the activities in the product's lifecycle but also to ensure that the information can be reused for future opportunities and for legal and contractual obligations [40]. The information generated and maintained within the PLM system for large-scale, complex, long-life products is typically spread across geographical locations and requires integration across this extended enterprise to other systems. Technology which require improved integration include the Product Data Management (PDM) and Enterprise Resource Planning (ERP) systems [41]. For example, improved integration will allow the Engineering BoM in the PDM system to be more effectively transferred to the ERP system for procurement and manufacturing planning. Engineering activities include aspects of the design and manufacture which cannot be undertaken by a single organisation and are therefore outsourced, resulting in collaboration with different organisations across the extended enterprise [42]. Outsourcing in engineering construction projects is also common due to fluctuations in workload which result in difficulties with maintaining a workforce. These collaborations provide challenges in realising the expected benefits as costs can increase as more organisations are involved in the collaboration, due to the resultant management overhead [43]

Challenges include how information can be managed and communicated throughout the distributed design teams [37]. This challenge is compounded due to the difficulty in exchanging product information across different organisations and their systems due to technological constraints and behavioural issues [44], [45], [46]. In order to achieve effective through-life product management, the relevant information has to be identified at key points throughout the product's lifecycle. It then has to be presented in a way which is useful, configured, controlled and reusable throughout the lifecycle [47]. The information management technology must capture, integrate and evolve information throughout the entire lifecycle of a product [47].

Large-scale, complex, long-life products have extended their focus from a design/manufacture perspective to include the product's behaviour in-service and after sales support. This is driven by the customer's need to increase quality and reduce costs [47]. This product-service paradigm means that information management technology must be robust enough to last the entire lifecycle of the product from concept through to disposal, which can often be in excess of 30 years [48], [47]. Ensuring that this information can be robustly stored, controlled and reused has been an area of research for industry and academia for decades [49], [50], [51] and has been identified as being a way to increase revenue and satisfaction for both the product provider and customer [52].

PLM Systems are now seen as a mandatory element in reducing risk in large-scale, complex, long-life products by supporting virtual simulation and prediction [53]. This is essential for defence products which have to undertake rigorous inspection and auditing in not only the virtual and physical elements but also with the supporting decision making information [30]. Therefore, PLM systems have a significant contribution to ensuring improved productivity, improved quality and reduced costs in products such as naval shipbuilding and submarines [54]. PLM also ensures that the design and build information can be efficiently transferred into an in-service support context [30].

2.2.1 PLM implementation

PLM implementation is extremely challenging and expensive with $29.9 billion being invested globally in PLM in 2011 of which $19.1 billion (64%) of that was in the applications themselves [5]. Despite these investments few companies have realised the projected benefits [10]. Reasons for the varying degrees of success include organisations typically focussing on individual aspects of PLM and failing to take a holistic approach. This may be due to the organisation not understanding what PLM means [18]. There are also gaps in literature relating to PLM [18] highlighting a lack of detailed research into actual PLM implementations [55]. The challenge of understanding which functionality should be adapted to support the business processes, and which processes should be adapted to support the functionality has an influence on PLM success [17]. Organisations have turned to system vendors or internal analysts/programmers to solve their PLM problems. This often leads to significant degrees of customisation of the PLM systems which, in turn, results in the organisation assuming more ownership of these systems, impacting on-going support and future upgrades [31]. This may however indicate immaturity or quality issues with the PLM Systems themselves [10].

When implementing PLM, the organisation should first understand its strategic objectives and core processes and use this to decide on the PLM approach which should in turn influence the PLM system implementation. This is not trivial as the alignment of business objectives, process and functionality is one of the key challenges to PLM implementation [56] and is an area that the PLM system vendors have difficulty in resolving [18]. This may be due to a lack of understanding on the part of the PLM system vendors about their customer's needs, which may in turn be due to a customer's inability to understand their own relationship between strategic objectives, process and technology requirements. Further research is required with respect to the implementation of the technology to align with the organisation's processes and the strategic vision, with problems arising from tracking performance and quality across the extended enterprise [1]. Without this research, it is possible that the organisation could suffer the same fate impacting other major enterprise IT investments: that of a disconnect between the investment in IT itself and lack of return in business value due to problems with aligning IT with other aspects of the organisational strategy [10].

The confusion between the concept of PLM and the enabling technology is propagated by the software vendors who position themselves as PLM solution providers. This causes difficulties for PLM implementation as organisations are confused between PLM technology and the core concept of PLM [18] which is the management of all integrated product information and processes throughout the product's lifecycle [17]. This impacts the PLM implementation as organisations find it difficult to decide which functionality, from the considerable capability available, can and should be used to benefit their business [56].

2.3 Safety, Health and the Environment

PLM contributes to a robust safety case to ensure that the product has been through a rigorous design, manufacture and support lifecycle with the necessary evidence to prove that the product is safe. It supports the activities to meet regulations for Safety, Health and the Environment (SHE) by assisting in capturing and formatting information as well as providing audit trails as to why particular decisions were taken [27]. This is a significant contributory factor in supporting the recommendations on safety case development from the enquiries relating to product failure [57].

The organisational improvements PLM supports are not only to improve business performance, but will reduce the environmental impact inflicted throughout the development of the product [55]. This includes the support PLM gives to working in an extended enterprise with a considerable reduction in the travel needs, and therefore the CO2 footprint of the organisation. The quality improvements also significantly contribute to a reduction in waste in the organisation through an improved understanding and robustness of the state of the product. The savings to time will contribute to improved transition across the product's lifecycle with enhanced access to robust, reusable information which in turn contributes to a healthier working environment.

PLM also contributes to the management of hazardous material considerations and to ensure that regulatory obligations to protect the environment are met. Regulations include: the End of Life Vehicle (ELV) which requires automotive manufacturers to recover 95% of materials at disposal; the Registration, Evaluation, and Authorization of Chemicals (REACH) to manage the use of banned chemicals; and the Restriction of use of certain Hazardous Substances (RoHS) such as Mercury and Cadmium [58]. PLM is an enabler for green manufacturing as it supports the tracking of all material information relating to the design, build and support to ensure SHE information is captured, managed and used to support a green life when in service and disposal [58], [59].

2.4 Characteristics of the problem of PLM implementation on ETO products

PLM research has been undertaken across many contexts including, many-of-a-kind and one-of-a-kind/few-of-a-kind products. Each of these contexts have their own challenges and can be categorised and should be approached differently on this basis [28]. However, the literature on PLM relating to ETO products is sparse.

When identifying PLM implementation challenges it is important to distinguish between the various product types. Each of these product types has their own difficulties but this research will describe the unique challenges affecting ETO products in comparison to others. Product types can be categorised as Make to Stock (MTS), Make to Order (MTO), Assemble to Order (ATO) and Engineer to Order (ETO).

The key difference between MTS and MTO is how the order is managed on its receipt from the customer [60]. With MTS, the order is ready to go upon receipt whereas with MTO there is some manufacturing required before shipment [60]. ATO allows a degree of customisation by the customer but only with regard to the assembly of pre-manufactured parts [61]. With ETO the order is received before the design stage and the customer typically has a large influence on the requirements and the resultant function of the product [60], which tends to be one or few-of-a-kind products which are large-scale, complex, long-life, and highly customised [9]. ETO products also have overlapping lifecycle phases where design, manufacturing and procurement can be undertaken concurrently to reduce the timescale for delivering the product [62].

Therefore ETO new product development and build such as First of Class (FOC) naval ships can be described as large-scale, complex, long-life, one/few of a kind, customised and where it is not cost effective or practical to have a physical prototype. The one/few of a kind and customised elements distinguish it from other large-scale, complex, long-life products such as commercial aircraft which can be more accurately described as ATO products. Challenges exist in all types of product development which can become apparent in the design, manufacturing, in-service or even disposal life phases. Stark describes multiple examples including [27]:

- Time to market such as with the A380 where a two year delay was estimated to cost $6B.
- During production such as with multiple computer manufacturers affected by faulty batteries made by Sony which were found to overheat and potentially pose a safety risk.
- In-service including engine defects in Nissan cars resulting in the recall of 2.55 million or with the Deepwater Horizon drilling rig when a blowout preventer failed resulting in the death of eleven people and considerable environmental damage.
- Disposal such as when the French aircraft carrier's dismantling project failed due to the large amounts of asbestos on board Resulting in failed attempts to dismantle it in Turkey and India.

The level of complexity and lifecycle of the new development of a product has a strong influence on the methodology used when implementing PLM. For instance, new developments in automotive can be described as a complicated, long-life product type due to the personnel, processes and technology required for its design, manufacture, support and the length of the product's lifecycle which can be measured in decades [28]. Other new product development such as with PC's or cameras can be described as complicated and short-life products due again to the people, process and technology required but, in this case, the product has a limited lifespan [28].

PC's and cameras can be categorised as many-of-a-kind, mass manufactured consumer products but they have different development processes to other product contexts due to their industry clock-speed [63]. Industry clockspeed 'gauges the velocity of change in the external business environment and sets the pace of their firms' internal operations' [64], this drives the speed with which newer versions or products are developed and released to the market. Slower clock-speed industries such as aerospace have more structured processes focusing on configuration management [31]. Faster industries such as those manufacturing PC's or cameras have leaner development processes to ensure their product gets to market as quickly as possible to gain competitive advantage due to the speed of obsolescence and limited market time.

There are other differences with these product types compared to ETO's such as naval shipbuilding [28]. It is useful to first explore the differences between the design, manufacturing and support environments and the end product itself. Short and long-life products such as cameras and cars can share a relatively short design and manufacturing lifecycle but there are obvious differences in the useful life-span of these products compared with ETO products. Within these consumer products, PLM supports managing the global supply chain, design collaboration and configuration management for the high volume of products produced, all of which is over a global extended enterprise for design, manufacturing and support [5].

To assist in understanding PLM in ETO products and it's similarities and differences with other product types it is worthwhile considering the he Architecture Engineering Construction (AEC) industry and their experiences with managing product processes, information and technology through their design and build lifecycle. Tolman asserts that information is the most critical material for building and construction [65]. Borrmann et al. described AEC industries as struggling with information management challenges, for instance it is not uncommon for digital information which supports the design and construction, such as documents, drawings, plans and 3D Models, not to be centrally stored or related to each other in a configured way [66]. Whilst other industry types have recognised the need for PLM to manage their information, AEC industries have yet to find a way to fully resolve this problem. This may be due to fragmentation between AEC planning and construction which can be under the jurisdiction of different organisations with little coherent integration. Other challenges faced by AEC industries are that their information is not broken down to a granular level, thus not having a full product breakdown structure which is critical to effective PLM.

Froese states that information management systems in the AEC industry have had three main eras [67]:

1. The development of bespoke systems for specific functions such as CAD, structural analysis and estimating, which started four decades ago and is still continuing.
2. More recently, (mid 1990's) web based document management emerged, which is still ongoing with business models still adapting.
3. Recently, more investment has been made in cohesive integrated systems, such as those in mature PLM environments, but these are still not in the mainstream.

It is apparent from the literature that AEC is immature in the use of PLM compared to ETO. Progress is being made with the Business Information Modelling (BIM) approach [68] but AEC projects can benefit from utilising PLM to improve their processes, information and technology integration to leverage the lack of maturity with BIM [69].

This research focusses primarily on ETO and the unique challenges it faces in comparison to other product types in relation to the implementation of PLM. These challenges are based on the design, manufacture and in-service support lifecycle as opposed to the operation of the end product itself. It will highlight that the size, complexity, long-lifecycle and lack of the ability to prototype results in significant challenges which necessitates a tailored approach to PLM implementation for these product types.

The approach should focus on ensuring that the PLM implementation supports the organisation's objectives, related processes, requirements and supporting technology. Fichman and Nambisan described this as a considerable challenge due to evidence of a lack of robust models to support the alignment of IT innovation and business value in general terms, or at least an inability to distinguish between those IT investments which provide value and those which do not [10]. Fichman and Nambisan also state that in the early days of IT investment, identifying value was easier due to complementary elements being obvious, such as with CAD being linked to manufacturing machines to produce higher quality products. As technology and organisational adoption matured it became harder to identify value from IT investment or where the actual problems lay with realising this value, for example problems with the technology itself or organisational aspects such as process, culture or resource [10]. The investment in IT initiatives such as PLM requires the alignment of complementary elements such as strategy, process and the technology itself. Stark [27] stated: 'companies in different industries have similar objectives for PLM, the exact requirements may differ. PLM is not off-the-peg, one size fits all. The functionality and implementation priorities depend on the market needs and objectives of the company'.

This research focusses on the specific requirements for PLM implementation on ETO products and will provide guidance in the form of an implementation framework to support meeting organisational objectives. The gap in knowledge is described in Section 3 and how the research has provided a significant contribution to knowledge in this area is described in Sections 7 and 8.

The following sections will describe the nature of the challenge of ETO products and will use other large-scale, complex, long-life, no physical prototype, highly customised, one-of (few of) a kind products such as AEC and industrial megaprojects to highlight similarities and differences with ETO products.

2.4.1 Megaprojects

Engineering to Order products can also be referred to as megaprojects due to their size, cost, complexity and effective life which typically spans decades [70]. Megaprojects are usually massive civil projects commissioned by governments, such as infrastructure development where the cost is multi-billion £'s and contracted to a private company [71]. Merrow defined a megaproject as a project which has a capital cost of greater than $1B in 2003 or approximately $1.7B in 2010 [72]. These products are complex, involve many partners, are politically sensitive, have a design, build and in-service lifecycle of many decades and increasingly are used to describe civil and engineering construction projects [71].

Flyvbjerg argues that we are now entering a 'Tera era' where megaproject cost is in excess of $1T, an example of which is the US debt to China which requires careful management due the effect mismanagement would have on the world economy [73]. Flyvbjerg states that many megaprojects are so large that if they were countries they would be in the top 100 measured in gross domestic product. These characteristics can be compared to ETO products which allow for a more thorough analysis and comparison of the unique challenges faced when implementing PLM on these product types.

This research is bounded by engineering products only as opposed to other megaprojects such as huge IT or macroeconomic projects due to their reliance upon an effective PLM implementation. A distinction can be made between traditional megaprojects and industrial megaprojects. It is recognised that the latter offers a greater challenge due to its specialised construction nature [74] and the end result is a functional product which is few or one of a kind. This greater challenge is due to industrial megaprojects tending to be a significant investment with smaller occurrences and therefore do not have the same repeatability and learning opportunities as traditional megaprojects. Industrial megaprojects are not common place, and result in a scarcity of skills, facilities and specialised nature required for their innovation requirements and the execution of the programme [74]. The specialised nature of the industrial megaproject requires software which is designed to support the delivery of the programme, including engineering software [75] of which PLM systems are amongst the most critical.

PLM literature related to industrial megaprojects is sparse compared to other product types such as MTO or ATO. Even when there is dedicated literature on the subject, they often ignore the more challenging aspects. Merrow for example described industrial megaprojects as projects which make a product for sale such as gold, petroleum, and chemicals and deliberately excludes others such as military projects and public works. Merrow stated that this is due to projects not necessarily being driven by a desire to make money but for political reasons such as economic growth or job creation. This is believed to introduce unnecessary complexity into some projects as often they will continue due to political support when the need has long since passed; such as military projects. Further examples of this are cited as being prestigious projects such as Concorde or those, which due to the amount of money already invested make cancellation unpalatable to the political establishment. Other complexities to these projects are the need to show value in spending tax payers' money [72]. This often results in long drawn out tendering and contractual processes, which takes years and whose value is questionable, and is driven by a desire to gain the best product at the best price but removes the benefits of establishing long term supplier relationships which are common place in other industries.

Therefore industrial megaprojects can be split into two distinct categories influenced by funding and motivation:

1. **Public industrial megaprojects** – those funded by the public purse, such as military, whose end result is a functional product which is few or one of a kind. Distinguished by the fact that the sponsor is not necessarily expecting to make money but is driven by a public need.
2. **Profit industrial megaprojects** – those funded by enterprises, such as oil and gas or mining whose end result is a functional product which is few or one of a kind. Distinguished by the overriding need to generate profit and provide shareholder value.

Ignoring public industrial megaprojects in favour of those which generate a profitable product is understandable as it simplifies and focusses research, but there is a need to highlight the gap in understanding of how the research in profit industrial megaprojects can benefit public industrial megaprojects. Table 1 provides examples of different profit and public industrial megaprojects [72] which are characterised as:

- They are important to the societies for which they are being undertaken;
- They are important to the health of the economies through the generation of jobs and the trade that they support;
- They are extremely important to those financing the megaprojects, whether they are public or privately financed; and,
- They are prone to problems whether it is schedule, safety, cost or environmental to an extent that it can bring down the sponsors such as governments or companies.

Profit industrial megaprojects	Oil rig construction Refinery construction Mining facility construction Power station construction Dams and hydroelectric construction
Public industrial megaprojects	Naval shipbuilding Submarine construction Space construction – rocket ships, space stations etc.

Table 1 Examples of profit and public industrial megaprojects.

The specialised nature of industrial megaprojects also contributes to the difficulty in estimating for project management. This commonly results in over ambitious estimates which lead to cost and schedule overruns [76]. Industrial megaprojects are typically funded by governments but are delivered by privately funded companies, such as with major civil or defence programmes [70]. Industrial megaprojects relating to defence procurement have been affected by major cost and schedule overruns such as seen recently with aerospace, submarine and naval ship programmes [77]. Megaprojects have a long history of cost overruns due to poor estimation, changes within the project or within the macro environment affecting it, and with faulty project management [78]. The time difference between the National Audit Office and Merrow reports differ by decades, however megaprojects still suffer from cost and schedule overruns suggesting that the challenges identified are yet to be resolved.

Project	**Cost Overrun (%)**
Suez Canal, Egypt	1,900
Scottish Parliament Building, Scotland	1,600
Sydney Opera House, Australia	1,400
Montreal Summer Olympics, Canada	1,300
Concorde supersonic aeroplane, UK, France	1,100
Troy and Greenfield railroad, USA	900
Excalibur Smart Projectile, USA, Sweden	650
Canadian Firearms Registry, Canada	590
Lake Placid Winter Olympics, USA	560
Medicare transaction system, USA	560
National Health Service IT system, UK	550
Bank of Norway headquarters, Norway	440
Furka base tunnel, Switzerland	300
Verrazano Narrow bridge, USA	280
Boston's Big Dig artery/tunnel project, USA	220
Denver international airport, USA	200
Panama canal, Panama	200
Minneapolis Hiawatha light rail line, USA	190
Humber bridge, UK	180
Dublin Port tunnel, Ireland	160

Project	Cost Overrun (%)
Montreal metro Laval extension, Canada	160
Copenhagen metro, Denmark	150
Boston-New York-Washington railway, USA	130
Great Belt rail tunnel, Denmark	120
London Limehouse road tunnel, UK	110
Brooklyn bridge, USA	100
Shinkansen Joetsu high-speed rail line, Japan	100
Channel tunnel, UK, France	80
Karlsruhe-Bretten light rail, Germany	80
London Jubilee Line extension, UK	80
Bangkok metro, Thailand	70
Mexico City metroline, Mexico	60
High-speed Rail Line South, The Netherlands	60
Great Belt east bridge, Denmark	50

Table 2 Large-scale projects have a calamitous history of cost overrun [73]

Rangan et al. argued that PLM implementation has evolved from an initial approach of multi-year projects involving extensive process evaluation, system configuration, training and on-going support, to one of rapid deployment involving existing infrastructure, processes and resultant reduced training [31]. PLM system vendors support this by making their functionality much more adaptable to organisational processes. For example, objects in a PDM system can be adapted to represent the different business needs such as a part to represent an engineering BoM and other to represent the assembly items in the manufacturing BoM. However, due to the nature of megaprojects and ETO products, such as their long lifecycle, it is inevitable that PLM implementation will differ dramatically from other industry types.

Product development processes and technology on one project may have been introduced a decade prior to the initiation of the next project using what was available at that time. For example the PLM implementation for the Type 45 Destroyer programme started in the late 1990's and has had to be re-engineered for later naval programmes such as the Queen Elizabeth Aircraft Carrier in the early 2000's and later still the T26 Global Combat Ship in early 2010's. This is due to:

- New technology which can provide additional benefits to the latest programme;
- Matured business processes to assist with managing the programme;
- Lessons learned from previous programmes across all aspects of PLM;
- Improved culture where more technological aware staff are more willing to embrace PLM; and,
- Funding from the customer to introduce capabilities whose investment can be offset against improvements provided by PLM.

Introducing new PLM approaches to previous programmes is not practicable due to the often decade long lifecycle which the product development has been running. These programmes will have information in specific technology formats, e.g. CAD model, and processes firmly embedded in the business which would cause impact onto a contractual and schedule/cost agreed programme.

Rangan et al. recognises that the transition from one PLM approach to another needs careful planning including business change management, education and transitioning to new processes but the emphasis is on a 'gradual' move with minimal impact to on-going business performance. This is perfectly valid for most industries but does not take into account a major change to technology and process which is necessary at the start of megaprojects and ETO products [31]. This is due to the commitment an ETO programme has made to its PLM approach and the impact of changing it when it is many years into the lifecycle of the programme. ETO has a slow clock-speed compared to other product types which can introduce new PLM approaches onto the next new product development programme.

2.4.2 Specific challenges with PLM implementation on Engineer to Order Products

ETO products have a long design and manufacturing lifecycle with many millions of labour hours consumed across years [79] and a working lifespan stretching decades [47]. These products have a wide variation in the operational procedures utilised, have a greater disconnect between the design and production environments than with consumer products due to the considerable timespan between design initiation and build, and regarded as a construction process as opposed to mass manufacturing production [75]. The literature on New Product Development (NPD) for ETO products is sparse in comparison to other types and significant challenges remain for successful development. Rhaim and Baksh investigated the need for a separate NPD framework for ETO products. This would assist ETO companies to:

- Reduce design iteration and rework;
- Recognise customer requirements up front; and,
- Build quality into design and manufacture.

They stated that ‘most NPD frameworks from the literature are meant for an MTS company. The design framework or models proposed for an MTS company are not suitable to be applied to an ETO company due to various differences’. They also stated that ‘very little attention is given to an ETO company that produces products on a low volume basis especially in terms of an NPD framework’. They went onto state that ‘so far the NPD framework for ETO is not adequately addressed and the process used most likely is derived from an MTS framework’. They stated that ‘an ETO company, due to its nature of operations that constantly requires new design for every product, is in greater need of an NPD framework’. The also stated that ‘the generic NPD framework developed for an MTS product is inadequate in addressing the differences in ETO and MTS operations. [80]. The main differences between ETO and MTS products are shown in Table 3.

Criteria	Engineer to Order (ETO) product	Made to Stock (MTS)
Design	Usually exclusive to one customer	General Market
Frequency of design	Very frequent	low to frequent
Use of design codes and standards	Yes	Generally no
Effort and cost in design per product	High	low
Chance of design rework and improvement during manufacture	Low	High
Design of prototype	No	Yes
Design options	Few	Many
Tooling requirement	Limited	Many
Constraint in design	Limited to availability of off the shelf components or parts	No limitation
Involvement of manufacturing engineers in design	Always	Rare
Design dependency on similar product	High	Low
Prototype	No prototype	Use prototype
Customer input during design	Customer usually gives input during design	Customer rarely involved in design process
Customer approve design	Yes	No
Product test and commissioning	Usually at customer site	At manufacturing site

Criteria	Engineer to Order (ETO) product	Made to Stock (MTS)
Customer technical knowledge of product	High	Low
Certainty of customer requirement	High	Low
Product complexity	High	Low
Product size	Generally big	Small and medium size
Customer requirements	Specific and technical	Vague and non-technical
Interpretation of customer requirements	Direct	indirect
Supplier involvement in design	Seldom	Rare
Contractor involvement in design	Seldom	Rare
Dry run/pilot run	No	Yes
Market research	Minimum	Extensive
Product launch	No	Yes
Market	Pull	Push
Product lifecycle	Long	Short
Compliance with legal requirements	Always	Rare
Documentation required by customers	Extensive	Minimum

Table 3 Differences between ETO and MTS in terms of product design [80].

Figure 6 illustrates how the committed costs early in the design lifecycle have a considerable effect on the costs incurred when they are realised later in the product's lifecycle. The figure contains the key deliverables across each lifecycle phase in FOC shipbuilding. It illustrates that there is an investment committed to produce each deliverable. If these deliverables are required to be changed, such as due to mistakes or poor quality, then the costs incurred are significantly greater than those committed the later in the lifecycle that have to be altered. Mistakes early in the lifecycle can incur substantial cost increases later within the project. This is particularly true of ETO products where the time difference between the costs committed and those incurred can be years. There is a significant difference in the values of the costs committed and those incurred between slow and fast industry clock-speeds as the time difference is greater between costs incurred and cost committed, resulting in greater impact. PLM implementation on ETO products must provide support to manage each of these lifecycle phases to assist in ensuring that there are not significant costs incurred due to issues from earlier phases.

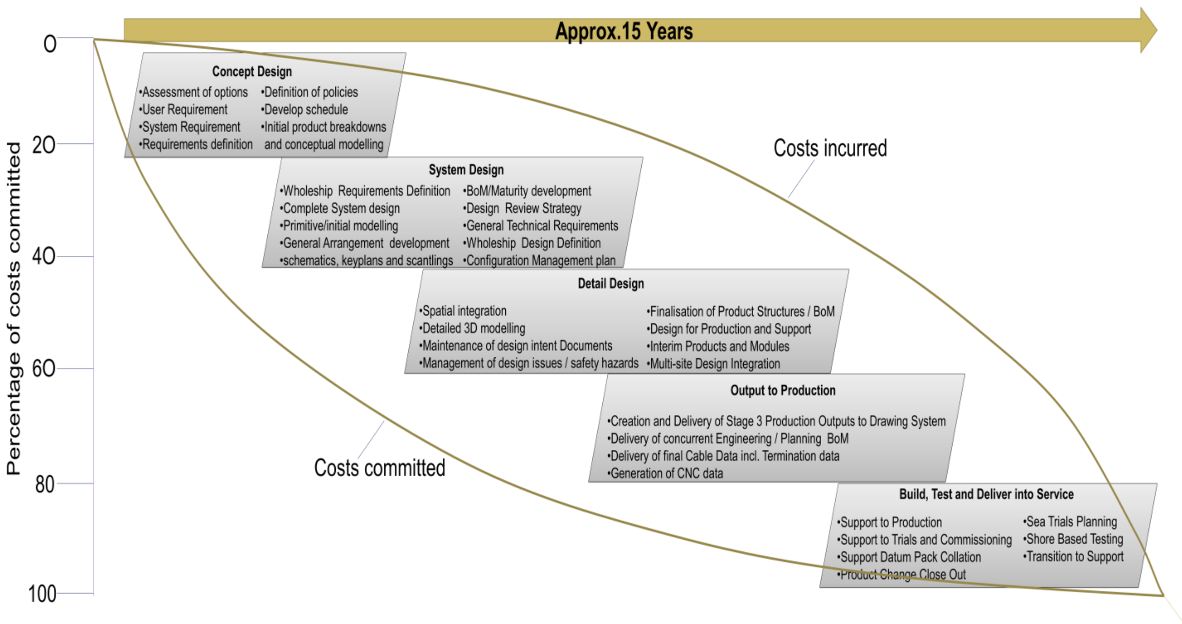


Figure 6 Engineering deliverables across the lifecycle of naval ship design with costs committed and incurred - adapted from [9].

2.4.3 Complexity and uncertainty

The level of complexity is one of the greatest challenges to manage within the development of ETO products. This is due to the large number of different types of elements interacting across their lifecycles in difficult to predict ways, such as various design systems being designed concurrently which are impacted by change [81]. Complex systems are unpredictable as a result of constant change within their operating environments, which differ from complicated systems where there are many interactions between the elements of the system but they can be predicated and understood with the right knowledge and tools [82].

An FOC naval ship can be described as complicated in its operational behaviour as a product but is highly complex in its design, manufacture and support due to unpredictability throughout its lifecycle. Weaver described disorganised complexity as when it is difficult to predict an outcome due to a high number of factors which can only be measured using statistical analysis, e.g., the behaviour of a large number of billiard balls as they move around a table. Organised complexity is when there are a large number of factors which are contained within an organised whole, such as the human body [83]. The complexity of ETO product delivery can be organised complexity in that while all the interactions are not fully understood at any one time they can be understood using scientific approaches. Homer-Dixon described complex systems such as the product development life-phase system as:

- ‘Comprised of a multiplicity of things; they have a large number of entities or parts. Generally, the more parts a system contains, the more complex it is.’ The parts themselves may vary in complexity; a naval ship for instance may have 10,000 procured equipment parts with 40,000 occurrences. These will vary from complex weapons to simple valves and are broken down into different procurable groups in order to manage these differences.
- ‘Containing a dense web of causal connections among their components. The parts affect each other in many ways.’ A major equipment part on a naval ship will require an electrical service and perhaps water and air cooling to be design concurrently. This requires other parts to be designed and procured to meet this need such as Air Treatment Units (ATU) for cooling.
- ‘Exhibiting interdependence of their components. The behaviour of parts is dependent upon other parts. If the system is broken apart, the components no longer function (like the parts of

the human body).’ The systems on a naval ship are designed to meet the overall requirement of the product. If that system is changed during design, such as with removing one of the ATUs, then the Heating Ventilation and Air Conditioning (HVAC) system will not meet the operating needs of the ship.

- ‘Open to their outside environments. They are not self-contained, but are affected by outside events.’ In a naval ship if the ATU fails due to poor design then the equipment parts will overheat and also potentially fail.
- ‘Normally showing a high degree of synergy among their components: the whole is more than the sum of its parts.’ A naval ship can be described as a system of systems, which are designed to be interrelated and connected to ensure that the ship can operate effectively.
- ‘Exhibiting non-linear behaviour. A change in the system can produce an effect that is not proportional to its size: small changes can produce large effects, and large changes can produce small effects.’ [84]. An increase to the wild heat generated by a major equipment item on a naval ship will result in the design of the HVAC system being inadequate and will result in other potential failures throughout the ship.

This organised complexity requires analysis and careful management throughout the new development process to meet the product’s objectives due to the large number of interacting elements during the concurrent design and build which will impact the delivery of a naval ship [81]. These could include a change to the wild heat which will result in changes to the HVAC system which may require bigger air treatment units which in turn will impact spatial integration, weight management and, if later in the lifecycle, manufacturing rework.

Examples of the key engineering deliverables in each lifecycle phase of a naval ship are shown in Figure 6. These phases overlap and there are stage gates to manage the promotion of specific design zones from one phase to another and the integration across multiple zones. Therefore there are major aspects of the design which will be in different phases at any one time, i.e., while one design zone has begun detailed design other zones are still undergoing system design. While this greatly compounds the complexity regarding integration and design maturity, a linear approach would result in a significant increase in the timescale of the new product development. Improved management of product information integration and maturity are a requirement on PLM for FOC Naval Ship NPD as discussed in Section 5.

These complexities create pressures on cost, long times and ever demanding expectations for higher quality [75]. There are a large number of interrelated known and emergent elements relating to the product which require careful management throughout its lifecycle, for example, changes to supplier provided equipment interface requirement such as wild heat. These emergent elements have interrelations with other aspects which may go unnoticed and contribute to the overall complexity and challenge for the product [78]. For example a change to the wild heat generation of equipment may not be communicated to the HVAC design team due to the huge amount of information flowing through the business from the supply chain. These challenges highlight the importance of PLM within ETO industry in order to improve the management of design information.

Froese described the complexity of the influences associated with design change in AEC projects where the intended use of a room may change its cooling or heating requirements. These may have a domino effect: the mechanical design may affect supplier contracts which may affect material delivery which impacts schedule, delays construction and increases costs [67]. These difficulties which are due to emerging patterns, interconnectivity and complexity are common place in ETO products. The complexity is increased due to a need to ensure quality standards are adhered to such as with ISO 9001, environmental considerations, and a drive to reduce costs and schedule.

The effective management of product information is necessary to support the capture, understanding and analysis of the impact to any changes. Having a coherent mechanism such as PLM to align the capability with this emergent behaviour of ETO projects is required to reduce cost and schedule overruns.

This requires PLM based on knowledge, process and supporting technology [36], all of which should be directed at contributing towards achieving the organisation's strategic objectives. Whilst AEC projects have similar challenges to other ETO projects, such as naval ships, they are not as well developed in terms of PLM environments and do not have the significant challenge of long term design lifecycles as discussed in the next section.

2.4.4 Customer interaction and procurement

The delivery lead-time for ETO products is considerably longer than other product types as the design and subsequent procurement is developed to satisfy customer requirements [85]. These delivery lead-times relate to the commitment from a customer on the order. The greater the lead-time the earlier a commitment from a customer is required. This is often called the customer order de-coupling point [86] or order penetration point [61]. The customer commitment points for various product types are shown in Figure 7 below. Significantly, the customer in ETO products commits to the order early in the design lifecycle and therefore has a significant input into the design, manufacture and procurement strategies [81]. In comparison, other product types have customer commitment when the design is mature; therefore any customer inputs are limited to configuration of the completed design such as with ATO products.

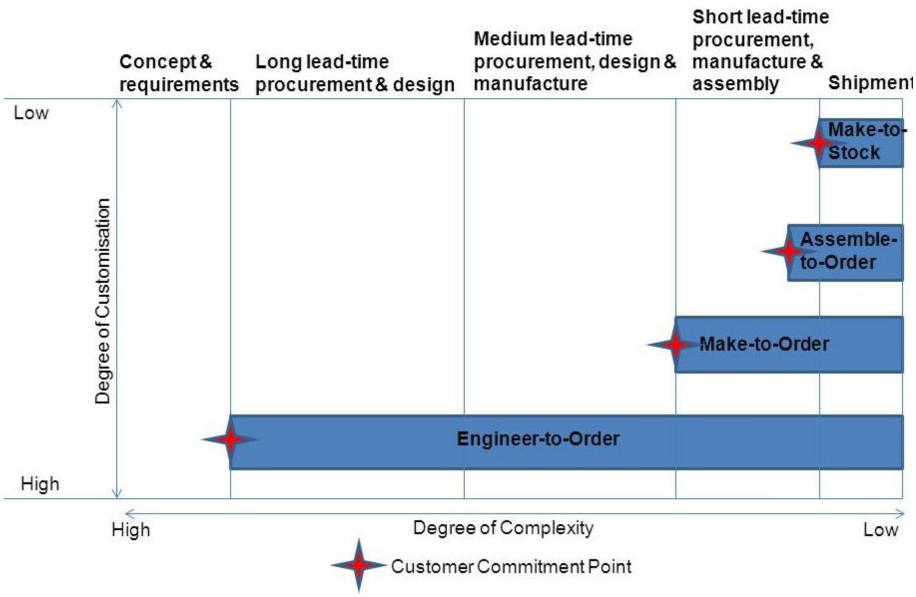


Figure 7 Delivery lead-times for different product types showing customer commitment points (adapted from [85] and [61])

Rahim and Baksh stated that the customer has a high degree of negotiating power over the requirements, price, delivery dates and product performance, which need to be balanced against the prime contractor's need to generate profit and reduce risk. Early customer engagement within ETO product development subsequently means that there is a great deal of focus on defining requirements [80]. These requirements often evolve and need careful management as changes to the requirements will have a direct effect on the evolving design and may introduce high levels of design changes as a result of the inherent complexity in ETO product development.

Ideally the requirement capture should be early in the New Product Development process and not subject to change. However the reality differs within ETO product development whereby the customer may struggle to define or articulate their requirements to a level that can be captured, agreed and baselined.

This subsequently increases the potential for design changes impacting the management of the project. There may be a reluctance to agree requirements earlier in the product's lifecycle as the customer would be liable to the cost of change, whereas the prime contractor would wish to agree the requirements as early as possible to reduce risk. Balancing the customer's requirement flexibility and cost liability, with the prime contractor's requirement rigidity and exposure to risk is challenging due to the long-lifecycle of the ETO product development process, and the difficulties in predicting the technology available from suppliers when the product is finally delivered. Often contracts are placed with the numerous suppliers in ETO product delivery when the supplied components are only in conceptual stage. The long lead times and the often conceptual nature of supplied products, which require integration into the overall design, emphasises the importance of maturity management which is discussed later in this section.

The customer may also put major supplier contracts out to tender, especially where there is a need to show taxpayer value for money, such as for defence contracts. As each contract for a new ETO product development requires tendering to show value for money then this reduces value in establishing long-term supplier relationships. It also adds additional management and process effort for tendering and contracting which requires enabling technology. These new contracts result in a sporadic flow of information from the supplier which is used to contribute to the overall design of the product and in turn, influences how the overall maturity develops with time. The intermittent delivery of information introduces risk to the project as the information is used to design physical locations and supporting systems, for example: a gas turbine's physical dimension provided by the supplier has significant influence on the size of a compartment; the turbine's electrical installation contributes to the overall electrical design and its thermal output influences the HVAC design.

2.4.5 Product customisation

Caron and Fiore [87] described ETO products as those 'involved with designing, manufacturing, installing and commissioning systems according to highly specialised customer requirement'. Hicks and McGovern stated that ETO products have a high level of customisation due to their low volume and high-complexity required to meet customer requirements [9]. They also stated that 'high levels of customisation lead to increased costs, higher risks and long lead times'. The components provided by suppliers that are integrated into the ETO product are a mixture of customised low volume and standardised high volume items. These customised low volume items do not have a large customer base meaning there is potential for missing information and resultant engineering revision [88]. This results in higher levels of risk relating to longer lead times and increased costs. The structure of ETO products consists of a mixture of supplier systems that are both designed bespoke or customised to perform a specific function. They are also subject to a unique and specific set of requirements, e.g., for a weapons system on a naval ship [9].These compliment aspects of the design which are commercially available off-the-shelf, which are subject to a more general set of requirements, such as valves.

This mixture of standardised and customised components results in differing degrees of complexity in the design and manufacturing process where the design is managed through careful interaction with the suppliers such as ensuring the electrical and cooling needs are understood and align with the overall design of the product. This is achieved using contract management principles and sporadic data drops through the lifecycle of the product [81]. The Large Hadron Collider (LHC) for example has 100 million components with 1.5 million documents and drawings. Many of the equipment items are specifically designed for the LHC and involve many years of research and development which then have to be integrated into the facility [11]. Heredia et al. classed ETO products as the most customised manufacturing environment compared to MTS and ATO [89].

The build process is divided between batch repeatable processes such as manufacturing standard pipework and those which are unique for that product such as installing an anti-submarine sonar system. Interaction with the bespoke supplier would generally be continuous with product information flowing in both directions, whereas interaction with COTS suppliers would be more discrete with information generally flowing from the supplier to the prime contractor, once the basic requirements are understood. The unique bespoke systems within ETO products require specialised tools for the design, such as PDM and in the manufacture, such as fitting specialised Government Furnished Equipment (GFE), typically military equipment.

Lee et al. stated that 'most of the items on a marine vessel are not available off-the-shelf but are available as made-to-specification and they need to be ordered as early as possible before the design is completed so that they will be available at the required time during the manufacture and assembly. Therefore, components which are purchased off-the-shelf as a commodity product or made to custom specifications must be managed. The BoM not only needs to distinguish between what is and is not ordered, but also needs to synchronise the delivery according to the PND (Product Necessary Date) recognising the required time for assembly or manufacturing' [38].

2.4.6 Bill of Material, configuration, change and maturity management

Customer commitment early in the design lifecycle requires product information management to ensure the evolution of the design is managed to conform to their specific requirements. The BoM is well defined within MTS and ATO products once manufacturing begins which means that there are few emergent patterns to contend with during the manufacturing planning and execution phases, such as design issues late in the product development lifecycle [38]. ETO products have an evolving BoM where the product information matures slowly, requires careful management due to emergent factors which effect the BoM and is dynamic in nature as information flows into the programme to mature the interconnected design systems [38]. The factors which effect the BoM include changes due to the evolving supplier information which impacts the design, e.g. the size of a gas turbine increasing which, in turn, affects the space allocated in the compartment [81]. In new ETO product development the manufacturing phase begins before the BoM is fully mature in order to reduce the overall design and manufacturing lifecycle as illustrated in Figure 6. Therefore changes to the BoM can have considerable impact to schedules and costs of the product if not managed effectively [38]. The impact of these changes increases as the design and manufacturing lifecycle evolves due to the locked-in costs and greater maturity of the lifecycle phases. When this happens, more rework is required which will have a potentially considerable impact on the product's development cost and schedule.

Hicks and McGovern described standard product development as a structured evolution from concept, design and manufacturing [9]. However, in ETO products, it is a highly iterative process which results in change in areas such as the design, manufacturing, contracts with supplier and customer, and with the cost model. Due to the close interaction with the various stakeholders, these changes must be analysed, understood and managed carefully, with impact-assessment being one of the key techniques used to support this management. Hicks and McGovern go on to state that whilst there is considerable research into change management there is little with direct relevance to ETO products [9]. The literature available includes aerospace who have mechanisms for predicting the complexity of design changes but do not establish how to control change given the challenges of ETO products. This is due to the complexity affecting ETO products throughout the lifecycle of the New Product Development, such as with bespoke suppliers providing increasing levels of maturity of their designs across many years.

Iakymenko et al. discussed the challenges and research needs of engineering change management in ETO products [90]. They stated that change is unavoidable and that the focus should be on efficient management and reducing the impact. They highlighted the differences between engineering change management in automotive, which they incorrectly refer to as MTO and shipbuilding, which they correctly refer to as ETO. They went on to describe that changes to a car's interior are typically batched and rolled into the next production run, therefore already procured parts can be used and phased out before new ones are ordered. In shipbuilding changes are incorporated into that order and if late in the lifecycle can lead to rework and scrappage resulting in significant cost and schedule impact. They stated that further research is required in the management of change on ETO products.

Stage gate processes have been used in the oil, nuclear and defence industries to mitigate risk through the lifecycle of the project by undertaking formal reviews to understand maturity and risks before proceeding to the next phase. An example of this is the CADMID cycle used by the UK Ministry of Defence (MOD) as shown in Figure 8. CADMID has 6 stages: Concept; Assessment; Demonstration; Manufacture; In-service, and Disposal. Each stage has different lengths and has formal approvals at the end of Concept (initial gate) and Assessment (main gate) [91].

At each gate the key stakeholders present and are assessed on their design, plans, quality, maturity and other inputs into the product delivery. A stage gate process will help to manage the level of uncertainty on ETO product delivery but, as shown in Figure 6, the decisions taken early in the stages will incur significant costs in later stages [9]. Stage gates have been used throughout industry, including ETO products, for many years but they have not solved the challenges affecting ETO products. These challenges include those due to the overlapping phases across the design and build lifecycle where a stage is passed to enter manufacturing but immaturity still exists across the design.

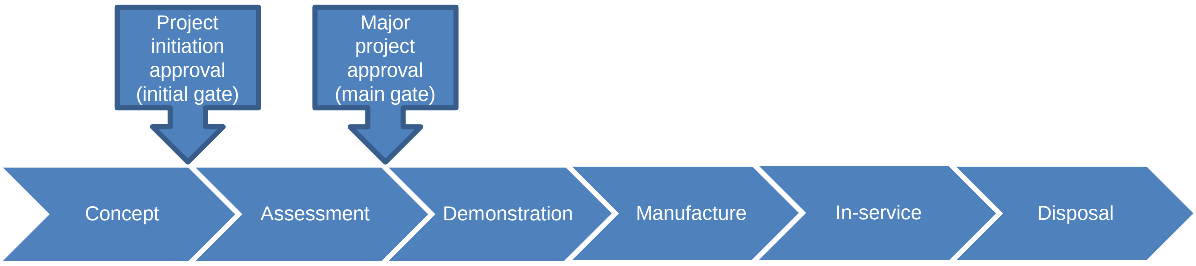


Figure 8 The CADMID cycle

FOC Naval ship NPD requires a more detailed level of control due to the challenges described in this section, such as the large volumes of information which is subject to emergent changes throughout the long lifecycle of the complex programme. The first layer of additional control is with the lifecycle itself. UK Naval Ship NPD is required to adhere to the CADMID lifecycle as this is aligned with customer review and contractual award gates, but the lifecycle is broken down to additional stages in the demonstration and manufacturing phases to enable greater control between detail design, production outputs, manufacturing and test and commissioning, as illustrated in Figure 9.

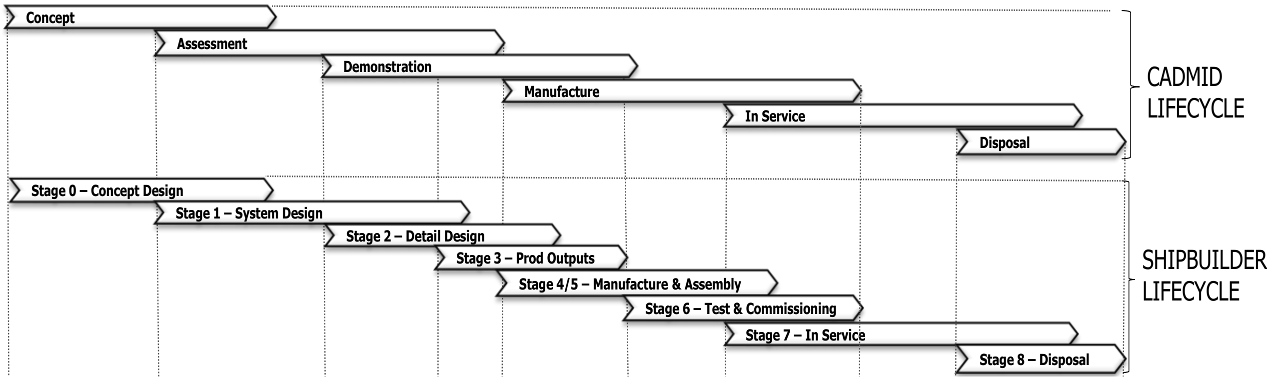


Figure 9 CADMID and Shipbuilder lifecycles

Whyte el al. stated that there is a greater requirement for configuration management in complex projects in order to manage their large volumes and various interconnections, and to ensure their integrity [11]. They described how configuration management has evolved from a paper-based approach to the digital systems which are being deployed with increasing ambition, resulting in increased rapid changes in interconnections within the systems. At relevant points in the lifecycle the configuration of the Naval Ship NPD has baselines enabled which configures the information into change management. Figure 10 illustrates the relationship to configuration baselines to the CADMID and shipbuilder lifecycles.

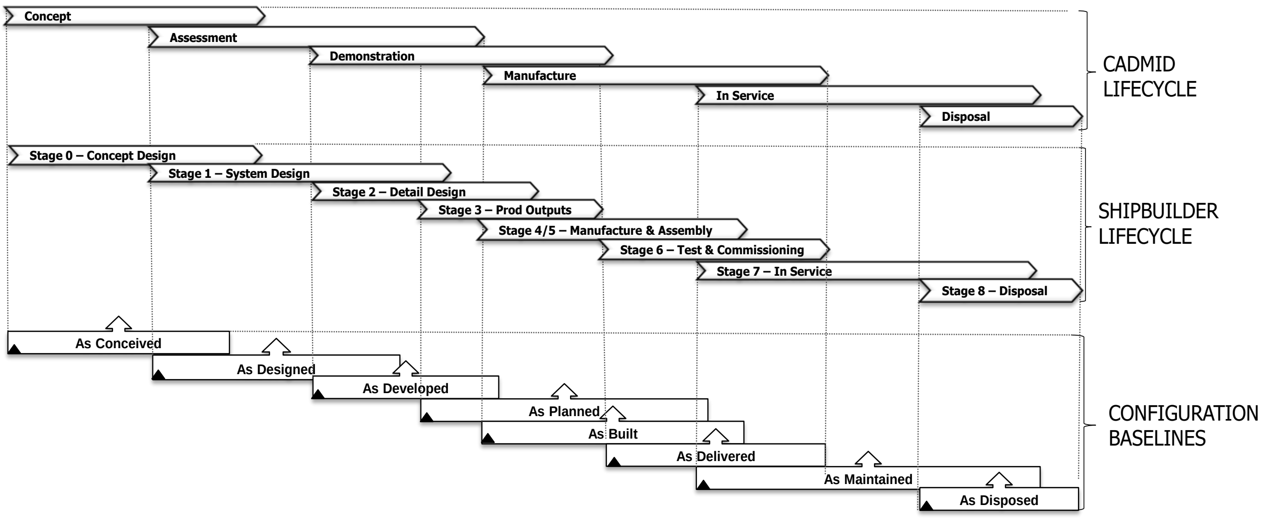


Figure 10 Configuration baselines relating to the CADMID and Shipbuilder lifecycles

Hicks and McGovern describe Capability Maturity Models (CMM) as a potential means to manage ETO product delivery [9]. Whilst these cover engineering, procurement, planning configuration, change, configuration and quality, there are significant gaps such as with construction and cross-functional integration which are relevant to ETO product delivery. CMM does not provide detailed guidance relating to ETO products necessary to manage PLM implementation.

PLM in ETO product delivery must be able to cope with managing the evolving maturity, quality, change, configuration, integration and relevance of the product, and the methodologies used on MTS, ATO and MTO do not meet these challenges [38]. ATO industries such as automotive and aerospace focus on variant management while ETO products such as naval shipbuilding and AEC have an emphasis on project management and BoM traceability to ensure assets can be traced through-life, such as for product recalls due to the focus on complexity, and maturity, and the differences in lifecycle and lack of a physical prototype [38]. Therefore the approach to managing product information within MTS, MTO and ATO product types is not suitable for ETO products, especially with BoM management [30]. The current PLM and ERP methodologies do not focus on these challenges but are designed more for the ATO and MTO industries [38].

The procurement for ETO products starts in the early stages of the engineering lifecycle and is constantly evolving and changing due to the immaturity of the early design which impacts the estimates and forecasting [38]. Engineering maturity management is one of the core capabilities required for successful PLM implementation in ETO products. Engagement with the supply chain starts early in an ETO product's lifecycle and those equipment or systems which are procured early tend not to be off-the-shelf. These require interaction with the prime contractor in order to inform the definition of the specification of the product. This requires careful management from a supply chain and product information management perspective [38]. Effective management of the object relationships and evolving BoM is a requirement of the PLM implementation across the lifecycle and the various disciplines involved. These objects are reused throughout the lifecycle in various aspects of the overall PLM environment, such as with supply chain information delivery, system design, 3D modelling to support Detail Design and Production Engineering.

As the design is immature early in an ETO product delivery lifecycle, it is not uncommon for a supplier to be given a development contract to assist in the integration of their product into the overall product to meet the requirements stated by the customer. This again contributes to the complexities of ETO product delivery and the challenges this has on implementing PLM which meets the needs of the customer and the organisation's strategic objectives. Other product types typically have a mature engineering BoM which supports improved integration with the organisation and the supply chain [38] and does not have to contend with new customer requirements or immature supplier information changing the design. The early design in naval ships is based around the function of the product which is based on the customer requirements. Once this functional design is complete it leads to a structural/physical design which supports the manufacturing phases [38]. Therefore with naval shipbuild the design and manufacturing take place concurrently [30], resulting in a manufacturing BoM being developed based on an engineering BoM which is not fully mature.

The approach to managing product information for ETO delivery must be able to manage a huge BoM across many different product configurations required to support different disciplines across an integrated product management system [30].

CIMData [5] summarise the relevance of PLM from a product data management perspective by stating: 'ERP systems provide necessary support for the procurement and manufacturing operations, but PLM is the only solution suitable for managing the product lifecycle's breadth and depth. Document control, security, engineering change management, product structure management, and reducing overall development time are all necessary functions. In addition, PLM offers companies the ability to coordinate the design process among hundreds of contractors and suppliers throughout the world and to provide a coordinated approach for the use of standard components and approved suppliers to decrease material and inventory costs' [5].

2.4.7 Project management

van Marrewijk et al. undertook an investigation regarding why large-scale complex projects 'often fail to meet costs estimations, time schedules and project outcomes' by comparing two megaprojects in the Netherlands and Australia. They concluded that project design is a factor and that the current project management guidance is unable to manage the 'complex project realities' [71].

There is a need for advanced project management on ETO products beyond those normally applied to less complex products [92]. The project management methodologies required include cost and schedule management which are tailored for large-scale, complex product development [92]. These are used to support specialised production processes which will have widely varying operational types spread across an activity-driven schedule which is based on the lifecycle of the product [75].

The project management challenges relate to the difficulty in taking a bottom-up approach to estimating and establishing plans for these products, the norm in other engineering and construction projects [78]. The lifecycle of these products means that the requirements are at a low-level of understanding before a gradual transformation into a physical product over a long period of time, this transition introduces changes to the product which affect the cost and schedule estimates [78]. This gradual evolution of the ETO product impacts the ability of the ETO programme to provide achievable schedules and budgets, as they can be impacted by maturity and change management challenges throughout the lifecycle. PLM must provide an environment which can be used to mitigate the project management impact and to enable the maturity and change position of the product to be understood. The extent of the project management challenges has been highlighted by Merrow who stated that 65% of 300 projects with a budget bigger than $1B failed to meet their objectives, whether it's safety, cost, schedule or realising the primary function of the product [72].

2.4.8 No physical prototype

With ETO products there is a need to ensure that it is 'right-first-time' due to the lack of a physical prototype which is due to the small number of similar products produced [30].

Prototyping enables the improvement of an early product by refining it through iterations until the product is ready [93], which includes aspects relating to design, manufacture and support. While considerable design and planning is undertaken prior to a physical prototype being developed, the prototypes have verified the design and manufacturing process and demonstrated the concept before actual mass production is started. In comparison, an FOC naval ship begins manufacturing prior to the design being completed.

Consequently, it would be accurate to state that an FOC naval ship is both a physical prototype as well as a delivered product [81]. PLM plays a significant role in virtual prototyping, in conjunction with the 3D models. This enables visualisations of the product to be produced, albeit that there are no physical prototypes produced prior to the FOC. This can only be used to support aspects of the design and manufacturing, but due to their scale prototyping cannot be used to verify the complete finished ETO product. Virtual prototyping is an important function when designing and manufacturing a product that has no prototype. The PLM system must therefore provide support for product data at the correct level of granularity to support modelling at different levels of fidelity across a diverse range of life-phase analysis. Automotive and aerospace in comparison will also develop virtual prototypes but have physical prototypes created prior to the production-line generating actual products.

2.4.9 Summary

This section has discussed the various product types: MTS, MTO, ATO and ETO and their differences in relation to PLM. It establishes that ETO products have challenges with respect to PLM implementation that are not adequately addressed within MTS, MTO and ATO PLM implementation. These challenges include those due to ETO having a significantly slow industry clock-speed compared to other product types where the majority of the costs are committed early in the products' lifecycle but are incurred many years later.

ETO product delivery is complex with many different elements interacting across the overlapping lifecycle phases, such as concurrent designs of different but integrated systems. This complexity is compounded by levels of uncertainty where design changes have an impact across the programme which are difficult to predict and manage.

Therefore, for PLM to manage complexity and uncertainty within ETO product development, it must be able to manage:

- Integration and design maturity within multiple overlapping lifecycle phases.
- Emerging patterns, interconnectivity, quality standards and environmental considerations within the system of systems.

The procurement process is also challenging due each major programme having to be retendered to provide evidence of value for money, resulting in difficulties with maintaining supplier relationships and accessing their information. Also in many cases there are long lead-times for delivery of equipment which is required to be integrated into the product. This delivery may not take place for many years after the contract is placed and the design completed. Some of these equipment items are customised in order to meet the specific requirement of the customer with the information gradually delivered by the supplier.

Therefore, to manage customer interaction and procurement challenges for ETO product development processes, PLM must be able to manage:

- The capture and control of information to meet customer requirements.
- Sporadic flow of information from suppliers.

ETO products are customised to meet the needs of a specific customer. Therefore the design elements such as equipment and systems contained within the product can be a mixture of high volume standard COTS products and those customised by a supplier. These suppliers provide product information throughout the lifecycle of the ETO programme which is used to design the integrated systems. Customisation results in a high degree of risk due to their low volume and lack of standardisation which may result in design changes that will impact the product in terms of schedule and cost.

Therefore to manage product customisation:

- PLM must be able to manage the integration of different types of supplier information throughout the lifecycle phases, as other supplied products are being designed and integrated in parallel.

ETO products have a maturing design over many years, throughout this lifecycle there will be changes to the configured design which are required to be managed. This is further compounded by the manufacturing beginning before the design is fully mature, resulting in change affecting not just the design but also potentially causing manufacturing rework. The relationship between the BoM, change, configuration and maturity management is an important factor in ETO products.

Therefore to manage BoM, change, configuration and maturity management:

- The PLM environment must manage the object relationships (and maturity of) within an evolving BoM for many different product configurations to support different disciplines across the engineering lifecycle.
- PLM must support the impact assessment and control of change resulting from all stakeholders as the design and manufacturing lifecycle evolves.
- PLM must manage BoM traceability for evolving maturity, quality, change, configuration, integration and relevance of the product.

In other product types manufacturing would not begin until the product is mature. Physical prototypes would be used to test the design and manufacture and product changes would be incorporated before full scale manufacturing begins. A full physical prototype for ETO products would be prohibitive from a cost perspective and time-consuming due to its scale.

Therefore to manage the lack of a physical prototype:

- As it is impossible to take a conventional physical prototype approach for an ETO product, PLM must be used to manage the evolving product design. This takes into consideration the maturity of the information provided by the supply chain, the management of change and the resultant impact on the lifecycle of the product.

This section also discusses megaprojects and their similarities to ETO product delivery and research which is available on various public and private megaprojects which supports identifying the challenges and the gap in knowledge. It concludes that large-scale complex projects have project management challenges which are required to be addressed due to the consistent cost and schedule overruns.

Therefore to support project management:

- PLM must support cost and schedule management across the lifecycle of the product by providing a structured environment which can be interrogated to understand the programmes status, mitigating the risks to the cost and schedule.

The next section will use the challenges identified in this section as the structure to review and critique the literature on PLM relating ETO products.

3 Review of literature relating to PLM implementation on ETO products

The characteristics and challenges associated with the product development process for ETO products have been described within Section 2 supported by literature and used as a basis to establish guidance for the provision of PLM within this context. This section will first critique the relevant literature on PLM implementation frameworks and its applicability for ETO products. It will then examine and critique the relevant literature with regard to the challenges of ETO products relating to PLM implementation including: complexity and uncertainty; customer interaction and procurement; customisation; BoM, change and maturity management; project management; and no physical prototype as described in Section 2.4. It is necessary to understand the business context in order to support the PLM implementation. Using the ETO challenges as the basis for the literature review, supports the critique of the published PLM literature based on the differences between ETO and other product types. The outcome of this review is the demonstration that there is a gap in knowledge relating to PLM implementation for ETO products.

The literature reviewed and critiqued in this Section was identified initially using a set of keywords relating to PLM and ETO products using Google Scholar and the University library search system, SUPrimo. The keywords used in various combinations included: PLM; PLM Framework; PLM implementation, PLM challenges and ETO. The literature was accessed from the relevant sources and imported into NVivo, reviewed and key points captured. The approach was supplemented by identifying publications from referenced authors from the identified PLM publications. Endnote was used to ensure correct referencing was applied using the Google Scholar Endnote import mechanism.

3.1 PLM Implementation frameworks

Frameworks have been developed by PLM researchers in order to provide guidance for PLM implementations. Vezzetti et al. undertook a review of PLM frameworks in order to understand how they measure business readiness for PLM implementation [94]. This approach was designed to contribute to the development of a PLM maturity model as they stated that 'PLM-related research is relatively young'. This maturity model would support an organisation's PLM implementation by assisting in understanding its readiness to undertake the initiative. This would enable organisations to better understand their as-is position and therefore provide an input onto planning and potential challenges with the PLM implementation. The PLM implementation frameworks reviewed include those by Sääksvuori and Immonen [17], Schuh [18], Batenburg et al. [19], Stark [20], and Kärkkäinen [21]. Vezzetti et al. determined that no single framework provided the necessary guidance for an organisation to assess their readiness for a PLM initiative. They propose a model which enabled each PLM framework to be benchmarked based on its strength and weaknesses relating to its PLM maturity guidance.

The conclusion that Vezzetti et al. established was typical for PLM implementation frameworks. It is difficult for a single framework to provide a 'one size fits' solution all for an organisation or product type. Each framework has its strengths and weaknesses and can contribute to a successful PLM implementation but they lack detailed guidance to support the specific business need for PLM implementation in ETO products. This supports the need for a PLM framework for a specific business context, for example a framework which addresses the challenges in ETO products.

Donoghue et al. conducted a literature review of existing PLM frameworks which can be used to support a PLM implementation [16]. These frameworks are those described above and Donoghue et al. concluded that these frameworks while valuable provide only a starting point on a PLM transformation initiative. An example of high level guidance which can be applied to any business is having simplified processes and a PDM centric PLM environment [27], [17]. Donoghue et al. proposed a theoretical high level framework for PLM which they stated could be expanded to assist with understanding the business strategy, objectives, operating model and products. The frameworks described above do not provide detailed guidance on PLM implementation on ETO products.

To ensure a thorough critique of the literature, those reviewed by Vezzetti et al. and Donoghue et al. are included in the research.

3.2 Complexity and uncertainty

The literature in Section 2 demonstrated that there is a greater degree of complexity in ETO product delivery such as naval ships in comparison to ATO product types for example. Batenburg et al. described a framework to assess and guide PLM implementations based on an assessment of 23 Dutch organisations [19]. They highlighted the difficulties with PLM implementation as it spans the lifecycle of the product across the extended enterprise and is a significant change to the business. They stated that PLM maturity in Dutch organisations was low, particularly with organisational policy and strategy, they went on to state that PLM must be embedded into the business culture. They also highlighted that different industries have different PLM requirements and proposed a framework which assesses the maturity of PLM in organisations. They did not discuss nor provide detailed guidance on overcoming the challenges of PLM implementation, such as with complexity and uncertainty in ETO products.

Rangan et al. stated that virtual prototyping has been used to tackle early lifecycle challenges in naval ships which have resulted in improved design decisions and increased collaboration [31]. They did not propose viable solutions to the PLM implementation related challenges of complexity for example with managing design changes due to new or updated supplier information. One example of this is new wild heat data necessitating a change to the design of the HVAC system which will have a resultant effect on other aspects of the design such as weight management and spatial design.

Hicks and McGovern recognised the challenge of complexity on ETO products [9]. They proposed the use of stage gates to manage these challenges and cited the oil industry as an example. Stage gate processes have been used for decades on ETO products such as with FOC naval ship as illustrated in Figure 8. This approach does not resolve the problem of emerging product development process behaviour impacting the NPD of ETO products across the lifecycle.

Sääksvuori and Immonen recognised the need for PLM to manage complexity with creating, maintaining and delivering products particularly when there are large amounts of data involved [17]. They provided descriptions of different product types including how ships are a unique product with similarities to sister ships. They went on to state that similar products are power plants and chemical processing plants. They also do not provide detailed guidance on how PLM can be implemented to support these product types. PLM was however correctly described as a holistic approach with different concepts, technologies and tools while PDM focuses on the management of product data. They then incorrectly distinguish PLM technology from CAD and ERP, when they are all aspects of the PLM system of systems; this suggests confusion between PLM and PDM.

Stark stated the need for PLM to manage complexity and uncertainty and highlighted the risk with developing new products [27]. He highlighted the risk with developing new products which may not be sold in the required numbers to provide a profit or to recover the investment made in NPD. He uses commercial aircraft as an example where a company may develop a product over many years but a customer may not take their option for purchasing or even be in existence. He did not provide detailed guidance on how complexity and uncertainty can be managed and does not discuss ETO challenges and how they can be overcome. The guidance Stark provided is generic and did not provide a solution to implementing PLM in the context of ETO products.

AEC projects are often described as being complex, such as with the Shalke Arena project [95] but, as they have a mature design before manufacturing begins this complexity is more manageable in comparison to naval ships and submarines. Froese provided some examples of complexity and the related emerging patterns, such as the change in the use of a room which propagates throughout the construction process and can effect schedule and cost [67]. Froese proposed that due to the complexity of construction projects from a project management perspective, individual work packages are typically developed to have 'views' which would support individual stakeholders by presenting the information that they need in the most appropriate manner. These work packages are undertaken independently as it is challenging to determine an overall integrated view of a complex project. Examples were provided of how to improve this using four different views: product; process, resource and time, but these are not as advanced as those already managed in the PLM environment of naval ship construction such as the management of a complex BoM with integrated change and document management. Froese also provided no details on the management of overlapping phases such as design and manufacture. This is due to the lower level of information management principles, such as a lack of a complete integrated product definition, practised in AEC projects where the architect's drawings are the only means to view the integrated product until the actual physical manufacture is undertaken.

Naval ship NPD have more process and technological maturity in their PLM environment and have driven improvement to manage some of the challenges associated with their complex environments, such as a full 3D model based on a managed bill of materials [81]. Froese discussed complexity in AEC projects but did not mention how design maturity should be considered and, whilst their research focussed on the need to manage the interconnectivity between work packages and the interrelationships between the views, there is no detail provided relating to a PLM framework that would support this.

Xue et al. conducted a review from 2000 to 2009 of literature relating to the use of IT to support collaborative working within the AEC industry and focussed specifically on collaborative design, collaborative construction project management and integrated inter-organisational management information systems [96], all of which are relevant to ETO NPD. Xue et al. described some of the shortcomings within the AEC industry including the lack of research 'on theories which have critical roles and guide the development of successful information systems'. However they do not provide clear guidance of how a successful system may be developed, which is also a gap within ETO products.

Bakis et al. researched product data sharing and exchange within the construction industry to improve integration [45]. They focussed on integration at three levels: conceptual (data modelling); physical (translating and transferring data); and data management (transaction management, access control, version management, and change promulgation). As this functionality is present to some extent within PLM, it is surprising that no direct mention of PLM is provided.

The opportunities for utilising PLM in AEC industries is increasingly being recognised with Aram and Eastman stating 'that until now only basic information collection and project and portfolio management capabilities of PLM systems have been adopted and only by a few AEC companies. We believe there is a huge potential for the AEC industry to benefit from integrating PLM technology in their business workflow' [69]. This highlights that the AEC industry does not have a solution for PLM implementation and also that a PLM implementation framework for ETO products can be utilised within the AEC industry.

Sharma and Kim discussed that compared to other industries, the complexities relating to: customisation; widely varying scales of operations; and, less compatibility between design and production systems, create significant challenges in shipbuilding throughout the design and build lifecycle, given the pressures on cost, lead times and the expectations for higher quality [75]. They stated that no PLM system exists to effectively support these complexity challenges within shipbuilding, that 'no PLM system covers the complete lifecycle of the ship/boat'. Accordingly they use this motivation to propose a concept for a Logic Based PLM (LBPLM) system for use in the shipbuilding lifecycle. Sharma and Kim provided details of the modules required for the LBPLM system such as design, procurement, project management, production and repair. They stated that the LBPLM system would additionally require security and the ability to share information across the enterprise and, whilst they discuss managing these complexities, they do not provide a detailed approach to solving it other than integrating various modules in a PLM system such as with the design and project modules. They do not consider the need for a framework to manage the evolution of maturity within multiple overlapping lifecycle phases. This focus on technology given the complexities of the PLM system of systems and the integration of the philosophy into the business would be prohibitively expensive to implement and high risk as it would be a customised system.

As illustrated in Figure 3, the technology in shipbuilding is fragmented and introduced at various times in the lifecycle, such as between procurement, design and project management but an improved bespoke PLM System on its own will not solve these challenges and, indeed, will add significant other difficulties with building, maintaining and evolving a bespoke system. This bespoke system would have to be managed by the organisation and would require huge investment in software engineering including resources, processes, technology and facilities, Most mature PLM environments will use proven COTS applications such as PTC's Windchill or Siemens Teamcenter, but technology on its own will not address the challenges with complexity and uncertainty in ETO products. This is demonstrated by the high investment in PLM technology but the continuing cost and schedule overruns experienced [5], [77].

Johnson et al. focussed on the management of complexities within the Virginia class submarine programme in order to reduce costs by $400M per boat [79]. The literature demonstrated the use of a system dynamics model to simulate the effect of the complexity associated with design changes and uses historical data to predict a number of cost influencing measures. Despite not specifically focussing on the use of PLM, Johnson et al. used concepts such as maturity, quality and rework, to illustrate that the ETO product development process is itself a complex system, where change is inevitable in complex programmes and pro-active change management is necessary. The output of the simulation was used to help with establishing contracts for the next phase of the programme. However, no detailed approach for achieving this was recommended and it instead focussed more on capturing the future impact of proposed change at a high level, such as with labour hours, which are a significant proportion of costs on a submarine project.

Gomez et al. described research on combining two topics related to PLM, data structure and knowledge management. Their research was informed by existing theory and directed towards relatively small scale products. The research addressed data structure and knowledge management individually but did not effectively combine both topics [35]. They presented a methodology for the integration of design, manufacturing and service knowledge to the data structure in PLM that could be used through life and applied to a vacuum pump manufacturer. This application is however conceptual and did not address the complexities relating to maturity within multiple overlapping lifecycle phases or the need to integrate multiple systems across the project's lifecycle. Gomez et al., however, highlighted the challenges relating to PLM implementation for the pump manufacturer as relating to the need for improving PLM capability and improving compatibility between all of the systems within the PLM environment.

Schuh et al. proposed a process orientated framework for PLM implementation. They state that there is a gap between PLM and the product lifecycle and its underlying processes, part of which is due to the confusion between PLM software and PLM as a concept [18]. The paper focussed on small to medium size companies and therefore did not address the types of complexity and uncertainty which affect ETO products. They investigated existing PLM solutions from 54 PLM vendors within Europe with respect to the fulfilment of a set of functional requirements. Despite these requirements being quite broad in terms of PLM functionality and reflecting the need from an ATO, MTS, or MTO perspective, Schuh et al. discovered the maximum average requirements fulfilment was only 59% (for system integration). The PLM implementation framework they proposed involved linking the PLM software, with requirements, a PLM knowledge base and a set of reference models. It consisted of ten steps which provided useful guidance relating to moving from the 'as-is' to the 'to-be' organisational state. These steps are:

1. Define the goal of the PLM implementation.
2. Analyse how the existing product information is structured.
3. Rank available reference processes (Schuh et al. uses reference models from the machinery industry).
4. Identify company maturity level (the as-is processes).
5. Select an appropriate reference model that best suits the company's characteristics.
6. Customise the reference model to suit the business needs.
7. Specify requirement for software systems.
8. Select software solution.
9. Define the evolutional path and implement software solution.
10. Teach employees.

Schuh et al. stated that these steps were derived from traditional process engineering but were enhanced for PLM. Whilst the framework formed the basis for a high-level understanding of PLM implementation and there were overlaps for use on ETO products, it lacked the specific guidance required to overcome the complexity challenges in ETO products. It relied heavily on guidance and reference models from similar industries which are commonly available, which is not be the case for ETO products due to their low volume and lack of standardised processes

Von Rosing et al. investigated combining Business Process Management (BPM) and Enterprise Architectures (EA) within IT projects to trace and measure IT investments to the business [97]. They asserted that the more complex the IT system, the less likely that it would be flexible enough to meet the needs of the organisation. They stated that BPM is about managing business processes and that Enterprise Architecture (EA) is the framework for business design. Von Rosing et al. discussed the relationships between organisational strategy and how this strategy needed to be reflected (via tactical challenges), within complex business IT systems, and how EA provided a basis upon which to manage this. They described how combining both EA and BPM would allow the business objectives to be enabled through alignment with IT investment. Ensuring that PLM technology alignment meets business objectives is important but this literature did not provide guidance on how the complexity of ETO products could be managed through aligning the business and technology architectures.

Terzi et al. provided a history of PLM and its current role using papers covering subjects including: extended enterprise, product-lifecycles, processes, integrated supply chain, IT, digital-mock ups, standards, interfaces, interoperability, and descriptions of PLM and their use on different product types. Their research used examples of long-life products such as turbines, aircraft and short-life products such as PC's or cameras. These NPD of these product types do not have the same complexity as ETO products as their product development process behaviour can be modelled, analysed, standardised and predicated, supporting a mature design prior to the start of the manufacturing phase. Terzi et al. provided a description of one-of-a-kind enterprises such as naval ships and civil construction and highlighted the early engagements of the customer and the importance of PLM in supporting this engagement. They also stated that many-of-a-kind enterprises face the same pressures as other industries such as increased quality demands, cost reduction and globalisation. [28] They did not provide detail on how to address the unique challenges with PLM implementation on ETO products. For instance, they describe ERP as transactional and PLM as iterative, this is true in normal manufacturing operations; however ERP in ETO products has to account for change due to emerging patterns in the manufacturing stage. Traditional ERP systems do not provide adequate support as, when it is planned in a work package, it is difficult to un-plan in a complex environment due to the many interconnections in non-repetitive tasks common in ETO product delivery.

Terzi et al. also stated that information flow breaks down after delivery to the customer in the majority of products, such as consumer electronics. This is not the case in complex environments such as with ETO products where product information must be configured, controlled and supported through-life. The paper does go on to state that the product service paradigm is critical in future PLM systems, but there is an information gap which requires resolving. There are no proposals for dealing with the specific challenges of the complexity of delivering ETO products where emerging patterns are common place and have high impact which increases as the product lifecycle evolves.

Lee et al. discussed the need to integrate the Bill of Material (BoM) across a shipbuilding product’s lifecycle [38]. It highlighted that shipbuilding BoMs differ from MTS and ATO products as the BoM evolves in shipbuilding. Lee et al. stated that shipyards have difficulty implementing organisational configuration of BoM's resulting in never ending PLM implementations. The complexity of shipbuilding BoM’s is mentioned frequently, but while it shows an evolving BoM, it does not provide a framework to manage complexity through its lifecycle when implementing PLM.

Bokinge and Malmqvist conducted a review of research on PLM implementation guidance with respect to their relevance and use in industry [56]. They stated that the literature highlights various recommendations for use in PLM implementations. They were not followed due to: a lack of awareness of guidelines; an awareness of the guidelines but a decision not to use and an awareness of guidelines but a failure to comply. They cited literature from several sources that highlighted the need for organisational improvements and aligning systems with processes. They found that some processes changed to align with system capabilities bit others did not, resulting in software customisation. Bokinge and Malmqvist found that the guidelines from the literature reviewed stated what needed to be accomplished but that the literature lacks guidelines on what is relevant for real industrial PLM implementation. Bokinge and Malmqvist also referred to proposed process models for PLM implementations. These were focussed on early in the lifecycle and did not follow later activities (such as with emerging patterns on ETO products which have a lifecycle and evolving design). Other proposed process models included how to configure the system to meet the needs of the business but the paper stated that no dominant PLM implementation guidelines exist. Bokinge and Malmqvist concluded there was a lack of research on PLM implementation guidelines that focusses on the operational level. They stated that thorough studies of industrial PLM implementations are required in order to elicit and capture knowledge which in many cases is implicit. The project studied was a PLM implementation for an unnamed multi-national organisation (the product was not described). This was however a shortcoming due to different implementation challenges for different product types, i.e., those which are useful for a mass manufactured product are not necessarily appropriate for an ETO product due to the differing levels of uncertainty and complexity. The paper supported the lack of PLM implementation guidelines in general and the need for further research is this respect.

Corallo et al. discussed research by the Collaborative Product Development laboratory of the University of Salento on PLM [98]. The research activities of the University were focussed on complex products such as aerospace, naval and automotive. Corallo et al. used literature to define what PLM is, i.e., an approach that includes a mixture of managerial, technological and collaborative features. They highlighted a gap in the current definitions such as: product data sources being spread across an organisation; the difficulty in ensuring uniqueness, relevance and traceability; and long term archiving regarding provenance for the information and its long-term archiving needs. Corallo et al. did not discuss the uncertainty and complexity challenges with ETO product types. Whilst aerospace and other industries were used when citing examples of the PLM definitions, the specific complexity and uncertainty challenges were not discussed, e.g., how uncertainty and emerging patterns could be captured and their impacts managed in a complex long product lifecycle with overlapping design and build phases.

3.3 Customer interaction and procurement

As described in Section 2.4, customer interaction and procurement is a challenge in ETO NPD compared with other product types. The literature required reviewing and critiquing to identify whether this problem had been solved. Batenburg et al. described the importance of integrating PLM with suppliers to enable collaboration and to ensure that all product information is stored centrally to support decision making [19]. There was no discussion on supplier information or guidance on manging information provided through the product's lifecycle.

Rangan et al. discussed using virtual prototypes to help support customer interaction but did not examine the challenges of integrating supplier information into the overall design for equipment that would not be provided until later in the product delivery life phase, sometimes as long as a decade after it begins [31]. These virtual prototypes provided benefit within the early life phases when discussing and agreeing on concept requirements. However, they are not appropriate for managing the procurement lifecycle such as with procuring a complex navigation system which is designed bespoke over a period of years to meet an initial requirement and, in reality, changes throughout the development life phase as other design or cost factors are negotiated.

Hicks and McGovern stated that detail design, manufacturing, assembly and construction typically happen after the customer order penetration (customer commitment) point [9]. Therefore, all the processes after the commitment point are specific to achieving a customer's requirements. Whilst the paper stated that ETO companies have increasingly become system integrators of technology provided by suppliers, and described the tendering process between the prime contractor in ETO product delivery and its customer, there was no discussion on managing the information provided by the supplier. Correctly managing supplier information is influential in the success of ETO product development as there are a number of uncertainties with bespoke equipment which require highly complex management processes and capability. This includes not only the design of the equipment, but also the supply of the equipment, such as with the stages with which a gas turbine is delivered that must align with the planned installation dates. All of this should be controlled through the various evolutional BoM views, e.g., alignment between the design and planning views that are controlled within the PLM environment. Sääksvuori and Immonen stated that PLM assists with procurement activities including managing supplier information [17]. They did not describe how the customer influences the supplier selection and that PLM must be implemented to manage the sporadic flow of information from these suppliers. No approach was offered to ensure that this supplier information is managed to ensure it is integrated into the overall design, such as thermal information on an equipment item used to support the design of the HVAC system.

Stark discussed the importance of PLM with managing the suppliers and ensuring they can work collaboratively with the other stakeholders when managing the product lifecycle [27]. He did not offer advice on how to overcome the challenges when a customer is involved early in the product's lifecycle and how their requirements influence the product development.

Sharma and Kim stated that the customer engagement point is before the start of the design process but did not provide detail on management of the evolving supplier information into the integrated design [75]. Approaches to e-procurement were also discussed which provide suppliers with secure access, but their proposals were immature as it described building a system for supplier engagement, such as tendering and responses being via fax/email. There are more sophisticated systems widely used by industry, such as Exostar which is in use by major defence companies, e.g., BAE Systems, Rolls Royce, Raytheon, Lockheed and Boeing. These provide capability for some of the common tasks in ETO products, such as: request for quotations; tender response management; material information exchange and e-auctioning.

Supplier engagement must be robustly monitored, such as with the reviewing of supplier deliverables and capturing feedback from the engineers. This must be aligned with the need for populating and promulgating the information through the PLM environment. For example, each drawing and BoM provided by a supplier for a gas turbine must be examined to ensure they meet the design requirements. This must be before they are entered into the PLM environment and consumed by the many disciplines in the project, such as electrical or HVAC designers. Sharma and Kim state the need for suppliers to be integrated and propose a module in their bespoke PLM system to manage this, but the development of a bespoke system is hugely risky and expensive. Whilst systems such as Exostar are mature and widely used, they do not fully address the challenges with supplier information relating to PLM but rather perform activities such as tender management, e-auctions, information exchange and other e-procurement activities [99]. The systems and related processes should address the sporadic delivery of engineering information from the suppliers over a period of time in order to feed the design process.

Tang and Qian discuss the relationships with the automotive manufacturers and their suppliers and proposed that PLM could be used to aid supplier integration in their industry [33]. Their proposal was simplistic in terms of ETO product delivery as it did not, for instance, have the difficulties with merging information during a long lifecycle. It described functionality such as information availability, permissions (controlling public and private information in the virtual environment) and information exchange. It also stated product model improvements could be carried out on-line (design collaboration). This becomes more difficult in complex product development, but has very important benefits. The customer engagement point in automotive is very different to ETO product delivery as the customers do not directly have an influence on the design or suppliers chosen. This simplifies the procurement process greatly as automotive manufacturers are able to select any supplier without customer influence. They also do not have to address the political complexities such as ensuring taxpayer value for money on publically-funded products.

Terzi et al. mentioned customer interaction in many-of-a-kind products but there are no proposals for dealing with the specific challenges of ETO product delivery such as managing the sporadic flow of information from the supply chain [28]. Johnson et al. discussed how the US Department of Defense is driving cost reduction which has an impact on the programme due to change [79]. This highlighted the influence that the customer has in ETO product delivery as opposed to other industry types. No proposals were described with regard to managing these challenges. Lee et al. discussed managing supplier information but no detail was given of supply chain complexities with evolving design other that supplier information is held against the BoM. There are no proposals for the management of developing maturity based on a customer's bespoke requirements, or how these can be aligned to the product delivery or how any changes could be managed effectively [38].

3.4 Product customisation

As discussed in Section 2.4 there are high levels of product customisation in ETO products in order to satisfy customer requirements. This customisation results in a lack of standardised approaches to ETO product development processes. This introduces risk and requires processes, information, people and technology management approaches to ensure that the evolving customised design can be managed effectively. Batenburg et al. stated an important driver for PLM was managing customisation due to more demanding customers [19]. They did not however provide any guidance on implementing PLM to support products which have a high level of customisation.

Hicks and McGovern stated that ETO products typically feature high levels of customisation which impacts cost, lead-times and higher risk, but no proposals were given to manage these challenges [9]. Sharma and Kim discussed how ships are highly customised, and have unique designs and variations in the production process [75]. They proposed a bespoke PLM System to help solve this. This approach increases the risk and cost to the implementing industry. Investment in technology has been seen by many industries as a way to improve business performance, however without the related investment in process, business change and alignment to the strategic objectives of the organisation, these are difficult to achieve [10]. Investment in a bespoke PLM system, as suggested by Sharma and Kim, attempts to resolve issues relating to PLM systems in terms of meeting business objectives, but the bespoke creation of a fully integrated system for ETO products will consume valuable core business resources which would be better invested elsewhere. It would be more beneficial to inform the PLM vendors in terms of the specific requirements for ETO products and allow them to make internal investment in their products which they can sell to the market place.

Sääksvuori and Immonen referred to engineered products as those which have a high degree of complexity and tailoring based on customer requirements [17]. They did not offer a solution as to how the combination of standard and customised design elements could be managed. They highlighted the importance of repeatable processes in their PLM maturity model, but did not discuss the challenges of identifying repeatable processes for highly customised products and how they can be overcome.

Stark highlighted the importance of PLM with managing product customisation [27]. He did not discuss the challenges with ETO products where the design is customised and evolves over a long period of time based on information provided by the suppliers. He also did not provide a solution to managing the information for customised design systems which are required to be integrated into the overall product.

Johnson et al. recognised that change is inevitable on ETO products but no proposal is submitted to manage these challenges [79]. The management of the ongoing customisation of the product through design evolution, followed by formal change management, is important for implementing PLM in ETO products. The design evolves based on the overlapping phases described in Figure 6 and the activities in each phase have a direct impact on those succeeding them, e.g., a change to the size of a gas turbine in the system design phase will have a direct impact on the spatial integration of the 3D model in a compartment in the detail design phase. The evolving customised product requires management to ensure that the interconnections to the various design systems are understood, communicated and controlled.

Tang and Qian focussed their PLM research on the automotive industry who have stable designs prior to manufacturing and do not have the complexities of manufacturing starting prior to the completion of the design, as occurs in naval ships and submarines [33]. They therefore provided no detail on managing evolving customised designs. Lee et al. identified that there is an evolving BoM but no solutions were discussed in detail to managing this in the context of aligning the objectives of the business with the technology [38]. Whilst they provided a description of the various BoM views in naval ships, they did not demonstrate how these were used to manage the integration, communication and interaction with the various suppliers who provided the data used to design the ship in an evolving basis. Other literature on PLM such as Terzi et al. did not raise or address the specific challenges with an evolving customised design with ETO product delivery [28].

3.5 Bill of Material, configuration, change and maturity management

Section 2.4.6 described the importance of managing the BoM through life and that the relationship to product maturity, change and configuration management is understood. Batenburg et al. stated that PLM software is required for product configuration and change management but do not provide any guidance on its implementation [19]. They do not discuss product maturity and while they raised BoM management as a key component of PLM, they offered no guidance on the relationship between BoM, configuration, change and maturity management.

Rangan et al. reviewed the evolution of PLM processes and systems using a number of case studies as the basis for their research. They stated that slow clock-speed industries, such as aerospace, have structured processes throughout their lifecycle which have an emphasis on configuration management to capture and control their data [31]. Change management was discussed but, for fast clock-speed industries only, with time-to market being a key aspect in introducing fixes or improvements. This is not appropriate for ETO product development due to their long development lifecycle. ETO products manage change as the BoM matures over many years and these changes become more critical as the lifecycle matures and the impact exponentially increases. Rangan et al. did not provide detailed guidance of managing BoM, change or configuration management in PLM implementation. They proposed using virtual prototyping to reduce change but did not discuss the challenges faced by a design that was not fully mature at the point when manufacturing has started, and the resultant change management impact. Whyte et al. confirmed that there were gaps in literature relating to configuration management and systems integration in complex products, and cited research undertaken by Airbus, CERN and Crossrail [11]. They stated that more research was required, including: understanding how configuration items are identified; when baselines should be struck; and with the relationship between configuration and change management. They stated that researchers could develop frameworks for understanding how change should be implemented in different circumstances.

Iakymenko et al. highlighted the importance of change management on ETO products due to engineering change being inevitable [90]. They compared different product types and concluded that change on large volume products is implemented in the design process or in the next release of a batch production run; this excludes safety related issues which may mean a product recall. They stated this approach was common in industries such as automotive, electronics and software. They highlighted that for ETO products, changes can be included in the current customer order which may have a significant impact due to design, production and procurement activities being undertaken concurrently to shorten the NPD lifecycle. They identified several challenges:

- Change propagation control which relates to consequential change and change on change;
- Impact on procurement where customised items are produced only for the ETO product and may have to be altered, or items already ordered may no longer be required;
- Impact to production activities such as stop work notices or rework due to change;
- Knowledge management where there is difficulty in identifying the reasons for previous changes which may assist in managing reoccurrence; and,
- Collaboration and integration where those stakeholders who are geographically dispersed and/or working within different disciplines are affected by a change.

Iakymenko et al. stated that empirical studies are required to supplement academic research into change management and recommended that additional research is required to address change management on ETO products, specifically: change propagation control; production and supply chain impact; collaboration and integration; knowledge management; and, IT solutions to support change processes.

Hicks and McGovern discussed in detail various approaches to manage product development, such as with Capability Model Maturity (CMM) and stage gates, but these did not provide detail on managing the configuration of the BoM in ETO products and its relationship to maturity[9]. They did provide a means to monitor the design at particular points in an ETO product's lifecycle but did not support the integration and propagation of change across engineering disciplines in order to ensure the design is consistent. Kärkkäinen et al. stated that academic PLM research is relatively young and suggested that CMM could be used to determine the maturity of an organisation to implement PLM [21]. They stated that the maturity models available to determine PLM readiness are generic and require tailoring to a specific organisational need. They provided no solution as to how this could achieved for PLM implementation on ETO products.

Sääksvuori and Immonen provided a possible information model for ship construction which illustrated the high level relationship between documents, design systems, geometry, schedule and cost [17]. They also provided a high level product structure for the design. There is no discussion on how this information can be managed as the design evolves through the long NPD lifecycle of a ship. They only discussed maturity in the context of business readiness for PLM, not how PLM can be used to manage product maturity. They described the importance of change and configuration management and that it can be enabled by PLM. They went onto provide details on change objects and workflows in PLM. They did not discuss the change and configuration management challenges in ETO products and how they can be overcome, such as managing and controlling evolving product maturity through the lifecycle of ETO products.

Stark described the BoM as a hierarchical structure of the elements which make up a product [27]. He went onto state that there may be several BoMs such as the Engineering Bill of Material (EBoM) and the Manufacturing Bill of Material (MBoM). He described configuration management and its importance in long life products; the elements of change management within PLM were also described. Product maturity was briefly discussed but was not covered in detail. There was no solution provided as to how ETO products could overcome the challenges of emergent issues facing the BoM. The evolving maturity of the NPD on ETO products was not discussed nor was there a solution provided in relation to managing the configuration and change to provide information stability to the product through life.

Kamphuis et al. described interconnected product systems and how they could be influenced by change, as well as how managing product information was important to the product development lifecycle [95]. Electronic Document Management and PDM systems were regarded by Kamphuis et al. as necessary, but the capability described was limited in its functionality in comparison to mature PLM environments. They did not address the challenges of an evolving BoM and the need for managing maturity. The information management systems implemented to manage the Auf Shalke project were designed to organise the information and make it retrievable. This was straightforward in comparison to managing emerging patterns and the basic nature of the system, an Excel spreadsheet, demonstrated the low level of functionality of their product information management capability.

The management of product information in AEC projects was discussed by Borrmann et al. where challenges such as large files make it impossible to create a Product Breakdown Structure (PBS) which is necessary for PLM environments. No solutions or guidance to solving was presented and there was no mention of maturity or change challenges [66]. Borrmann et al. stated that a new initiative was being formed to attempt to improve product information management in AEC projects, but it focussed on rudimentary PLM and not the challenges identified with ETO product delivery.

Tegtmeier et al. stated reasons for poor information management in AEC projects were due to disparate organisations in the design process and, also, that they have their own systems that did not allow for interoperability [100]. They also stated that 3% of project costs are due to interoperability issues as most information exchange is via email, rather than workflows or robust information exchange necessary for PLM environments. They highlighted that civil engineering project partners typically managed their own data, which was normally file based, with most of the design information based on 2D drawings.

The literature describes Product information in AEC projects as managed within Excel spreadsheets or industry specific systems such as Electronic Document Management Systems (EDMS) or Business Information Modelling (BIM), which were limited in their capability to manage complex product data in comparison to PDM systems [69]. The fragmented nature of AEC projects results in limited data standards, meaning interoperability, i.e., data exchange, is extremely difficult. The literature highlighted that improvements were necessary but focusses on the management of CAD data for geological information management. It does not cover the challenges discussed in a mature PLM environment for ETO product delivery.

Froese stated that information management systems in the AEC industry are immature [67]. He highlighted that during the design phase; only the architects' drawings provide an overall view of the integrated product, until the actual physical product begins to appear. This differs significantly compared to ETO products such as naval ships where there is a huge investment in providing a BoM and 3D models of the integrated product, albeit the BoM and models are subject to change due to the product development process behaviour experienced throughout the evolving lifecycle. Xue et al. discussed managing product information in a large-scale collaborative design environment but did not provide detailed guidance on how the information should be managed [96].

Sharma and Kim stated that no PLM systems could currently manage the complete lifecycle of a ship [75]. They suggested that this was due to a lack of integration of PLM system modules and described the different components of ship information. No approach was proposed to manage maturity and aligning it with the emerging needs of the product delivery. They focussed on the development of a bespoke PLM system. The PLM environment itself is a system of systems and no single system can be designed to manage all aspects of the ETO product delivery as they are all designed to perform specific functions as illustrated in Figure 3. Instead they must be configured and integrated in such a way that the organisational objectives can be realised and the evolving lifecycle managed.

Johnson et al. recognised that the maturity of the design evolves through the design and build of a submarine and change to a mature design will have an impact to the programme. However no mechanism for managing this was proposed [79].

Lee et al. highlighted that in shipbuilding, BoMs differ from MTS and ATO products as the BoM becomes available gradually as the design progresses, and continues after manufacturing starts [38]. They described that in contrast to ETO shipbuilding products, MTS and ATO have a mature BoM before manufacturing begins. They proposed the creation of an integrated BoM across the organisational structure in an integrated PDM/CAD and ERP environment which was achieved using an enterprise BoM to link the BoM across multiple lifecycle phases. They stated that there was little research on BoM's for ETO products, with most of the focus on ATO, MTO and MTS. Lee et al. proposed a prototype structure and software to manage these multiple BoM's, such as a hierarchy for BoM's and a bespoke tool to demonstrate it. Whilst they recognised the key challenges of BoM management in shipbuilding and proposed the use of evolutionary BoMs they did not provide detailed guidance on PLM implementation, such as how the BoM configuration and its relationship to maturity should be managed, but rather focussed on the implementation of prototype technology to explain their evolutionary BoM proposal.

Gomez et al. proposed a PLM data structure, which included a BoM, to facilitate the implementation of PLM [35]. They discussed the challenges of managing data structures but used a small sample of non-complex product types and did not address the management of the individual components in the BoM to reflect the evolving maturity in the lifecycle. They suggested that their approach would help support PLM implementations by improving the structure of the information. It used a basic configuration of a PDM system as an example of an as-is model, where the system (Teamcenter) was only used to store CAD data while other functionality, such as workflows, were not used. Their research made recommendations that the company would need to build a complete data structure, customise its PLM system to enable the use of its capability, and improve compatibility with other systems, e.g., ERP. However they did not provide the detail required in order to achieve these complex objectives. No mechanism is suggested as to how to achieve this. These recommendations would not address the PLM needs of an ETO product such as managing the maturity of the evolving BoM to mitigate risk when changes to the design will have a significant impact to the product.

3.6 Project management

Section 2.4.7 described how New Product Development within ETO has a history of cost and schedule overruns and that PLM must provide a stable environment to manage the evolving product maturity as change can have a significant impact. Batenburg et al. stated that PLM is important to manage the product through-life but provided no guidance on how this can be achieved [19].

Hicks and McGovern stated that ETO products are typically developed within project-based organisations which have acquired the required expertise to support the project management, including the adoption of stage gates [9]. They did not however discuss how the project management should be adapted to manage the emergent behaviour within the project to avoid cost and schedule overruns. This is surprising given the level of risk management which must be implemented to mitigate any changes to the agreed cost and schedule which may occur during the lifecycle of the product.

Sääksvuori and Immonen highlighted that PLM can be used to support project management processes such as improving the quality of planning, which can enable a reduction in engineering changes late in the delivery lifecycle [17]. They did not discuss, or offer a solution, as to how cost and schedule in the gradual evolution on ETO NPD can be managed by PLM.

Stark discussed cost and schedule overruns across a number of product types both for NPD and in-service [27]. These product types included aerospace, automotive, computers and naval ships. He discussed project management concepts and software systems but did not provide guidance on how the cost and schedule can be managed on ETO products when manufacturing begins before the design is fully mature.

Kamphuis et al. discussed at a high level the need to decompose products to manage interactions between disciplines but there were no detailed proposals of the practical application of achieving this [95]. Borrmann et al. discussed how the PDM system could be used to improve data management in the AEC industry but that planning and construction processes are 'strictly separated from one another', which impacts project management [66]. Tegtmeier et al. described the difficulties in establishing a coherent and consistent view of the overall development status of AEC projects due to the fragmented nature of the stakeholders which retain and manage their information individually [100]. This would be unacceptable in extended enterprises such as aerospace or naval shipbuilding where product information must be published to a master environment for configuration control. This stakeholder arrangement described by Tegtmeier et al. also increases the risk of data being lost once a partner has executed their part of the project. The configuration and record management and archiving by comparison is deficient, and could result in poor project management execution. They stated that improvements are necessary but focusses on the management of CAD data for geological information management and does not cover the project management challenges and the relationships with PLM environments for ETO product delivery, such as schedule management using planned data provided by a supplier.

Froese stated that due to the complexity of construction projects, the project manager is challenged with integrating independent work packages to ensure that the inputs and outputs have the necessary detail and that, as few people as possible have the responsibility for optimising the whole project [67]. Froese stated that more effort should be made to improve the support for these interdependencies in construction projects. He proposed that there should be multiple views to provide access to integrated data, including product, schedule, cost and build but further development was required on management practices and technology. ETO product development has the same project management requirements and the focus is on attempting to improve their use as there have been demonstrable issues with due date and cost performance.

Xue el al. undertook a literature review on IT to support collaborative working in the AEC industry [96] focussing on the concept of Collaborative Construction Project Management (CCPM). They considered areas such as improved communication between workers using wireless technologies and basic data exchange methodologies using XML. It stated that construction industry projects contained fragmented organisational elements. No guidance for improving project management practices in this respect using product data management systems for civil engineering projects was made, other than saying further research was required.

Sharma and Kim stated that shipbuilding was described as a construction process as opposed to manufacturing production [75]. They discussed an activity-based approach to ship construction and stated in adopting such an approach, but did not provide a meaningful way to solve them, other that providing a bespoke PLM system which would have integrated design and project management modules.

Johnson et al. recognised the unique nature of project management in ETO products, due to the evolving programme, but also that learning from experience (LFE) improves from one submarine to a later vessel [79] but no detailed guidance was provided.

3.7 No physical prototype

Section 2.4.8 described that a challenge of ETO products was that they do not have a physical prototype to test the design, manufacturing, cost and schedule. Sääksvuori and Immonen stated that prototypes are produced before a new product is introduced [17]. They did not discuss how products which do not have physical prototypes can be managed using PLM.

Stark stated that one of the causes of serious problems with a product may be due to the lack of prototypes [27]. He stated that virtual prototyping applications can be used to represent physical products to analyse and test a product without a physical prototype. He did not present a solution to how this would overcome the challenges of NPD of an ETO product when manufacturing begins before the design is complete.

Andrade et al. stated that there is a lack of literature for PLM supporting ship design [101]. They stated that the majority of PLM literature related to advertisements from software providers such as Siemens. They went onto state that virtual prototyping could assist with ship design but provided no detailed solution as to how this could overcome the changes with ETO product NPD.

Rangan et al. also used an example of developing a virtual prototype for creating ship systems [31]. They detailed the challenges of integrating ship systems, processes and technology but did not address the aspects of managing an evolving product design and manufacturing process in ETO delivery, and the emerging challenges which are unique to these product types. Rangan et al. described a PLM system implementation within automotive, aerospace and shipbuilding using a Virtual Prototyping Environment (VPE). Automotive and aerospace differences with ETO products have been discussed within Section 2 but VPE in this context relates to the design of ship systems. It differed from the wider challenges of ETO products as it focussed on the integration of systems, processes and technology in order to better understand requirements, improve configuration management, improve collaboration and reduce design iterations. These would be benefits but the VPE did not solve the challenges relating to the management of the evolving BoM, the maturity of the information provided by the supply chain, management of change and the resultant impact on the lifecycle of the product.

Hicks and McGovern recognised the complexity and lifecycle of ETO products and suggested that stage gates were useful in mitigating risk, but there was no detailed discussion on how to manage the emerging patterns and support PLM implementation to mitigate the risks of having no prototype [9]. Froese described the use of virtual prototyping for managing project information but stated that the work was conceptual and did not discuss a solution in detail [67]. Johnson et al. described the use of virtual prototyping for managing project information but that the work was conceptual, again there were no detailed solutions presented to manage the risk of having no prototype and how PLM could be used as the enabler for risk mitigation [79].

3.8 Summary

This section provided a critique on the literature relating to PLM implementation frameworks and the characteristics of the challenges of PLM implementation on ETO products as described in Section 2. ETO products have been identified as having the following key challenges with PLM implementation to meet business objectives:

- Complexity and uncertainty;
- Customer interaction and procurement;
- Product customisation;
- Bill of Material, configuration, change and maturity management;
- Project management; and,
- No physical prototype.

The literature reports on PLM in detail and why it is important, including definitions and challenges and in some cases how they can be overcome. It provided guidance on PLM implementation, but significantly they lack detail in order to solve the challenges of ETO products described in Section 2 in other words they do not provide the necessary business context. The majority of the literature focussed on non ETO products, those which did include ETO did not provide the necessary guidance to overcome the challenges of PLM implementation on these products. The literature which included PLM relating to ETO products either recognised the need for further research as no solution was available or did not provide a viable solution. Therefore PLM literature does not enable implementation for ETO products as the guidance is generic or for other product types which do not address the unique nature of ETO NPD. Undertaking the review based on the ETO challenges enabled a direct critique on whether the PLM literature addresses the challenges experienced by ETO products and confirms a gap in knowledge in relation to the significant contribution of this research.

5	PLM challenge discussed with viable solution proposed for ETO products

Table 4 shows a synthesis of the literature review critiqued against these challenges. It summarised whether the literature discussed these challenges to the extent that they are either:

- Not discussed - 0
- PLM challenge discussed but not in context to ET0 products - 1;
- PLM challenge discussed in context to ET0 products with no solution provided – 2;
- PLM challenge discussed with solution proposed which is not viable for ETO products – 3;
- PLM challenge discussed with solution proposed for ETO products with no detail – 4;
- PLM challenge discussed with solution proposed for ETO products which is viable- 5.

AEC industries were examined as they are required to manage uncertainty but do not have the same challenges in emerging product development processes behaviours, such as they do not start manufacturing before the design is complete. It was also clear that AEC industries have made progress with BIM, but lack PLM environments and can therefore provide limited assistance in solving the challenges with PLM implementation facing ETO products such as naval ship and submarine construction. Other authors propose solving the ETO PLM challenges by building bespoke PLM systems. These approaches do not solve the problems described, and also drive additional challenges into the product by managing and building a bespoke IT system. Customisation in the design and the variations in production processes are discussed but no solution is proposed.

The literature acknowledges that ETO products have an evolving BoM and that there is a high level of change which impacts the delivery, but no effective proposals for managing these were presented. Aspects of the problem are described in the literature in detail, such as customer influence early in the design lifecycle but, once again, they lack any detailed guidance on how they can be solved or how they relate to other product types. There are individual elements of PLM implementation guidance including frameworks, but there is not a complete framework for PLM implementation on ETO products. In summary, the problem characteristics of ETO product development including: customer interaction in the supply chain; maturity management; no physical prototype; product customisation; and, project management necessities mean that no single approach used on other product types, such as ATO, can be utilised.

Literature source	Assessment Characteristics					
	Complexity and uncertainty	Customer interaction and procurement	Product customisation	BoM, configuration, change and maturity management	Project management	No physical prototype
[9] Hicks and McGovern	2	2	2	2	2	2
[17] Sääksvuori and Immonen	2	2	2	4	2	2
[27] Stark	2	2	2	4	2	2
[28] Terzi et al.	2	0	2	4	2	2
[31] Rangan et al.	2	0	2	2	2	4
[33] Tang and Qian	1	0	0	3	0	0
[35] Gomez et al.	0	0	0	3	0	0
[18] Schuh et al.	1	3	1	3	1	0
[38] Lee, Kim and Lee	2	2	2	4	2	0
[45] Bakis, Aouad and Kagioglou	2	0	0	3	0	0
[56] Bokinge and Malmqvist	3	1	4	4	1	1
[66] Borrmann et al.	0	0	0	1	1	1
[67] Froese	1	0	0	1	1	0
[75] Sharma and Kim	3	3	3	3	3	3
[79] Johnson et al.	2	2	2	4	2	2
[90] Iakymenko et al.	0	0	0	4	0	0
[19] Batenburg et al.	1	1	1	1	1	1
[21] Kärkkäinen et al.	0	0	0	4	0	0
[95] Kamphuis, de Ridder and Schemers	2	2	0	2	2	0
[96] Xue et al.	2	0	0	2	2	0
[97] von Rosing et al.	0	0	0	0	3	0
[98] Corallo et al.	1	1	1	2	1	1
[100] Tegtmeier et al.	0	0	0	1	3	0
[101] Andrade et al.	0	0	0	0	0	4

0	Not discussed
1	PLM challenge discussed but not in context to ET0 products
2	PLM challenge discussed in context to ET0 products with no solution provided
3	PLM challenge discussed with solution proposed which is not viable for ETO products
4	PLM challenge discussed with solution proposed for ETO products with no detail
5	PLM challenge discussed with viable solution proposed for ETO products

Table 4 Synthesis of PLM literature within the context of ETO product development.

4 Research methodology

'A philosophical stance of worldview that underlies and informs a style of research' [102].

Kothari described the research methodology as the logic used to conduct the research and the particular methods that were identified and undertaken in the context of the problem [103]. The methodology explains how the research methods support the determination of the research results so that it can be evaluated or repeated by others. It also describes why other research methods were either less, or not at all suitable. The methodology should describe how the research problem has been defined and how the hypothesis will be proven. It provides the boundaries and architecture to systematically solve the research problem in a scientific way to create the significant contribution to knowledge. The methodology represents a combination of techniques for data collection and analysis which provides a link between theory and methodologies. Consequently it also describes how the data is collected and the results determined. The research methods are those methods and techniques which are used to conduct the research, prove the hypothesis and ultimately solve the research problem. The methods reflect the approach to selecting and constructing the research technique, while the technique is the approach to conducting the research. In summary, the methodology provides the scientific reasoning of what methods are used to reach the research objective.

The selection of an appropriate research methodology demonstrates that the researcher has a good understanding of the various approaches available and that the most appropriate has been identified, demonstrating that the research has a robust architecture. The methodology should provide the link between the aim, research question and the significant contribution to knowledge as well as the ongoing research itself.

This section describes the methodology adopted for this research including the research philosophies, approach, strategy and data collection method.

4.1 Research philosophies

Easterby-Smith et al. discussed three main perspectives from a researcher's point of view to the research problem: Ontology, Epistemology and Methodology [104]. They stated that it is important to consider and choose the appropriate philosophical position for the research to enable the best research outcome. This is due to the researcher considering what evidence should be captured and reviewed and how it provides answers to the research questions. It also assists in determining the research design to establish what is appropriate to achieve the research aim.

The ontology is the philosophical perspective about the nature of reality, based on the researcher's beliefs and values. Wand and Weber described it as 'a branch of philosophy concerned with articulating the nature and structure of the world' [105]. The ontological question represents the form of the nature of what is reality, and what can be known about it [106]. It is important to understand the researcher's ontological perspectives, as this will dictate how the research is carried out. For instance, a researcher with a realism ontological perspective believes that there is a single truth, that facts exist and that they can be revealed, such as through observation or measurements. A relativism perspective is that there are many truths, meanings and facts dependent on the viewpoint of the actors in the environment [104]. Thus, with an ontological perspective of realism, a realist would find a quantitative research approach as being most appropriate, as the truth can be captured through measurement such as surveys. Whereas with relativism, a relativist believes that truth evolves and changes depending on a point of view, so a qualitative research approach would be suitable using structured interviews and case studies for example.

The epistemology is a set of perspectives about ways of inquiring into the nature of the world. It is the theory of knowledge and justification, and how it relates to belief and options. From a philosophical viewpoint it asks how we know what we know to be true or false, and what approach we need to take to gain further knowledge, which is worth knowing, and how we know it to be true [107]. Within this research, it is particularly important for the researcher to understand the epistemological perspective to ensure assumptions are not made solely on the basis of what the researcher believes to be true. Any potential bias as a result of the researcher's experience of the subject matter should be avoided. Examples of this are with the selection of the participants for interviews and the creation of the interview questions.

The epistemological perspective of this research is based on a belief that experienced practitioners in the fields of PLM are able to provide knowledge to contribute to solving the research problem. However the choice of questions may lead the participants into providing answers which the researcher believes to be true due to bias, and not those which actually contribute to solving the problem. Therefore, the epistemological position will be used to support the practical and effective application to the creation of new knowledge which can be justified as being true. An understanding of potential bias enables the research methods to be designed and chosen to ensure that the right knowledge can be captured and justified using the techniques described in this section.

The methodology perspective provides the link between the theory and the methodologies and is how the researcher finds out what they believe can be known. The methodology perspective helps the researcher to identify the tools and techniques to undertake the research in a scientifically rigorous way. This must be determined by the epistemological and ontological perspectives since the methodology will have differing degrees of objectivity [106]. An example of this would be a researcher with a realist ontological perspective that may believe that results could be determined through experiments as a technique, as there is a single truth to be found.

It is important to relate philosophies to the paradigm used to understand the researcher's view of the world, and therefore to guide the research. The appropriate paradigms can be identified through understanding the philosophical perspective of the researcher and can therefore be used to explain how they have influenced, informed and guided the research [108]. The paradigm can be described as a basic belief system based on epistemological, ontological and methodological assumptions [108].

There are multiple debates on paradigms and their appropriateness to research approaches due to the difficulties in determining which is most appropriate. Guba and Lincoln stated that 'paradigms, as sets of basic beliefs, are not open to proof in any conventional sense; there is no way to elevate one over another' [106]. They stated that the beliefs are basic in the sense that they must be accepted simply on faith (however well argued); there is no way to establish their ultimate truthfulness' [106]. This is due to philosophical assumptions and paradigms being interrelated and determined by the researcher's view of the world. Guba described competing paradigms which are used particularly in qualitative research, these include positivism, post-positivism, critical theory et al. (which includes it's related positions such as critical science, poststructuralism and postmodernism), and constructivism [106] as shown in Table 5.

Other authors add to, adapt and debate these paradigms such as with Merriam and Tisdell who discuss positivist/postpositivist, interpretive/constructivist, critical, and postmodern/poststructural [109] and Swanson and Holton who focus on positivism, interpretivism and critical science for their work on research in organisations [110]. These examples show that there are different ways of describing interrelated paradigms depending on the author's own philosophical perspectives. Also, the paradigm used to support any research will ultimately be selected depending upon the researcher's philosophical assumption and are, therefore, used to evidence the selection.

Item	Positivism	Postpositivism	Critical Theory et al.	Constructivism
Ontology	Naive realism – 'real' reality but apprehendable	Critical realism – 'real' reality but only imperfectly and probabilistically apprehendable	Historical realism - virtual reality shaped by social, political, cultural, economic, ethnic, and gender values; crystallised over time	Relativism - local and specific constructed realities
Epistemology	Dualist/objectivist; findings true	Modified dualist/objectivist; critical tradition/community; findings probably true	Transactional/subjectivist; value-mediated findings	Transactional/subjectivist; created findings
Methodology	Experimental/manipulative; verification of hypotheses; chiefly quantitative methods	Modified experimental/manipulative; critical multiplism; falsification of hypotheses; may include qualitative methods	Dialogical/dialectical	Hermeneutical/dialectical

Table 5 Basic beliefs (metaphysics) of alternative inquiry paradigms [106]

For the purposes of this research and its focus on research within organisations, positivism, interpretivism and critical science are described, followed by evidence to support the selection of the paradigm used to guide this research based on the researcher's point of view. These are summarised in Table 6 and discussed in more detail within the following paragraphs.

Gephart described positivism as a view that the objective world exists and that it can be measured and mirrored using scientific methods to uncover relationships between variables and uses quantitative measures to test and verify hypotheses [111]. Positivists, therefore, would have an ontological perspective of a reality which exists and can be found, and an epistemological perspective of knowledge gained through objectivity which to be maintained would require research undertaken at a distance. Therefore this would influence the methodology, with quantitative methods such as experiments being appropriate as shown in Table 6.

Interpretivism, which is related to constructivism, assumes that knowledge or meaning can be gained through the members' or actors' interpretation of a situation; the real world of first person, subjective experience. Whilst interpretivists seek to understand the first person view they also attempt to disengage from the experience in order to objectify it [112]. However they still construct meaning though interaction with the environment. Interpretivists, therefore, would have an ontological perspective of relativism as they believe there are many truths, facts or meanings based on the viewpoint of the actors in the environment. The epistemological perspective of an interpretivist is subjectivism as there are only subjective truths and it is interaction with the actors, or participants, in the research who co-create the meaning and ultimately the findings. So, a researcher would accept the meaning of a viewpoint of the participants through capturing the subjectivity of their experience. Therefore, the methodology would be qualitative in nature where the researcher would interact with the participants to capture and interpret truths, meanings and knowledge through capturing patterns in the results. The tools and techniques used for the methodology must be carefully selected to ensure that results are evidenced and can be objectively proven to ensure the findings are not contaminated with untruths or poorly evidenced facts. Interviews can be undertaken with robust instruments to capture, analyse, cross-reference and describe the results to provide a consensus on the knowledge generated.

Critical science is a combination of critical theory and postmodernism created by the Frankfurt School in Germany to combine the work of a number of philosophers and political theorists, such as Karl Marx and Immanuel Kant [113]. As stated above, Guber and Lincoln term all related critical science paradigms as critical theory et al. with the argument that they all relate to the epistemological assumption of value-determined inquiry related to, amongst others, social, economic and political values [106]. The ontological perspective is historical realism, which states that what is real is shaped by, amongst others, social, political and economic factors, as shown in Table 6.

	Positivism	Interpretivism	Critical Science
Assumptions	Objective world that science can mirror with privileged knowledge	Intersubjective world that science can represent with concepts of actors; social construction of reality	Material world of structured contradictions and/or exploitation that can be objectively known only by removing tacit ideological biases
Key Focus or Ideas	Search for contextual and organisational variables that cause organizational actions	Search for patterns of meaning	Search for disguised contradictions hidden by ideology; open spaces for previously silenced voices
Goal of Paradigm	Uncover truth and facts as quantitatively specified relations among variables	Describe meanings, understand members definitions of the situation, examine how objective realities are produced	Uncover hidden interests; expose contractions; enable more informed consciousness; displace ideology with scientific insights; change
Nature of Knowledge or Form of Theory	Verified hypotheses involving valid, reliable, and precisely measured variables	Abstract descriptions of meanings and members and definitions of situations produced in natural contexts	Structural or historical insights revealing contradictions
Criteria for Assessing Research	Prediction-explanation Rigor; internal and external validity, reliability	Trustworthiness Authenticity	Theoretical consistency Historical insights Transcendent interpretations Basis for action; change potential and mobilization
Unit of Analysis	The variable	Meaning; symbolic act	Contradictions; incidents of exploitation
Research Methods and Type(s) of Analysis	Experiments; questionnaires; secondary data analysis; quantitatively coded documents	Ethnography; participant observation; interviews; conversational analysis; grounded theory development	Field research; historical analysis; dialectical analysis; deconstruction; textual analysis
	Quantitative: regression; Likert scaling; structural equation modelling Qualitative: grounded theory testing	Case studies; conversational and textual analysis; expansion analysis	

Table 6 Alternative paradigms for research in organisations [110] adapted from [111].

Through these philosophical stances described above this researcher believes his paradigm to be interpretivist with the related ontological perspective of relativist and epistemological perspective of subjectivism. This has influenced the methodology to be qualitative in nature. Based on the understanding of his philosophical assumptions, this researcher is able to define an appropriate research approach to generate the significant contribution to knowledge. As an interpretivist, the meanings, truths, facts and ultimately knowledge will be derived through capturing the interpretation of participants who are experts in PLM implementation on ETO products. With an ontological perspective of relativism there are many truths based on the viewpoint on the participants. Through his epistemological perspective, it is understood there must be interaction with the participants to co-create the findings. A qualitative approach also supports a deeper understanding of issues relating to a particular case study which is described further in the following sections [114].

4.2 Research approach

Merriam and Tisdell stated that 'In fields from education to social work to anthropology to management science, researchers, students, and practitioners are conducting qualitative studies. It is not surprising, then, that different disciplines and fields ask different questions and have evolved somewhat different strategies and procedures'. They go onto summarise qualitative literature that covers different qualitative research approaches. Due to this variety they chose to present the most common qualitative research approaches [109]. These include:

- Phenomenology – a focus on peoples' experience and how experiencing something is transformed into consciousness by interpreting it. It is useful for studying emotional human experiences relating to certain phenomenon. As PLM requires in-depth analysis of engineering products this approach is not suitable for PLM implementation on ETO products.
- Ethnography – a research process which focusses on human society and culture using field work. There are cultural elements to PLM but it also includes process, information and technology are therefore not solely suitable for PLM implementation on ETO products.
- Grounded theory – the creation of a theory from the ground up using data collected by the researcher. This approach can be used with thematic analysis to enable the coding of information based on data collected and subsequent analysis. This approach was considered for PLM implementation on ETO products as the use of thematic analysis would support the researcher's paradigm of interpretivist by obtaining knowledge from participants. This is a candidate approach for PLM implementation on ETO products.
- Narrative inquiry – analysis of peoples' accounts of experiences that are told in story form with a beginning, middle and end, and are therefore not suitable for PLM implementation on ETO products as story's are not appropriate for complex engineering products.
- Case study – in-depth description and analysis of a bounded system. Case studies can be applied to ETO products and this is a candidate approach for PLM implementation on ETO products.
- Action research - focusses on solving a problem in practice and implementing change during the research process. Due to the long lifecycle of ETO products solving problems and implementing change during the research process is applicable, this is a candidate approach for PLM implementation on ETO products.

Action research is a theory first developed by Lewin [115] and is described by Reason and Bradbury, as 'a participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment' [116]. Action research reflects how participants make meaning or interpret problems in their environment and can be conducted as an insider or outsider. It also uses these actors to contribute to solve these problems or to generate understanding on the environment itself. They also influence the methods or direction of the research as understanding is captured from the results [109]. There are various types of action research which differ based on the approach or the level of collaboration [109]. Once such type is Participatory Action Research (PAR) which Greenwood et al. described as 'a form of action research in which professional social researchers operate as full collaborators with members of organisations in studying and transforming those organisations. It is an ongoing organisational learning process, a research approach that emphasises co-learning, participation and organisational transformation' [117]. PAR is an approach that enables a change through research which can be implemented in a practical way [116], [118].

PAR is a well suited approach for this researcher's philosophical assumptions as it supports interaction with actors in an environment to solve a problem and to gain knowledge. This is well aligned with the significant contribution to knowledge, as the framework should enable change with the implementation of PLM in Engineer to Order products to enable organisational objectives. As the research seeks to enable change within an organisation as a key objective, PAR is a suitable approach.

Greenwood et al. described PAR as: 'a highly collaborative process between expert researchers and members of the organisation under study'. This choice of approach is further supported by the researcher's organisation providing resources to enable successful completion of the research problem. Greenwood et al. go on to state that PAR is 'an emergent process largely controlled by local decisions' and 'is a powerful way to resolve complex organisational problems' [117], two key criteria of the research.

The research strategy BAE Systems Naval Ships is undertaking reflects a major business improvement initiative with a view to winning global export orders and continuing to be the lead UK Naval Ship provider.

PLM has been identified by the business as being core to achieving this goal and being a key differentiator for UK export business winning [81, 119]. The results of this research will be a major contributor to realising these business objectives.

The research strategy will be to use major ETO products to evaluate PLM implementation and will utilise PAR to bring about change, where appropriate, within the Type 26 programme. The results of this change are discussed in Sections 8 and 9. The case study approach has been identified as a well suited approach to suppliant PAR as it is important for the researcher to gain knowledge of the context of the research and the processes [120]. The case study is described in Section 5 and with the findings of the research cross referenced with the case study in Sections 8 and 9.

The research also involves an empirical investigation using multiple sources into a real life environment which supports the use of PAR and case study [121]. The Type 26 programme will be the main case study to contribute to the development of the framework and to evaluate its usefulness. Triangulation from other ETO products will be used to develop the framework, and evaluate the research in a wider context. This should ensure that the findings provide value and are understood and that the problem solved is not limited to a single business entity [122]. The following products were identified as accessible to the researcher and appropriate to develop the framework:

- UK Type 26 Global Combat Ship;
- UK Queen Elizabeth Aircraft Carrier;
- UK Type 45 Destroyer;
- UK Submarine Successor;
- Australia Landing Platform Helicopter;
- Australia Air Warfare Destroyer;
- Australia Hunter Class Frigate Programme;
- CERN Large Hadron Collider;
- US Arleigh Burke Destroyer;
- Canadian Surface Combatant; and,
- UK Sellafield Nuclear Power Station.

Yin highlighted that case studies may be vulnerable in that they produce significant amounts of data which are then generalised, and may result in researchers making invalid, incomplete and erroneous interpretations [123]. He proposes that case study research should have clear designs before any data is collected. To mitigate this risk, PAR will be used and the results referenced back to the originating data as described in Section 6, i.e. the key points from the interviews. Also, Section 5 will describe the approach to developing the case study and how this was embedded into the organisational strategy. Siggelkow stated that case studies are important for demonstrating the value of a research question and useful for identify ideas and concepts [124]. The example that is cited is with regard to the talking pig, i.e., you only need to identify one talking pig to prove that they are capable of intelligent thought. The Type 26 case study will demonstrate the value of the research by describing how guidance from the framework relates to an industrial PLM implementation, this is explained in Section 9. Saunders et al. described two time horizons for research [122]:

- Cross sectional, where information is captured at the same time but in different contexts. It is an observational study at a single point in time that would include different subjects, such as age groups.
- Longitudinal, where data is captured over a long period of time. This data is captured through observation and can take many years, the benefits being that changes can be observed over a longer time period.

The time-horizon chosen for this research will be longitudinal as the case study design, data capture, framework development and evaluation was over a period of approximately eight years during the lifecycle of Type 26.

4.3 Research design

A formalised approach to the research was required which would provide quality through proven and scientifically rigorous techniques to assist in the development of a framework for PLM implementation on ETO products. The approach would also provide a roadmap for describing the research design and enabling measurements against progress. For instance the schedule for the research was linked to phases using the research design to measure performance against the plan. The research design would also support the structure of the thesis to assist with demonstrating that the research was undertaken in a scientific and rigorous way. Six Sigma was chosen as this been demonstrated to be a proven approach which is not only widely used in industry and but is increasingly being used to provide support to research projects [125]. Six Sigma is a methodology which utilises proven, highly focussed and rigorous principles and techniques for the implementation of quality processes and solutions [126]. The Six Sigma methodology is used to develop high performance processes or products or improve existing processes beyond just incremental improvement [126]. Six Sigma can be integrated with action research to provide a more powerful set of tools to aid the introduction of improvements [127]. It will be used to support the PAR research approach described in Section 4.2 as Six Sigma will provide tools for assisting in the interaction with actors to enable change within an organisation. Whilst it is more commonly used for improving existing processes, using the DMAIC (Define, Measure, Analyse, Improve and Control) concept, Six Sigma can also be used for developing an innovative solution such as with creating new products, process or services utilising DMEDI (Define, Measure, Explore, Develop, Implement) [128].

The key difference between DMEDI and DMAIC is that the former can be used to develop an innovative solution whether product, process or service, whilst the latter focusses on process improvement as shown in Table 7. This was achieved by: defining the problem and the requirements; exploring and creating the design concept; developing the findings; and, evaluating and implementing the results.

DMEDI supported the development of a framework for the implementation of PLM on ETO products as this is an innovative solution which requires creativity as opposed to a process improvement. This was achieved by: defining the problem and the requirements; exploring and creating the design concept; developing the findings; and, evaluating and implementing the results.

Define, Measure, Analyse, Improve and Control (DMAIC)	**Define, Measure, Explore, Develop, Implement (DMEDI)**
Define – Determine project scope, objectives, resources, constraints.	**Define** – Very similar to DMAIC.
Measure – Determine customer groups, determine critical customer requirements, and obtain data to quantify process performance.	**Measure** – Define customers and needs using voice of the customer and QFD, determine critical customer requirements.
Analyse - Analyse data to identify tangible root causes of defects.	**Explore** – Develop design concepts, and high-level design.
Improve – Intervene in the process to improve performance, pilot new process.	**Develop** - Develop and optimize detailed design.
Control – Implement a control system to maintain performance over time.	**Implement** – Validate design with pilot, establish controls, full-scale implementation.

Table 7 Description of DMAIC and DMEDI approaches to Six Sigma [129].

DMEDI has been used throughout industry for this purpose [130] such as by PricewaterhouseCoopers who use DMEDI for NPD [131] and was selected as a proven and robust methodology for managing the creation of the novel significant contribution to knowledge. Figure 11 illustrates the relationship between the DMEDI approach, the research design and the structure of the thesis. It shows how each of the elements of DMEDI was used to develop the research with the related sections in the thesis.

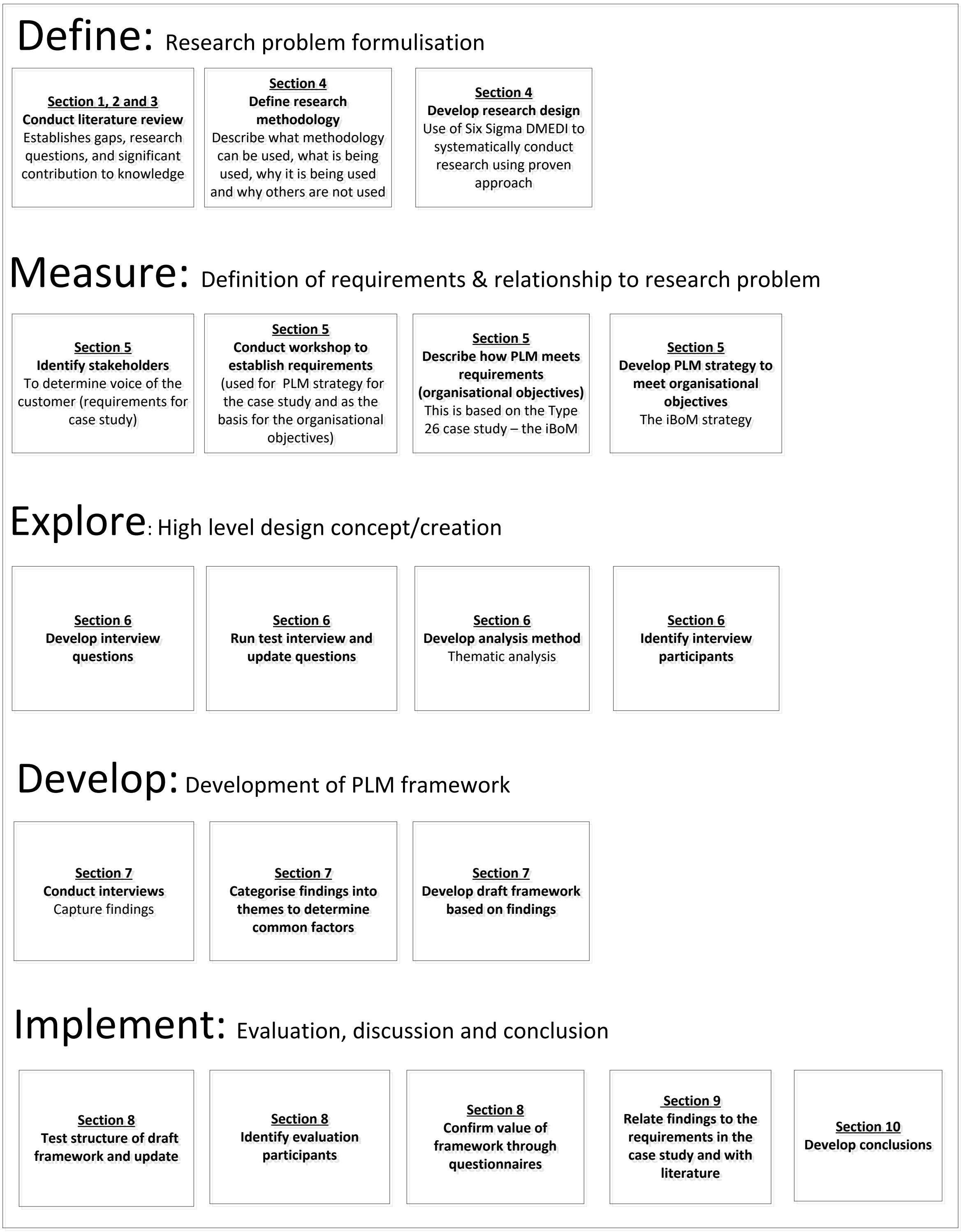


Figure 11 DMEDI research design related to thesis structure

4.4 Summary

This section has described the research methodology chosen for this research. It first described the three main perspectives from a researcher's point of view to the research problem: Ontology, Epistemology and Methodology. The importance of understanding these perspectives was to ensure the research outcome was based on the appropriate philosophical position.

The ontology was described as the philosophical perspective about the nature of reality, based on the researcher's beliefs and values. As the knowledge for a PLM framework on ETO products exists within experts in the field, relativism was identified as the most appropriate as this perspective is that there are many truths which are dependent on the actors in the environment. The tools and techniques used for the methodology must ensure that the truth, meaning and knowledge can be captured through patterns in the results. They must be carefully selected to ensure that results are evidenced and can be objectively proven to ensure the findings are not contaminated with untruths or poorly evidenced facts.

The epistemology was described as a set of perspectives about ways of inquiring into the nature of the world and that it is the theory of knowledge and justification, and how it relates to belief and options. The epistemological perspective identified was subjectivism as the research perspective is that there are only subjective truths and it is interaction with the experts in the field of PLM on ETO products that co-create the meaning and ultimately the findings.

The methodology was described as a perspective which provides the link between the theory and the methodologies and is how the researcher finds out what they believe can be known. The methodology perspective helps the researcher to identify the tools and techniques to undertake the research in a scientifically rigorous way and must be determined by the epistemological and ontological perspectives. The methodology perspective identified for this research is qualitative and was determined by the ontological perspective of relativism and the epistemological perspective of subjectivism due to the interaction with experts in the field of PLM in ETO products.

The paradigm used to understand the researcher's view of the world was discussed, this was described 'as a basic belief system based on epistemological, ontological and methodological assumptions' [106]. The paradigm identified for this research was interpretivism, which assumes that knowledge or meaning can be gained through the members' or actors' interpretation of a situation; the real world of first person, subjective experience of those experts in the field of PLM in ETO products.

Research approaches were discussed and participatory action research was identified as well suited as it supports interaction with experts in the field of PLM in ETO products.

The research strategy uses business transformation within BAE Systems Naval Ships as the motivation and the Type 26 Global Combat Ship as the case study to support the PAR research approach. The longitudinal time-line was chosen as the time horizon for the research as the case study design, data capture, framework development and evaluation was undertaken over an eight year period through the lifecycle of Type 26. The development of the framework and the valuation was triangulated from other ETO products to ensure its usefulness across the ETO industry.

The research design using Six Sigma was described, including how this provides a proven formalised design structure. Six Sigma has a set of tools to assist with PAR for supporting the interaction with actors to enable change within an organisation. It described DMEDI which enables the development of a new product, process or service and how this approach will be used to assist in the development of a PLM implementation framework for ETO products. This was achieved through: defining the problem and the requirements; exploring and creating the design concept; developing the findings; and, evaluating and implementing the results.

5 Definition of requirements for a PLM strategy for a new generation Royal Navy product

This section describes the requirements for the implementation of PLM to meet business objectives on an ETO product NPD. It uses the Type 26 Global Combat Ship as the case study where a PLM to-be environment to meet business objectives was developed. This environment is described and used as the case study for PLM implementation with which to discuss the framework for the implementation of PLM on ETO products in Section 9.

At BAE Systems Naval Ships, a comprehensive overhaul of all aspects of its approach to the engineering, design and manufacture of complex warships has been undertaken. Significant investment in technology, infrastructure, people and processes is intended to enable a step change in efficiency, quality and safety, to ensure Naval Ships remains competitive, delivers profit for the company, best value for money to its customers and to secure export orders.

On 11th September 2014, a facilitated workshop was undertaken to capture the BAE Systems Naval Ships business requirements for the implementation of PLM improvements to support Type 26 and future programmes. These requirements were based on identified business improvements which had been approved by the Type 26 senior management team; each lead for the business improvement was invited to the workshop. This workshop included representation from across the functions of the business including engineering, supply chain, programme management, in-service support, manufacturing planning, manufacturing and IM&T. The aim of the workshop was to identify the requirements for PLM implementation which would meet the objectives of the business functions. The structure of the workshop was as follows:

1. The workshop began by discussing the identified business improvements using the template illustrated in Figure 12. The completed template described the business benefit and is evidence of its approval status. The template provided an overview of the assessment of the benefit including:
    a. Priority;
    b. Initial assumed technical difficulty;
    c. Assumed probability of implementation;
    d. Cost information; and
    e. Approval status.
2. The estimated incurred cost and realised cost benefit was discussed within the workshop using Figure 13. This assisted with understanding when the costs would be applied and to what programme area. The information was used to assess the impact on the current PLM architecture and where targeted improvements could be made. For example with the stage 1 system design BoM.
3. The IM&T team then identified whether PLM technology could enable the realisation of the improvements.
4. Those improvements which could potentially be enabled through PLM were captured and agreed.
5. The workshop concluded with an action plan to capture those requirements which required further investigation. This requirement elicitation used the existing BAE Systems IM&T process resulting in the creation of a requirements specification.

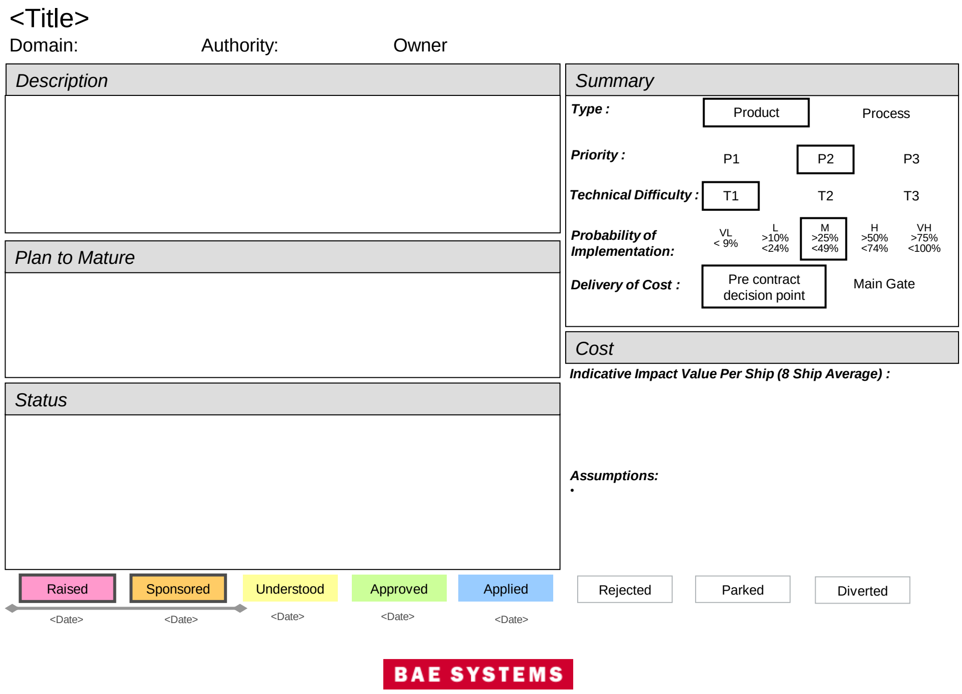


Figure 12 Business improvement template

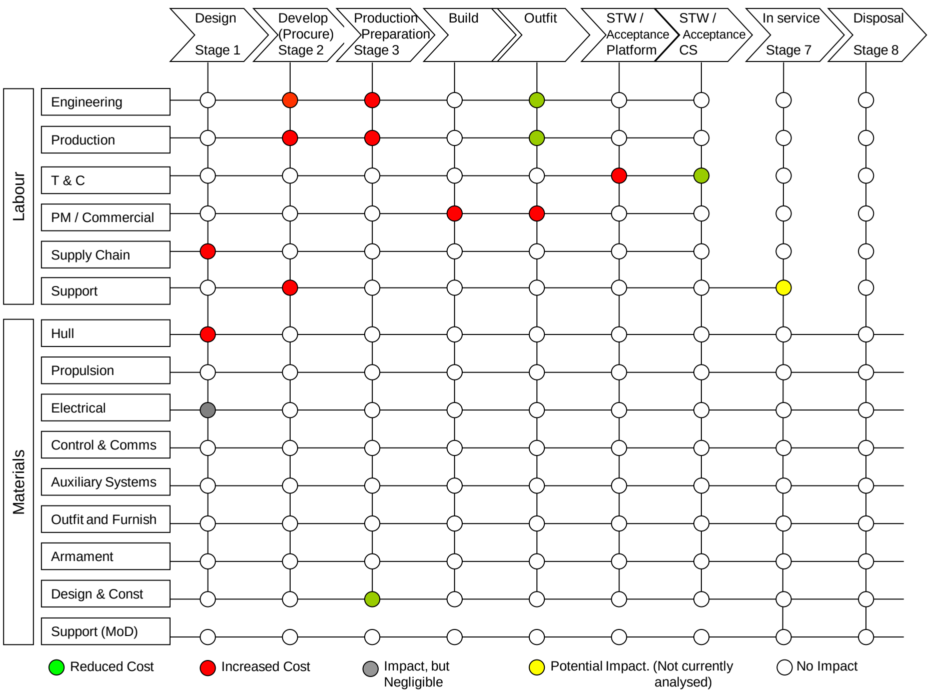


Figure 13 Business improvment template to capature cost impact and benefits to the NPD lifecycle

The House of Quality (HOQ) shown in Figure 14 illustrates those improvements identified and agreed by the stakeholders at the workshop. Hauser and Clausing described the HOQ as part of Quality Function Deployment (QFD) and were first developed at Mitsubishi's Kobe shipyard in 1972 [132]. It was since adopted worldwide to understand customer requirements (the voice of the customer) which are the demanded improvements of quality. It is then used to translate it to the functional requirements (the voice of the engineer) which reflect how the customer requirements will be met. They go onto say that the first activity is to identify the customer needs in their own words, which are the benefits they want the solution to provide, these are normally captured in facilitated discussions, such as the workshop used to identify the PLM improvements. The second step is to structure and prioritise the customer needs to identify the top five to ten primary or strategic needs which will drive the strategic improvement direction of the solution [132]. This was achieved in the workshop using Figure 12 and Figure 13 which not only described the business benefit but enabled prioritisation based on when the improvement was required, e.g. early in the programmes lifecycle.

Figure 14 shows the ten strategic customer requirements that were captured at the workshop which have been identified as requiring the implementation of PLM improvements, these are:

1. Improved first time quality of product information;
2. Improved schedule and cost accuracy and adherence;
3. Improved stability of design information
4. Reduction in change and rework;
5. Reuse of product information through the lifecycle of the programme;
6. Optimised design and manufacturing;
7. Increased repeatable manufacturing processes;
8. Plan manufacturing earlier and more accurately using engineering BoM and 3D model.
9. Improved logistical management (material flow - what, when and where required) ; and,
10. Earlier and improved identification, management and reporting of completion.

These requirements were then weighted in terms of importance based on the facilitated workshop. The weighting reflected the lifecycle phase of Type 26 at the point in time where the manufacturing phase was still several years away, therefore greater importance was placed on improvements to managing the design information, change and supporting the cost and schedule accuracy. The lower weightings were related to manufacturing planning, logistics control of equipment, and manufacturing and completion activities.

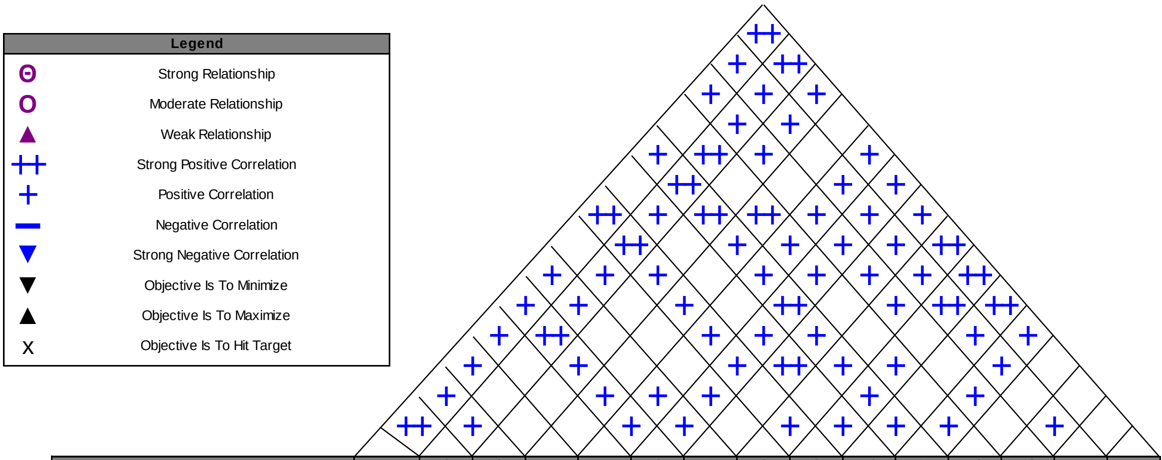
The improvements identified by the customer requirements cannot be achieved by PLM alone but aspects can be enabled by improvements to PLM. For example PLM will not solve the problem of first time quality in the design of ETO products where an engineer has made a mistake, but it can enable improved identification of poor quality. The next stage in the HOQ approach was to capture the functional requirements (engineering characteristics) for improvements to PLM which are required to be implemented. These requirements were first identified in the facilitated workshop and further established through more detailed requirement elicitation sessions following the BAE Systems IM&T processes. The required improvements to PLM are:

- Cross functional BoM ownership and Improved BoM level of detail;
- Improved data integration/alignment (PDM/CAD/ERP);
- Association of related design artefacts (modules, mounts, cabinets, Planning paths, test paths, etc.;
- Improved supplier data capture;
- Create views of product data which will evolve through product lifecycle for different stakeholders needs;
- Improved access to the right configured information;
- Centralisation of product management processes, and capability provision;
- Toolset (technology) rationalisation;
- Digital (model based) planning;

- Improved identification of change affected items;
- Enable single point of truth and a reduction in data duplication;
- Capturing, management and presentation of maturity information;
- Classification of design artefacts based on design, supply chain, manufacturing processes;
- Identification of BoM artefacts to enable repeatable manufacturing; and,
- Integrate the BoM with configuration and change management across CAD/PDM and ERP.

The relationship between the customer and functional requirements were identified and agreed with the key stakeholders at requirement sessions following the facilitated workshops, these were categorised as being strong, weak or moderate. No weak links were identified as all aspects of the functional requirements were required to support the customer needs in some way and it was agreed with the stakeholders at the follow on requirement sessions that these could be achieved by the functional requirements.

The difficulties of applying the PLM improvements were discussed and agreed with the PLM team, these are shown in the difficulty section at the bottom of the HOQ in Figure 14. A PLM implementation plan was created which included resource and timescales which reflected the challenges with meeting the functional requirements. This plan was included in the overall Type 26 schedule and was managed through the BAE Systems programme management process. The direction of improvement was captured and is shown at the top of the HOQ in Figure 14. Those identified as new capability were marked as *Target* and those which were believed to be further improvements on existing PLM capability within the business were marked as *Maximise.* For example the requirement of 'Cross functional BoM ownership and Improved BoM level of detail' was identified as new capability but was not viewed by the PLM team as being extremely difficult to implement. The roof matrix displays the strong positive, and positive correlations between the functional requirements. These were captured by the PLM team and used to input into the creation of the PLM strategy to show relationships across the functional requirements. The PLM strategy is a document which contains the demanded quality from BAE Systems Naval Ships and how they will be realised by PLM through the functional requirements, as shown in Figure 11. The Naval Ships PLM strategy is an important document as it enabled the communication, review and approval of the PLM improvements by the customer requirement owners and the senior management team. The PLM strategy formed the basis for improvements to PLM to support the design, build and in-service support for the FOC new generation Royal Navy vessel, the Type 26 Global Combat Ship. The PLM strategy was also intended to support future programmes and to provide a competitive advantage to the securing of export orders.



Row #	Weight / Importance	Column # → / Demanded Quality (a.k.a. "Customer Requirements" or "Whats") ↓ Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	▲	▲	▲	x	▲	x	▲	x	x	▲	▲	▲
			Cross functional BoM ownership and Improved BoM level of detail	Improved data integration/alignment (PDM/CAD/ERP)	Association of related Design artefacts (modules, mounts, cabinets, Planning paths, test paths, etc.	Improved supplier data capture	Create views of product data which will evolve through product lifecycle for different stakeholders needs	Improved access to the right configured information	Centralisation of Product management processes, and capability provision	Toolset rationalisation	Digital (model based) Planning	Improved identification of change affected items	Enable single point of truth and a reduction in data duplication	Capturing, management and presentation of maturity information	Classification of design artefacts based on design, supply chain, manufacturing processes	Identification of BoM artefacts to enable repeatable manufacturing	Integrate the BoM with configuration and change management across CAD/PDM and ERP
1	10.0	Improved schedule and cost accuracy and adherence	O	O	O	O	Θ	O	O	O	O	Θ	Θ	Θ	O	Θ	Θ
2	8.0	Earlier and improved identification, management and reporting of completion	O	Θ	O	O	Θ	Θ	O	Θ	O	Θ	Θ	O	Θ	O	O
3	10.0	Reuse of product information through the lifecycle of the programme	Θ	Θ	Θ	Θ	Θ	O	Θ	Θ	Θ	O	Θ	Θ	Θ	Θ	Θ
4	10.0	Reduction in change and rew ork	Θ	Θ	O	Θ	Θ	Θ	O	Θ	O	Θ	Θ	Θ	O	Θ	Θ
5	8.0	Improved logistical management (material flow - w hat, w hen and w here required)	Θ	Θ	Θ	Θ	Θ	Θ	O	O	Θ	Θ	O	O	Θ	Θ	Θ
6	9.0	Increased repeatable manufacturing processes	Θ	Θ	Θ	O	O	O	Θ	O	Θ	O	Θ	O	Θ	Θ	Θ
7	10.0	Improved first time quality of product information	Θ	Θ	Θ	Θ	Θ	O	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ
8	10.0	Optimised Design and Manufacturing	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ	Θ
9	10.0	Improved stability of design information	Θ	Θ	Θ	O	Θ	Θ	Θ	Θ	O	Θ	Θ	Θ	O	Θ	Θ
10	9.0	Plan manufacturing earlier and more accurately using engineering BoM and 3D model	O	Θ	Θ	O	Θ	Θ	O	Θ	Θ	Θ	Θ	Θ	O	Θ	Θ
		Target or Limit Value															
		Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	7	10	7	6	8	6	6	7	9	8	9	8	7	8	10

Figure 14 House of Quality for PLM to enable Type 26 objectives.

BAE Systems Naval Ships has defined its PLM strategy as the Integrated Bill of Materials (iBoM) Strategy. The vision for the iBoM is that it provides a comprehensive integration of information and processes associated with BoM elements broken down to the levels required by the business through life which will deliver improved cross-functional product data integration, for example an integrated Engineering and Manufacturing BoM. The iBoM strategy was developed to address significant issues associated with BoM management due to the challenges associated with ETO products as described in Section 2 and those experienced on previous Naval Ships programmes Lessons from previous and current programmes across the lifecycle and the business functions were captured, and distilled down into key areas for quality improvement using the templates shown in Figure 12 and Figure 13. This led to the identified business benefits which required improved PLM capability, as illustrated in Figure 11.

The workshop enabled the gathering of the customer requirements which were then mapped to the functional requirements for a PLM implementation. This utilised the BAE Systems requirements elicitation process. A proposed PLM implementation is discussed in the following sections which aimed to satisfy these functional requirements. With this more detailed description of the PLM implementation, it is then possible to gather the evidence for a more generalisable PLM implementation framework for ETO products as described in Section 7. The detailed PLM improvements described in the following sections can be related to the PLM implementation framework developed in Section 7, enabling an improvement understanding of PLM implementation on ETO products. This is described further in Section 9.

5.1 Maturity management to support product evolution and cost/schedule adherence

Capturing, management and presentation of maturity information was identified as a functional requirement from the HOQ as shown in

Figure 14 and is a key challenge relating to PLM implementation on ETO products as discussed in Sections 2.4.6 and 3.5. The iBoM is a critical element of the maturity measurement and management approach for Naval Ships in order to understand the evolving design information throughout the lifecycle of the ship. This also provides a mechanism for reporting on programme schedule and cost adherence as it can be measured against pre-defined maturity criteria which is a challenge for ETO products as described in Section 2.4.7. In order to enable the appropriate management of the parts and their associated occurrences within the iBoM, PLM capability has been developed by BAE Systems Naval Ships to capture maturity criteria on key technical attributes which can then be measured against predefined criteria. Examples of these technical attributes include electrical and weight which have maturity codes which are assessed at design reviews to determine if they have reached the required criteria to progress through the stage gate. This is discussed further in Section 9.1.

5.2 Cross functional BoM hierarchies and improved BoM level of detail

Cross functional BoM ownership and improved BoM level of detail, and the creation of views of product data which will evolve through product lifecycle for different stakeholders' needs, were identified as a functional requirement from the HOQ shown in Figure 14 and is a key challenge relating to PLM implementation on ETO products as discussed in Section 2.4.6. Cross functional BoM hierarchies relate to a BoM that evolves through the lifecycle of the product and is required to be reused by various business functions such as design, manufacturing planning and in-service support, it is also referred to as an enterprise BoM by Lee et al. [38]. As shown in Figure 15 the iBoM consists of hierarchies that break the product definition down that is structured in accordance to different business needs. Examples of these business requirements include a design BoM which reflects engineering parts and their occurrences, or a manufacturing BoM which is used to digitally plan the build processes. These hierarchies are interdependent forming the iBoM, and are achieved using a set of configured items to identify part usage across each of the hierarchies. For example equipment occurrences in Figure 15 can also be broken down to an installable level for digital planning. These configured items uniquely identify every occurrence of each part and are linked to the applicable hierarchies to create a product definition for each applicable business function.

This integration across the different hierarchies and business functions results in information being reused for different purposes and which is fully integrated but viewed differently depending on the roles of the user. Each BoM structure is owned and managed by the relevant business owner and has associated product development processes. These product development processes will result in interdependencies within the activities, such that a change within the design process could have implications on digital planning, as well as in-service support tasks from a maintenance perspective. These interdependencies and their management throughout the product development process are an important aspect to the challenges with BoM configuration, change and maturity management.

The concept of cross functional BoM hierarchies was identified as a significant enabler for an improvement in the quality as it assists with removing disconnected and out of date BoM information which may be used by differing business functions. For example an equipment occurrence that has been removed from the design BoM which is being digitally planned for manufacture. This will also assist with a reduction in the number of product changes due to incorrect or inconsistent information as identified in the HOQ in

Figure 14. The iBoM concept aims to improve information interconnectivity helping to manage the complexity and uncertainty of the product design as discussed in Section 2.4.3.

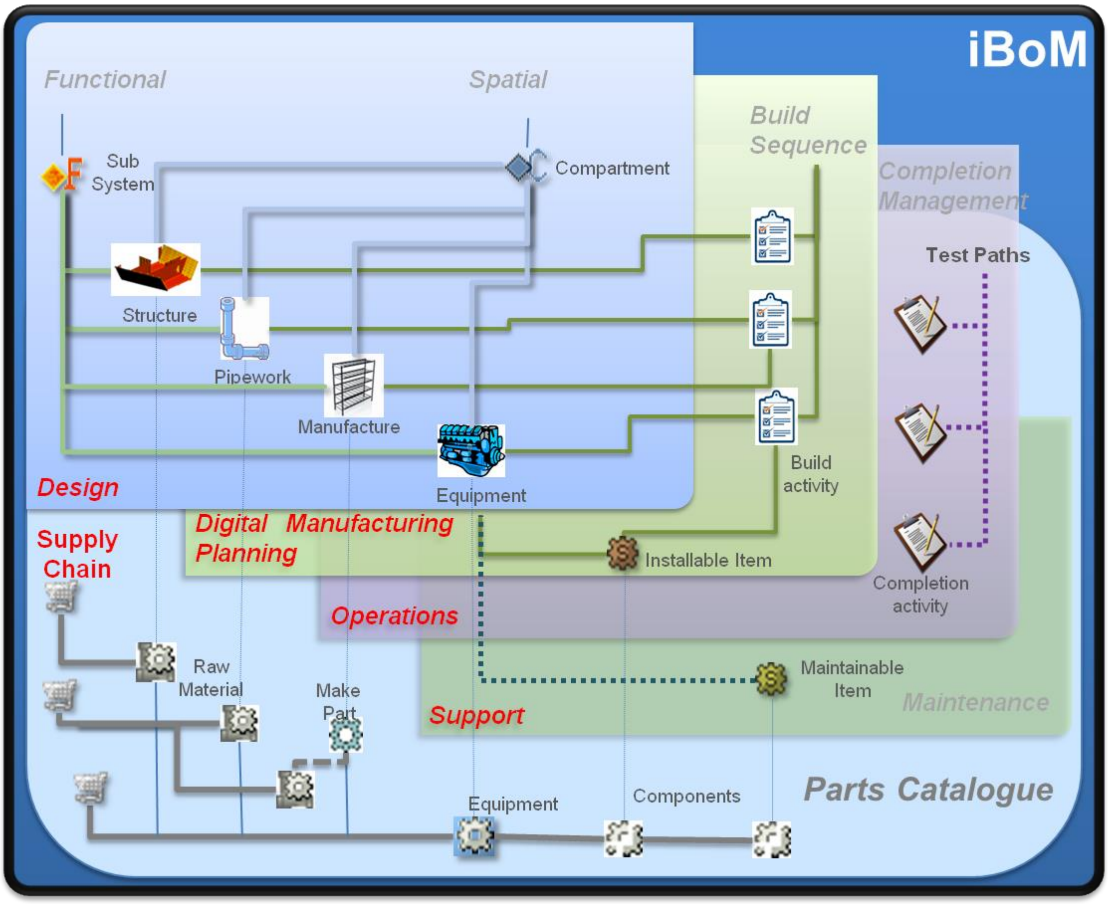


Figure 15 Cross functional BoM hierarchies.

5.3 Association of related BoM elements

The association of related design artefacts, improved access to the correct configured information, and improved identification of change affected items, were identified as a functional requirement from the HOQ shown in

Figure 14. Where there are components within the BoM that are related but are required to be configured separately, these will be related and managed through the iBoM. An example of this would be a seat or mount for equipment. Due to the complexity, uncertainty and long lifecycle of the design, there are different requirements for managing the product information. One stakeholder could for example require the management of the relationship between an equipment item and its mounting arrangement; whilst

a different stakeholder would require the management of an equipment item and the grouping with other items into a module for ease of build. A further stakeholder could require the contents of a server to be managed; whilst another stakeholder would only require the spatial elements of the server for CAD integration. The association of these BoM elements is a key requirement for PLM to aid with their identification and be managed throughout the lifecycle, but also for the identification of affected change items.

5.4 Data, process and technology integration with PDM as the master

Enabling a single point of truth; a reduction in data duplication and improved data integration/alignment; toolset (technology) rationalisation; centralisation of product management processes; and capability provision and integration of the BoM with configuration and change management across Computer Aided Design (CAD), Product Data Management (PDM) and Enterprise Resource Planning (ERP), were identified as functional requirements from the HOQ shown in Figure 10. Improved BoM quality can be enabled by reducing duplication through integrating the CAD, PDM and ERP systems as illustrated below in Figure 16 and earlier within Figure 3. This figure shows a visualisation interface between PDM and ERP which is developed with managing the instability in the manufacturing environment due to the emerging product development process behaviours described in Section 2.4.3, which is discussed further in Section 5.5.

The aim is to control the evolving BoM in the PDM system where it can be managed more effectively. This management is necessary due to the PDM system being iterative and the ERP system being transactional, as discussed in Section 3.2 and stated by Terzi et al. [28]. The main benefit of integrating these systems is a reduction in rework resulting from improved alignment and consistency of the product data, particularly between the CAD and PDM systems. This improvement is significant as the PDM system is widely used in the system design phase of the programme with CAD usage increasing in the detail design phase, as illustrated within Figure 6 in Section 2.4.2.

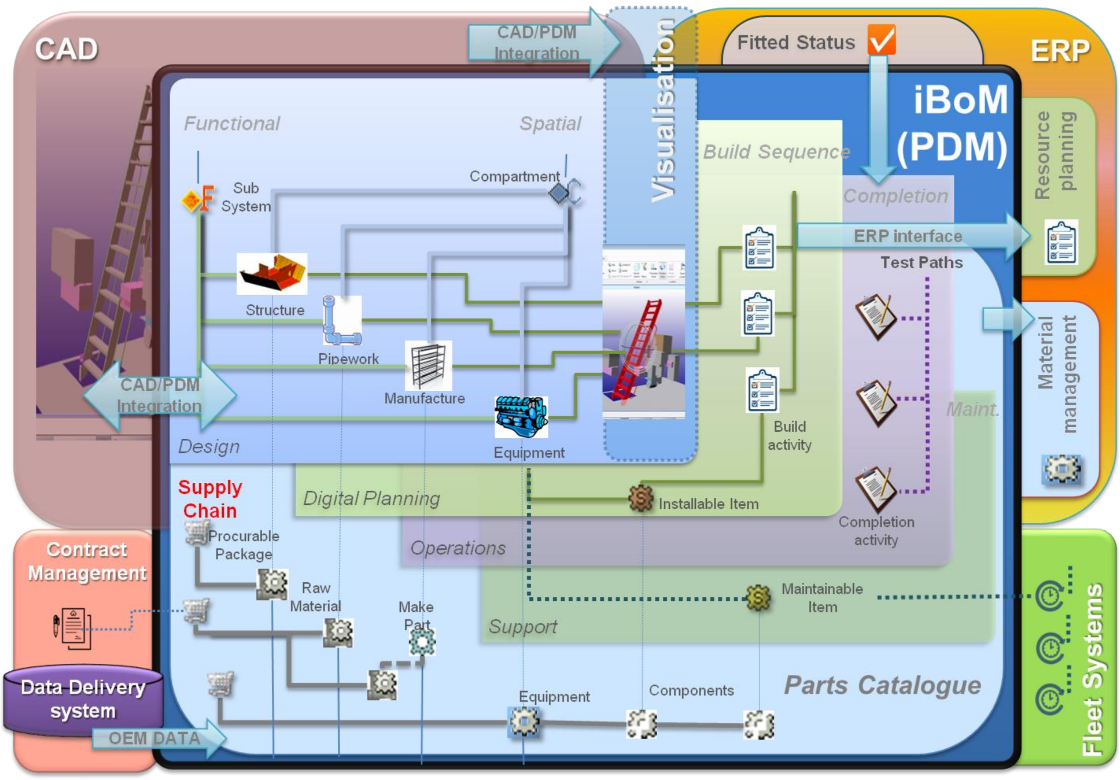


Figure 16 CAD, PDM and ERP integration.

Without CAD/PDM integration, the system and detail design phases can become misaligned and inconsistent through design evolution and emergent change, resulting in significant cost and rework, particularly if the inconsistencies are identified late in the lifecycle, such as within the manufacturing phase, resulting in significant incurred costs as illustrated in Figure 6 in Section 2.4.2. Integration across CAD/PDM and ERP enables improvements to the processes for managing the evolving design, the flow of information from suppliers and change and configuration management, as the data and toolsets can be better aligned, mitigating the challenges described in Sections 2.4.3 and 2.4.6 0. Therefore, the reduction of the consequential cost of change has a positive impact in that it should allow engineers to spend more time focussed on value-adding activities to improve the quality of the product. This approach also enables PLM toolset rationalisation, as the technologies that would have been implemented to manage disparate information sources are no longer needed and removed. This reduces data duplication, misalignment of data and information technology costs.

These improvements to BoM quality assist with right first-time aspirations which in other products would be managed through physical prototypes; therefore this mitigates the challenge of no prototype described in Section 2.4.8.

5.5 Digital planning

Digital (model based) planning was identified as a functional requirement from the HOQ as shown in Figure 14. An iBoM that defines the product breakdown to an installable level is integrated with the design environment and accurately describes its maturity; this in turn enables the manufacturing planning activities to be undertaken more effectively. Figure 17 illustrates the digital manufacturing planning BoM integrated with the design BoM and broken down to installable level. This improvement with traditional planning approaches is due to manufacturing planning activities requiring manufacturing drawings, which are typically not available until the end of the design process. This results with earlier planning activities which can subsequently inform the cost and schedule, helping to mitigate the project management challenge described in Section 2.4.7.

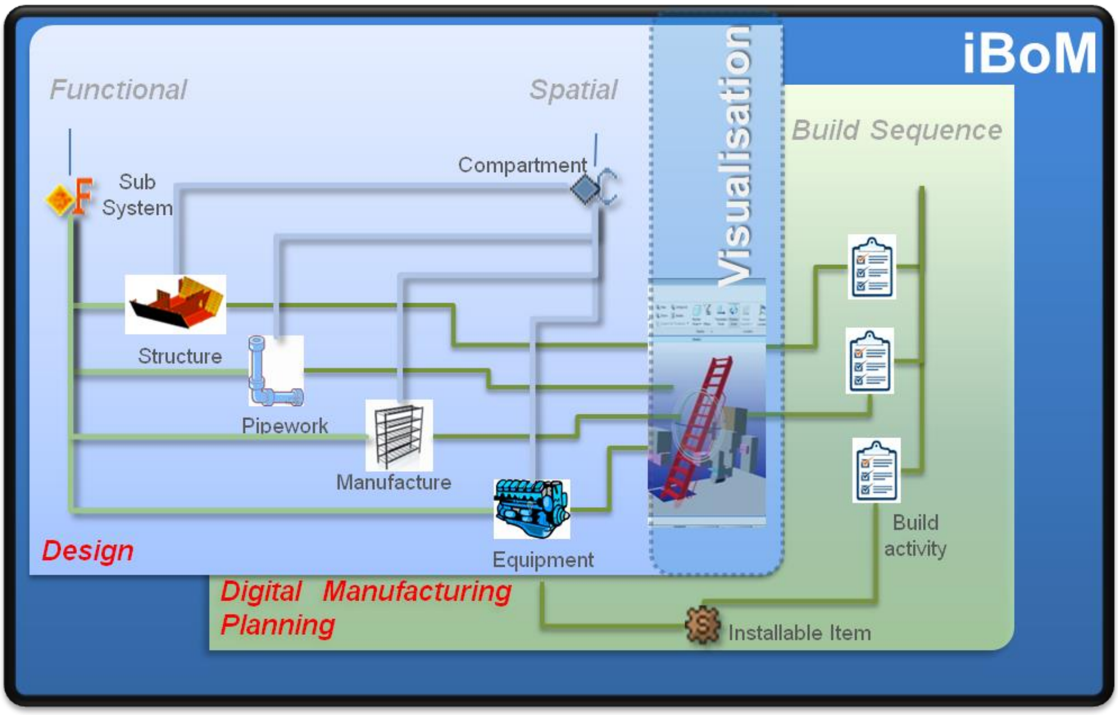


Figure 17 Digital planning in the PDM system.

With the availability of digital planning, the full engineering BoM created in the 3D model is published from CAD into PDM along with 3D visualisations of the BoM in the CAD model. This enables the manufacturing planning team to link BoM items to planning work packages, based on the maturity in the design BoM. A sequence is chosen directly from the CAD model, resulting in the creation of a manufacturing BoM. This sequence can then be displayed in the CAD visualisation to allow stakeholders, such as the manufacturing team, to provide feedback on the build sequence months before the build is due to start. This approach will assist with the mitigating the challenge of not being able to physically prototype the build as described in Section 2.4.8.

Once the sequence is agreed, the manufacturing planning team can then transfer mature information across the PDM to ERP interface as described in Section 5.4. The BoM information in the ERP system is then used for more detailed planning and procurement activities. This also assists with the challenges of product change management in ETO products as the manufacturing BoM is integrated with the engineering BoM, so product changes can be more readily identified and progressed through the lifecycle.

5.6 Design for in-service support

Cross functional BoM ownership and improved BoM level of detail was identified as a functional requirement from the HOQ shown in Figure 14. Capturing and managing in-service support product data within naval shipbuilding programmes is challenging due to:

- Not effectively capturing the required support data within the BoM, resulting in missing data, misalignment and quality issues;
- A lack of transition planning, including responsibilities and process, between the design and manufacture team, and the In-Service Support team;
- A lack of coherence between naval and engineering numbering structures; and,
- Different IT systems being used for the management of the BoM.

It is necessary to ensure alignment between the BoM for design and support due to the design evolution and emergent change throughout the programme which can impact the in-service support activities due to BoM misalignment.

The iBoM concept aims to address these challenges by providing a maintainable parent and child breakdown, and associated data from the supply chain that will be captured and integrated with the design configuration in the engineering BoM, as shown in Figure 18. This will be supplemented with the use of in-service support naming and numbering conventions for BoM occurrences, resulting in the removal of misalignment and translation activities due to different conventions.

The PDM system will also master both BoM's to support integration and alignment until the design is mature and the information can be exported to fleet support systems which use the maintainable BoM information to support the ships in-service. This approach will enable improved BoM quality and a reduction of rework between the design, build and support activities as maintainable items are identified and managed directly from the design. The in-service support team will also have improved functionality to be able to identify what product change will impact their requirements and decision making, allowing the in-service support team to influence the change process and assess impact on through-life support. Ultimately, the customer will receive a product which will be more easily maintainable, with data that meets their through-life requirements.

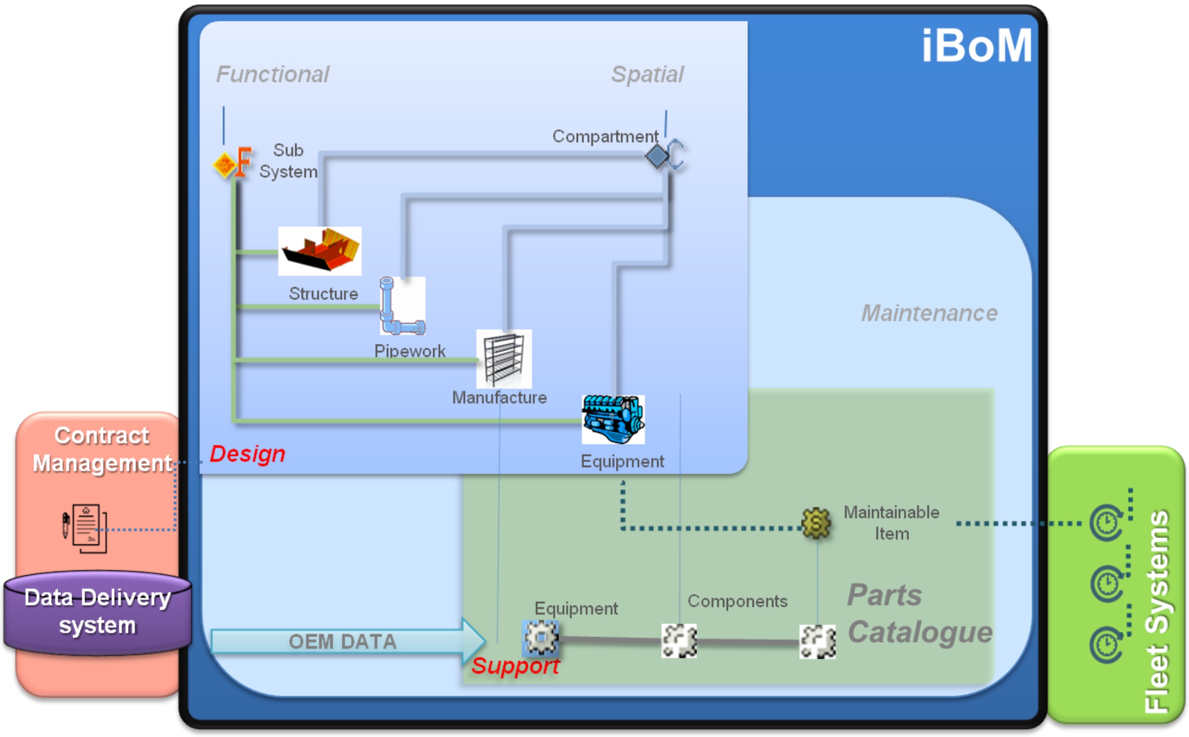


Figure 18 Integrating the Engineering and in-service Support BoMs.

5.7 Supply chain data capture and delivery

Improved supplier data capture was identified as a functional requirement with a strong relationship with the customer requirement of improved first time quality of product information as shown in the HOQ in Figure 14. The challenges identified in Section 2.4 identified the importance of managing supplier information through the lifecycle due: to the customer interaction and procurement approach; the level of product customisation; the importance of project management; and the relationship with the BoM and maturity management. Supplier information is used within ETO product development to evolve the design of the integrated systems through-life. The effective capture of this information is a key requirement of PLM on Type 26. Due to the procurement approach as described in Section 2.4.4, suppliers provide deliverables to the Type 26 programme that are at agreed dates in the lifecycle of the programme. These are then reviewed and either accepted or rejected by the programmes contract management team. One of these deliverables is the BoM information of their products which may be highly customised, including: their parts and occurrences; their technical attribution, for example electrical and weight information; and the BoM breakdown, including the maintainable breakdown, as illustrated in Figure 5 in Section 2.2.

In previous programmes this has been provided in various formats which were then manually entered into a PDM system. This caused information quality issues due to the possibility of data entry mistakes, was time consuming which impacted schedule performance, and was costly due the resource requirements. The iBoM strategy included an approach to create a mechanism for BoM information to be entered by the supplier, ensuring that the Original Equipment Manufacturers (OEM) BoM information is formatted correctly and can be automatically entered in a supplier review portal. As shown in Figure 15, once approved by the contract management team, the BoM information is then automatically loaded into the PDM system, enhancing BoM information quality and reducing schedule and cost impact. The capture and efficient import of good quality supplier BoM information will support the evolution of the often highly customised integrated design. It will also improve the understanding of BoM maturity which will as a consequence assist in the mitigation of the cost and schedule challenges of the project management.

In addition, since this approach increases the BoM quality from the supplier and they are provided with a standardised mechanism, it can be easily reviewed, with any issues identified prior to automatically uploading into the PDM system. This will significantly reduce the time required to conduct supplier reviews and enable more efficient and speedy input of data into the product development programme. The supply chain review process enables improved identification of issues and questions which otherwise may go unnoticed or require supplier interaction later in the design or build lifecycle, such as installation tooling guidance. As a consequence, supplier queries are reduced, resulting in a reduction in cost for suppliers to answer questions or provide additional information later in the lifecycle. In addition, supplier related issues that may impact the programme are identified earlier and their impact reduced.

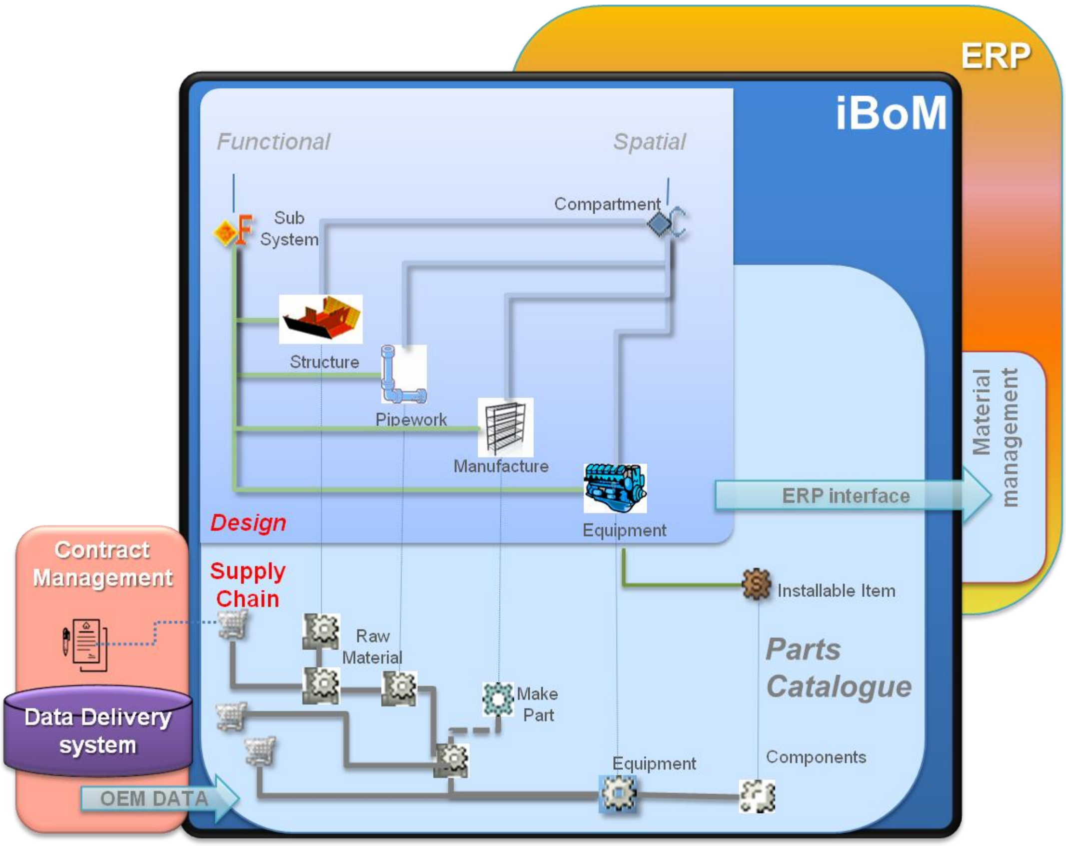


Figure 19 Integration of supply chain information with the iBoM.

As the full parent/child breakdown to maintainable level is more easily captured and loaded into the PDM system, this results in improved management of lost or damaged child items during build e.g., a handle of a valve, which otherwise may require the full equipment item to be replaced incurring cost and schedule delays. It also enables the capture and comprehensive attribution of BoM information for engineering, support, planning, and supply chain. This reduces the use of disconnected data repositories such as spreadsheets, and assists with the collaboration of the design and build, increasing toolset rationalisation.

5.8 Repeatable manufacturing identification

Increased repeatable manufacturing processes is a customer requirement, and classification of design artefacts based on design, supply chain, manufacturing processes and identification of BoM artefacts to enable repeatable manufacturing were identified as functional requirements in

Figure 14. One of the key challenges related to PLM implementation on ETO products is product customisation which impacts standardisation as described in Section 2.4.5. There are opportunities to introduce standard processes and information within the design and manufacturing environments. One of the requirements for PLM on Type 26 is to use the iBoM to support the identification and management of repeatable manufacturing processes, and use product information to reduce the number of bespoke activities during build; this is illustrated in Figure 20. The benefits of this approach are that the build timescales can be reduced due to the identification of standard manufacturing processes in the design lifecycle.

The customisation of the ETO product results in numerous specialised processes that are difficult to manage and typically have increased resource and time demands. With the identification of BoM items which can have manufacturing standardisation applied, the ETO product can provide the project management benefits of mass production where appropriate, such as with piping, steelwork, and HVAC items. Manufacturing standardisation also has the benefit of reducing quality issues and rework which otherwise may occur within bespoke manufacturing, and enables a reduction in the investment required to support these various manufacturing approaches. There is also an improvement in safety as the variety within the Standard Operating Procedures are reduced and, therefore, these processes are more widely understood and can be managed more effectively with risk assessments.

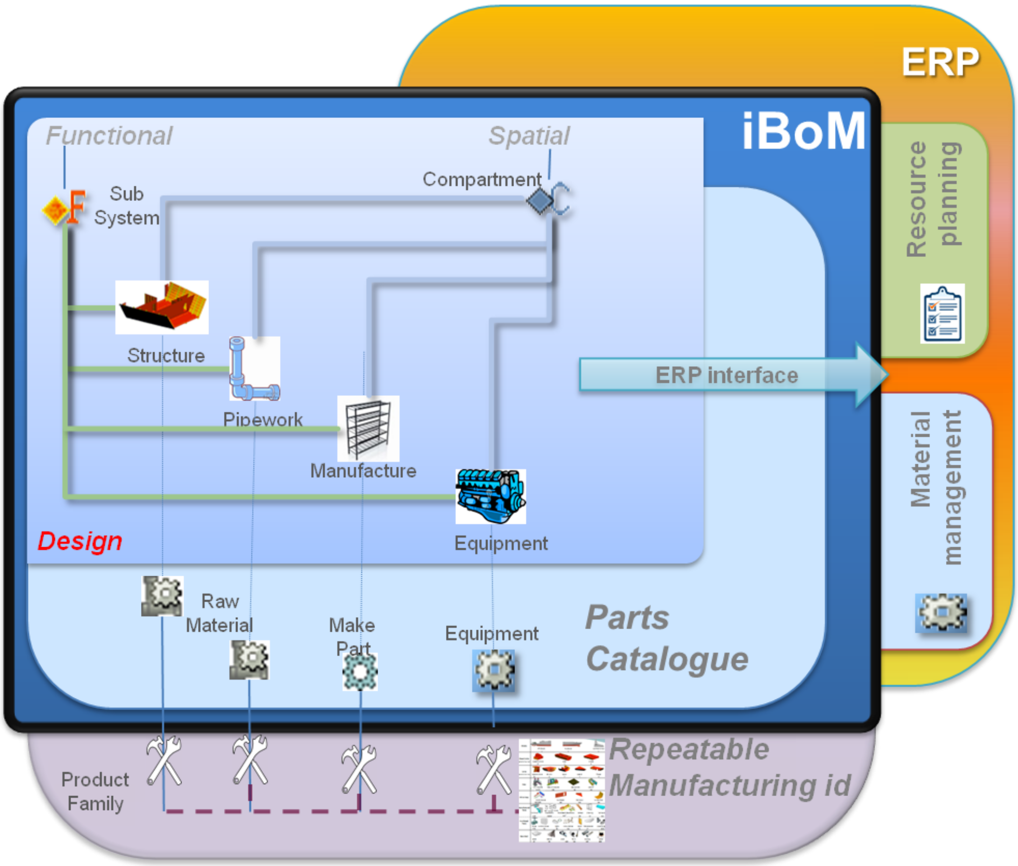


Figure 20 Enabling repeatable manufacturing standardisation in the design.

These improvements in the build phase will also reduce the design effort, as the engineers will be able to pick from a standard set of a controlled, refined parts catalogue that have been approved for use within manufacturing. The benefits for the supply chain are that there is a reduction in material variation which simplifies the procurement processes and allows for savings with larger volumes of standard product elements. The standardisation also enables simplified manufacturing planning processes as the team can more easily identify what product elements go to what manufacturing shop, as opposed to trying to understand how a bespoke manufacturing product should be processed. This simplification in planning and build enables more effective schedule and cost estimation and adherence.

5.9 Completions management

Earlier and improved identification, management and reporting of completion were a customer requirement identified in

Figure 14. Due to the long design and build lifecycle of an ETO product, there is a requirement to manage the ongoing completion of the product through the various phases of the programme. These completion activities may span years from completion planning, to installation, commissioning and acceptance. The iBoM enables improved management of completion through associating and integrating the BoM master data to completion activities. This requires the implementation of solutions to the PLM functional requirements illustrated in Figure 14.

The creation of a completion hierarchy in the iBoM is required, as illustrated in Figure 21, where design BoM elements are associated to completion activities in this hierarchy. This enables improved understanding of the impact of design change on completion activities, as they are both integrated. It also assists with the identification of change affected items which assist with the reduction of rework if these items were missed later in the build lifecycle, which is a customer requirement as shown in Figure 14.

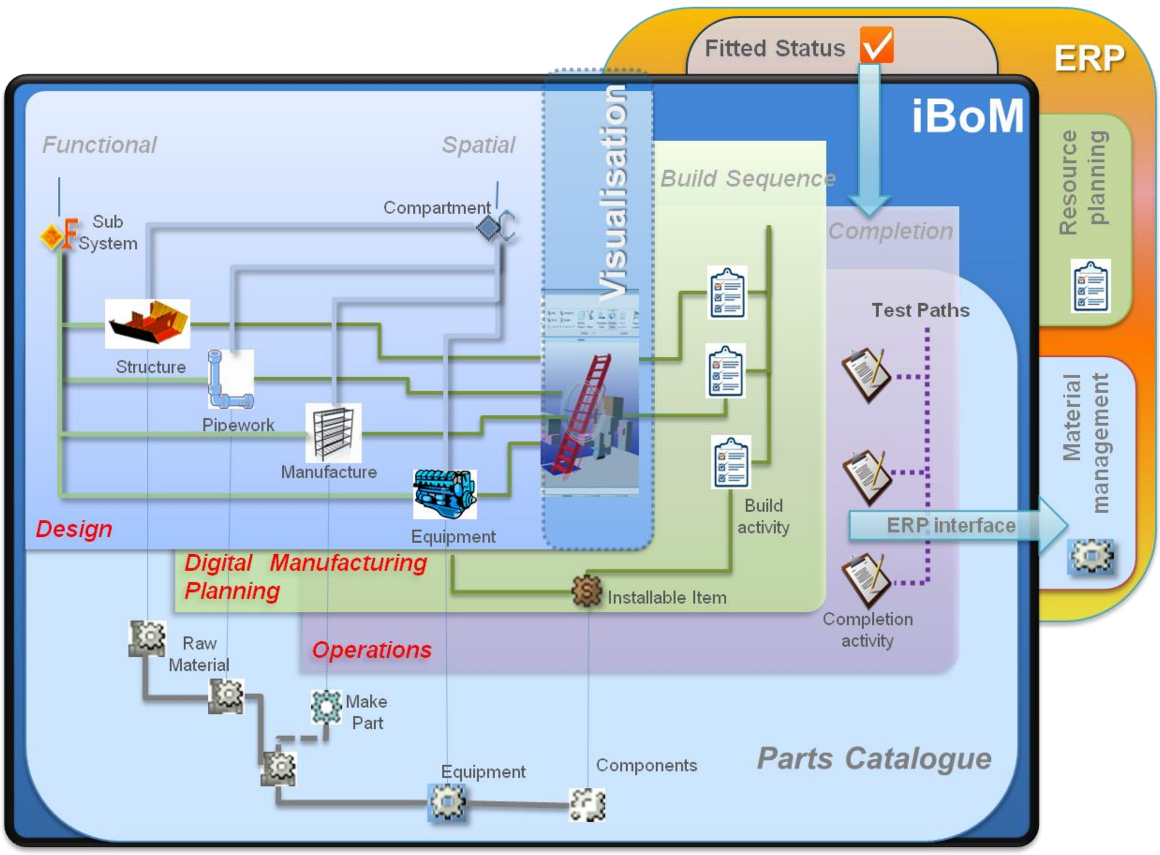


Figure 21 Completions management using the iBoM.

Without the iBoM, the completion activities would use BoM data in a disparate system, such as a standalone completion management system which would not contain the design BoM. This could cause misalignment between the master engineering BoM, which is subject to design evolution and change, and the completion activities, resulting in quality issues and rework later in product development where the cost implications tend to be significant, as shown in Figure 6. To solve this, source data in the design BoM is broken down to the level of detail that supports completion and the quality of the build relating to the design can be more effectively monitored. There is also integration with the programme planning system to understand cost and schedule implications. This provides an improved view of the overall programme status and allows improved management of the plan.

5.10 Summary

This section described a case study for the creation of a PLM environment based on a set of functional requirements to meet business objectives on the Type 26 GCS and future programmes. The HOQ was created using the output from a workshop with stakeholders within BAE Systems Naval ships. The HOQ captured the objectives of the stakeholders as customer requirements, and the PLM functional requirements to meet those objectives. Relationships were created within the HOQ which was used as an input into the BAE Systems Naval Ships PLM strategy, branded as the iBoM strategy, and associated implementation plan. Details of the elements within the PLM strategy were described, including the relationship between the PLM environment and the business objectives and the functional requirements described in the HOQ. It also related the customer requirements, functional PLM requirements, the PLM environment and the challenges related to PLM on ETO products discussed in Section 2.4. Section 9 discusses the relationship between the findings from the semi-structured interviews used to develop the PLM implementation framework with the implemented improvements to PLM illustrated in Figure 14. The results will be used to inform the updated BAE Systems Naval Ships PLM strategy.

6 Description of data capture and analysis approaches

This section describes the data capture and analysis approaches used as a basis to construct the framework for PLM implementation on ETO products. It describes why the data capture and analysis approaches were used and why others were not. These approaches will relate to the research methodology for PAR and case study as described in Section 4.

6.1 Data capture through interviews

Due to the extent of the influence of PLM within ETO as discussed within earlier sections, to develop a framework for PLM implementation on ETO products requires knowledge that comes from a wide range of sources. The literature review in Section 3 established that no detailed guidance or complete frameworks exists on PLM implementation for ETO products. There are a range of ETO programmes which have recently completed their design and build, and several of which are at various stages of their lifecycle, all of which will have utilised, or are currently applying, PLM to some extent. The knowledge to develop a PLM implementation framework exists within the experts in the field of PLM in these ETO products. These programmes include for example the UK Type 26 Global Combat Ship; and the CERN Large Hadron Collider, where the expert knowledge was elicited. The full list of programmes is listed in Section 4.2. The researcher's methodological perspective has been identified as qualitative due to the ontological and epistemological stance directing interaction with experts in the field of PLM, as described in Section 4.1.

Merriam and Tisdell stated that: 'In most forms of qualitative research, some and occasionally all of the data are collected through interviews'. They added that 'The most common form of interview is the person-to-person encounter, in which one person elicits information from another' [109]. DeMarrais described a research interview as 'a process in which a researcher and participant engage in a conversation focussed on questions related to a research study' [133].

Unstructured interviews were considered but not used as they may not have given a consistent set of results which could be analysed, and therefore would not provide a coherent and accurate set of findings required to form the basis for the PLM implementation framework.

The primary data collecting approach for this research has been chosen as semi-structured interviews. Semi-structured interviews reduce the likelihood of observer bias due to the questions being the same for all interviewees. The interviewer has the flexibility to follow-up the answers which has the benefit of following a defined pattern but not being constrained by it. The questions were structured to allow for a comparable set of responses which could be subsequently analysed. This technique also had the flexibility to enable responses that were otherwise supporting or not obvious to flow to the surface, especially if an answer from one question related to another question [122].

Questionnaires were considered but rejected on the grounds that semi-structured interviews and secondary material would give the desired results. Focus groups were also considered and although they will be used to supplement the research for case study development and validation, it was considered that they would not provide the level of detail required in comparison to individual interviews [122].

The choice of investigative technique was to record each semi-structured interview and capture the key points in an interview response document [103]. This recording approach allowed the accurate capture of the data and enabled further analysis to be undertaken later as discussed within Section 6.5.

Using secondary material was chosen, as this allowed the results of the interviews to be analysed and discussed against available literature and the Type 26 case study to assist in answering the aims of the research in Section 9.

6.2 The Interview schedule

The interview schedule was based on the characteristics of ETO products relating to PLM implementation as discussed in Section 2, the results of the literature review in Section 3, and the Type 26 case study described in Section 5. Each question was developed to relate to PLM implementation in ETO products as described in Section 2. The questions were designed to capture findings for PLM objectives, challenges and enablers, ultimately to capture the framework for PLM implementation in ETO products. They were designed to have the flexibility to allow the interviewees to expand their responses.

The interviews were conducted face-to-face where possible or via telephone conference where there were significant geographical restrictions. Face-to-face interviews were preferred due to the interviewer being able to follow-up on questions based on the facial expressions and body language of the interviewee.

The questions were altered based on the feedback from the test interview and the initial responses. Table 8 below describes the developing questioning schedule.

Version	Date	Change	Reason	Impact
V1	01/04/2016	First published questions for test interview.		
V2	24/05/2016	Introduction added.	Feedback from the test interview was that an improved introduction was required to help contextualise the questions. A slidepack was then produced which gave an overview of the research, its purposes and how the interviews contributed to the research.	None
V3	25/07/2016	Q3 changed from 'Can you describe your PLM architecture?', to 'Describe your current PLM environment from your perspective'.	After six interviews this was changed due to the feedback being that this appeared to be a technical IT question which would be more difficult for many to answer. A more accurate output was to determine what the PLM environment was in terms of what was important to the interviewee. From six responses gained, the interviewees had answered it from their perspective. A person from an IT background would answer it from an IT perspective, whilst others from their own business perspective.	None
V4	18/08/2016	Cost/impact note removed from questions.	Removed due to not adding value to the question responses.	None

Table 8 Developing nature of the interview questions.

The final interview questions (Version 4), and their reasoning to capture meaning, are described as follows:

Introduction – A brief overview of research using appropriate diagrams. To provide context to the research (based on feedback from the test interview) including the characteristics of the problem of PLM implementation in ETO products, the research aims, how their responses were planned to be used to generate the PLM implementation framework, and as a lead-in to question 1. The material used for the overview is shown in Appendix A.

Q1 - Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any? This question was used to assess the appropriateness of the challenges identified through the literature described in Sections 2 and 3 and communicated to the interviewees in the introduction. It was also used to capture any additional challenges not considered in the literature.

Q2 - What are the typical key business objectives which you require a PLM environment to support? This question was designed to stimulate the interviewee into considering why they need PLM. It was expected that these would be at a detailed level but would be an input into the thematic analysis described in Section 6.5 to allow themes to be generated at a high level. The responses to these questions were planned to be compared with the literature and to form the basis of the PLM objectives section of the framework.

Q3 - Describe your current PLM environment from your perspective? This question was used to allow the interviewee to consider the PLM environment from their perspective. The question was designed to stimulate the interviewee into considering the environment within which they work regarding PLM, and was intended to provide a link between the objectives and the following questions. The question was used to enable the interviewee to describe their PLM environment with objectives, challenges, and enablers raised across process, people, information and technology depending on what interests them the most. The responses were planned to be compared to the literature and used to support the findings and discussion Sections.

Q4 - Describe the typical challenges you experienced with utilising PLM? Now that the foundation has been captured with regard to the context of the research, their own PLM objectives and the PLM environment with which they work, the key findings can be elicited. The first stage was to capture the interviewee's beliefs in terms of their typical challenges with utilising PLM, based on their PLM environment. This was intended to set the basis for the following questions regarding what improvements could be enabled.

Q5 - What improvements would you make to a PLM environment to ensure it meets your business objectives and why? After considering the challenges with utilising PLM, the interviewee would be asked this question to capture what improvements could be enabled to the PLM environment to meet their objectives.

Q6 - Can you prioritise the improvements in terms of business impact? This question is only used if there are multiple responses to Question 5 to allow the interviewee to convey what improvements are more critical. It could be ignored if there are only a small number of responses.

Q7 - Can you prioritise the improvements in terms of effort required? This question is only used if there are multiple responses to Question 5 to allow the interviewee to convey what improvements are more critical. It could be ignored if there are only a small number of responses.

Q8 - How could you better enable the implementation of these improvements? In Question 5, the interviewee was asked to state what improvements should be made to PLM to meet their objectives. This question was designed to stimulate the interviewee into considering how these improvements could be enabled.

Q9 - What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)? Now that the improvement enablers have been captured, this question was designed to identify what potential challenges could be encountered with the enabling of these improvements. The results may follow on from Question 4, for instance, the interviewee may have people challenges which may impact the enablement of improvements. It may also elicit new challenges which could be valuable to the research.

Q10 - Can you prioritise the challenges in terms of business impact? This question was only used if there were multiple responses to Question 9 to allow the interviewee to convey what challenges were more critical. It could be ignored if there are only a small number of responses.

Q11 - Can you prioritise the challenges in terms of effort required? This question was only used if there were multiple responses to Question 9 to allow the interviewee to convey what challenges were considered to be more critical. It could be ignored if there are only a small number of responses.

Q12 - How could you overcome difficulties associated with these challenges? Related to Question 8, this was designed to stimulate the interviewee into considering how the challenges could be overcome. It was designed to supplement Question 8 in terms of improvement enablers and to elicit any which may arise in the implementation of the PLM improvements which had yet to be considered.

Q13 - Would a framework assist with the transition from as-is to the to-be, if so how? The intention of this question was to assess whether a framework conveying the results of the research would assist in the implementation of PLM. It was also intended to capture the ways in which the framework would assist and any enhancements in its design and use.

Q14 - What other ETO industries would benefit from a framework? This question was used to capture what other industries would benefit from a framework for ETO PLM implementation. It was intended that this question would assist in identifying further interviewee candidates, areas with which the research could be targeted to improve industrial performance, and also, for future research opportunities.

6.3 Identification of the participants

McCracken stated that 'interviews are used to discover shared understandings of a particular group. The sample of interviewees should be fairly homogenous and share critical similarities related to the research question' [134]. Reybold et al. stated that 'the results of a study are not so much found as they are constructed through researcher choice and interpretation. Researchers, then, should examine and reveal the complexity of their selection process in order to satisfy their readers', and their own, trust in qualitative research methods'. They also stated that 'there must be an accounting for the relationship between the researcher and those chosen to represent a reality'. They argue that participant selection is one of the least critiqued methods in qualitative research and conduct a literature review of selection approaches. Of these, they stated that: 'there is general agreement among qualitative researchers that purposeful selection is the best strategy to obtain 'information-rich' cases that can give in-depth insight into the subject of study' [135]. Maxwell stated that purposeful selection is when people are deliberately identified as they are uniquely able to provide information as they are experts in a field or have been observers in an event, and are therefore able to answer the interview questions [136].

As described in Section 4.1 the philosophical position of the researcher directs the research outcome. The ontological perspective of relativism directs the researcher to identify experts in a field as there are many truths that are dependent on the actors in the environment. Therefore experts in the field of PLM in ETO products will be identified for the research. The researcher's epistemological perspective of subjectivism means that there are only subjective truths and it is through interaction with the experts that the meaning and the findings are co-created. The researcher's paradigm was identified as interprevatism which states that knowledge or meaning can only be gained through actor's real work subjective view. Therefore the selection of relevant experts in the field of PLM in ETO products is a fundamental input into the research. This purposeful selection approach has been chosen to capture the information required to develop the PLM implementation frame for ETO products due to the philosophical perspectives directing the research.

As highlighted in Section 4.2, 11 ETO products were identified from which PLM experts could be approached for interview to subsequently generate the information required to develop the PLM implementation framework for ETO products. At least one expert from each of these ETO products was to be approached for the interview process. The next step was to ensure that each of the business functions were represented, including engineering, supply chain, programme management, in-service support, manufacturing planning, manufacturing and IM&T. The customer and suppliers were also approached for inclusion. Preliminary engagement was undertaken through email to engage potential experts. These experts where identified through the researchers own experience with PLM in ETO products and also so through wider stakeholder engagement where PLM experts were sought.

Through this process 28 experts were identified and semi-structured interviews on PLM implementation were undertaken from these ETO products in the UK, France, Australia, USA and Canada. The interviewees were selected based on their relationship with PLM in ETO products either as an implementer or as a key stakeholder in its successful use within their organisation. The interviewees were identified through the researcher's contacts within the ETO industry and through contacting suitable candidates based on research findings, such as from other industries suggested in Q14 of the interview questions.

6.4 Ethical considerations

The interviewees were identified and written to explaining the purpose of the research. This included that it was sponsored by BAE Systems and the research was being undertaken in conjunction with the University of Strathclyde. It was explained why they had been chosen, asking if they would be willing to take part in semi-structured interviews, detailing how many questions there would be, and approximately how long the interview would take.

The research method was explained as well as the aim of the research being to create a framework for the implementation of PLM in ETO products. It was also explained that the intention was for the results to be published. This was repeated at the interview where they were also asked if they would be willing for the interview to be recorded in audio, and whether they would allow any further follow up on the key points captured in the notes. The role of the researcher was explained to the interviewees as a part-time PhD student who was also a PLM practitioner in ETO products. This was important to establish trust, openness and to reduce ethical problems. The interviewees were advised that the results of the research would be made available to them to help improve PLM implementation within their business. This initial communication was very positively received and there was a universal request from all the interviewees to receive the research findings.

6.5 Data analysis method

The philosophical perspectives have been discussed in Section 4.1 that established the importance of engaging with experts in the field of PLM. The ontological perspective of relativism means there are many truths dependant on the actors in an environment, and that through the epistemological perspective of subjectivism, the truths are subjective and can only be established through interaction with these experts. Therefore the analysis of the findings from the interviews must be analysed appropriately and the key points identified across the responses.

The responses from the interviewees were captured in Microsoft Word against each of the interview questions and analysed to produce the findings and recommendations for the PLM implementation framework. The interviews were transcribed and are included Appendix B, and are directly referenced in the Section 7.

Braun and Clarke stated that 'Thematic Analysis provides a flexible and useful research tool, which can potentially provide a rich and detailed, yet complex, account of data' [137]. This enables meaning from the subjective views of the interview responses to be generated. The phases of the Thematic Analysis conducted within the research correspond to Braun and Clarks' proposal and are shown in Table 9.

No	Phase	Description of the process
1	Familiarising yourself with your data.	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2	Generating initial codes.	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3	Searching for themes.	Collating codes into potential themes, gathering all data relevant to each potential theme.
4	Reviewing themes.	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis.
5	Defining and naming themes.	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and name for each theme.
6	Producing the report.	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Table 9 Phases of Thematic Analysis [137].

Braun and Clarke go on to state that Thematic Analysis is a straightforward approach to undertaking qualitative analysis but there are potential hazards that may impact the quality of the research. It was important to ensure that the data was collected and analysed across the entire content of the research, in this case all of the interview responses, from all the interviewees. This was undertaken to ensure that themes are spread across the entire research findings. Another potential hazard was that the themes do not relate to the research goals themselves, therefore, care was taken to ensure that the key themes captured relate to the development of a PLM implementation framework. The identified themes should be supported by the data itself to ensure that they are not generated based on weak data such as from a single individual's view, therefore, there should be data to support each of the themes [137].

To overcome these potential hazards the NVivo software, was chosen to provide a platform to capture and analyse the interview responses. NVivo provided a means to demonstrate how the findings from the interview responses related to each of the themes. The Thematic Analysis approach used to capture the themes in NVivo is illustrated in Figure 22. The responses expressed through the interviews were captured and classified into various categories (codes and themes). These categories provided a structure through which further analysis could then take place [122]. The initial analysis carried out from the interviews was to capture commonality through a coding structure, which was then grouped into themes. These themes were used to generate the findings which allowed the analysis and conclusions to be drawn and related to the research aims.. This Thematic Analysis approach will not only show how the results were gathered but will mean that the key points from the interviews can also be captured and referred to in Section 7.

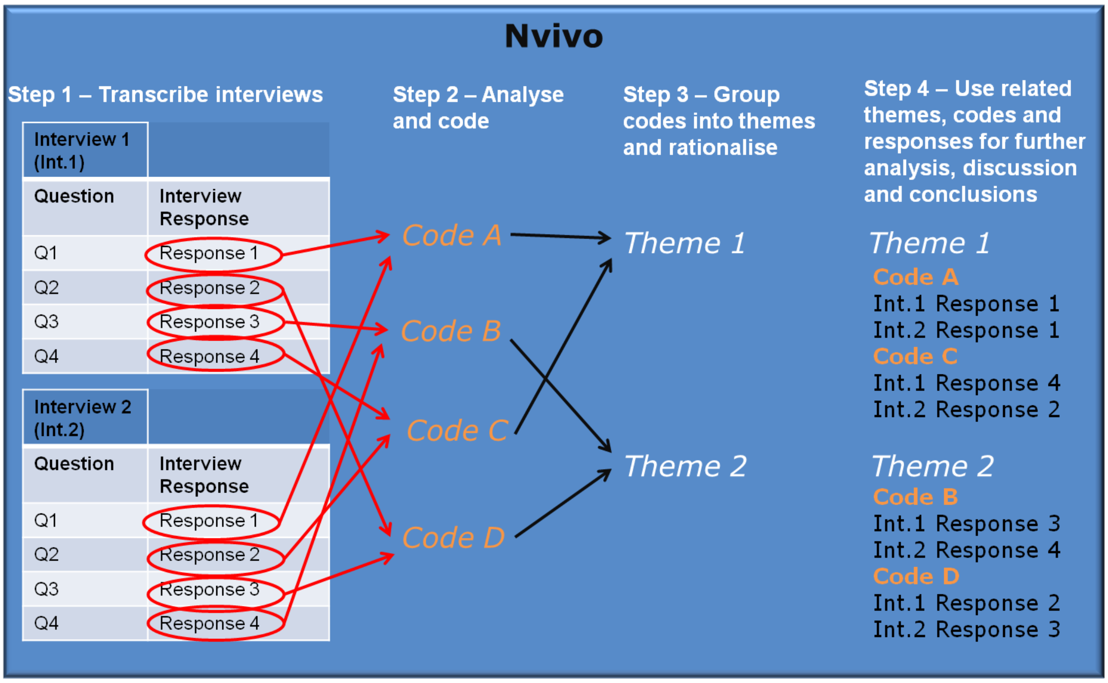


Figure 22 Approach to thematic analysis using NVivo

Guest et al. stated: 'data analysis software is an important component in most qualitative research studies' [138]. NVivo was been used as the software tool to analyse the data and provide the means to perform thematic analysis due to its capabilities to capture source data and allow recording and linking of key themes [139]. This enabled the provenance of the research findings to be demonstrated as shown in Appendix C which shows all of the codes and themes captured through the data analysis. Borrego et al. using research from Lincoln and Guba, Tashakkori and Teddlie, and Chism [140], [141], [142], stated several factors which can be used to determine the quality of research against the research aims. For qualitative research, these are:

- Credibility: establishing that the results are credible or believable;
- Transferability: applicability of research findings to other settings;
- Dependability: researchers account for the ever-changing context within which the research occurs; and,
- Reflexivity: researchers examine their own bias and make them known.

Borrego et al. went on to state that 'the term trustfulness is often used to describe the extent to which a study meets these criteria' [143]. They then described how trustfulness can be established through creating an audit trail which provides a clear link between the raw data and the findings [143]. The relationship between the raw data from the NVivo software output in Appendix C and the generated themes provides the basis for the trustfulness for this research.

6.6 Summary

This section described the data capture and analysis approaches used as a basis to construct the framework for PLM implementation on ETO products. The philosophical perspectives have been discussed in Section 4.1 which established the importance of engaging with experts in the field of PLM. The ontological perspective of relativism means that there are many truths dependant on the actors in an environment, and that through the epistemological perspective of subjectivism, the truths are only subjective and can only be established through interaction with these experts. This directed the use of semi-structured interviews to capture data to develop the PLM implementation framework on ETO products. The interview questions, their development and reasoning was described including how they would be used to develop objectives, challenges and enablers for the framework.

The interview participant selection was described including how purposeful selection was chosen to specifically identify experts or those who were appropriate observers in the field of PLM on ETO products. Ethical considerations were described including the approach to engaging with the interview participants. Secondary data from literature and the case study will be used to supplement the interview findings in order to generate the significant contribution to knowledge.

The data analysis method was described including how the philosophical assumptions of using experts who have a subjective truth influenced the method selection. Therefore the analysis of the findings from the interviews must be carefully analysed and the key points identified across the responses. Thematic analysis was chosen using NVivo to generate codes and themes which relate the relevant interviewee responses to generate meaning.

The next section describes the development of the framework for the implementation of PLM on ETO products. It will explain the structure of the framework including its relationship to the semi-structured interview questions and how it was influenced by Enterprise Architecture. It also describes how thematic analysis was used to generate the findings. These findings are then described in detail.

7 Development of the framework

This section describes the development of the framework for the implementation of PLM on ETO products. The Cambridge dictionary describes a framework as ‘a system of rules, ideas, or beliefs that is used to plan or decide something’ [15]. The framework will provide guidance to organisations on what is required to successfully implement PLM on ETO products. Sections 2 and 3 have shown that a framework for PLM implementation is necessary to support the successful NPD for ETO products and that a framework that achieves this does not currently exist within published research. Without a framework, it is posited that ETO NPD organisations cannot not fully understand their PLM objectives, the challenges they will face, the improvements that are necessary, and how they can be enabled to ensure the successful implementation of PLM.

As described in Section 6 the results of the semi-structured interviews were used as the primary approach for developing the framework. These interview results are supported by literature as a secondary means to contribute to the development. This section will explain how the thematic analysis approach described in Section 6.5 was applied in order to generate the themes necessary to develop the framework.. As described in Section 6.2 the interview questions were designed to identify the objectives, challenges and improvement enablers required for a successful PLM implementation. This approach supports the structuring of the framework into PLM objectives, challenges and enablers which assists in the presentation of the guidance to improve understanding and ease of use. Each question which relates to objectives, challenges and improvement enablers is shown in Table 10.

Question No	Question	Relevant section in findings section where response is captured
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Further validation of the research aims and gap in knowledge
Q2	What are the typical key business objectives which you require a PLM environment to support?	To identify PLM objectives
Q3	Describe your current PLM environment from your perspective?	where appropriate the response was used in objectives, challenges or enablers section
Q4	Describe the typical challenges you experienced with utilising PLM?	Challenges
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Enablers
Q6	Can you prioritise the improvements in terms of business impact?	Enablers
Q7	Can you prioritise the improvements in terms of effort required?	Enablers
Q8	How could you better enable the implementation of these improvements?	Enablers
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)?	Challenges
Q10	Can you prioritise the challenges in terms of business impact?	Challenges

Question No	Question	Relevant section in findings section where response is captured
Q11	Can you prioritise the challenges in terms of effort required?	Challenges
Q12	How could you overcome difficulties associated with these challenges?	Enablers
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Used to support the significant contribution to knowledge - The Framework
Q14	What other ETO industries would benefits from a framework?	Used to identify industries where an interview could be targeted

Table 10 The relationship between the interview questions and the framework structure.

The following sections will describe the development of the framework for the implementation of PLM on ETO products. It explains how the structure of the framework was influenced by Enterprise Architecture. It also describes how thematic analysis was used to generate the findings. These findings are described in detail with references to literature and the interview responses where appropriate. Each subsection within the objectives, challenges and enablers section describes the themes used in the framework. The final framework to support the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) products is illustrated in Figure 23.

	Objectives	Challenges	Enablers
Information	• Through life capture, integration and management of all evolving product information from all stakeholders. • Management of product configuration and emergent change. • Manage security, export and IPR obligations. • Management of evolving product maturity. • Up-to-date, traceable, relevant and configured information that can be accessed.	• Identifying, managing and presenting emergent complex information for management decision making. • Integrating complex product information through-life across multiple PLM technology toolsets. • Management of product information maturity and its relationship to change, configuration, schedule and cost.	• Develop policies to capture what information is required and how it will be used within an evolving complex product. • PLM information integration, policy development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team. • Develop data quality and governance policy and adherence approach. • Develop configuration and change management approach across ETO product classes and variants.
Process	• Support the design and build for product safety and environmental considerations. • Enable quality through right first time and reduction in rework. • Enable product development and build collaboration across all stakeholders. • Cost, profit, risk reduction and value for money. • Enable standardised design and build.	• Creating processes which meet business objectives but are not overly complicated.	• PLM business process ownership, development, standardisation, learning from experience and adherence using suitable expertise within a dedicated functional team. • Guidelines and governance over process complexity to ensure they are simple and useable. • Mandate utilisation of PLM processes internally, to partners and the supply chain.
People	• Enabling collaboration across multiple sites. • Demonstrating to the customer that the product meets requirements. • Support organisational knowledge management and learning. • Enable improved decision making.	• Education, adoption and understanding value, and its relationship to quality. • Lack of PLM expertise to enable and support PLM. • Obligations and through-life implications of their actions or inactions. • Understanding processes, toolsets and through-life product information integration. • Working collaboratively across all functional areas.	• Provide continuing evidence of benefits to senior management to enable support and maintain PLM sponsorship. • Develop and implement a comprehensive business change initiative on PLM. • Develop and implement a cross functional PLM education programme embedded within the core business training programmes emphasising core values and objectives. • Develop PLM objectives, education approach and support to the business using suitable expertise within a dedicated cross functional team.
Technology		• Technology robustness and longevity to support long-life product design and build. • Toolset complexity and simplicity balance to meet business objective. • Creating a system to systems through toolset integration and rationalisation.	• Identify and implement configurable PLM toolsets with minimal customisation. • Drive integration and information through toolset rationalisation. • Focus on toolset development on business objectives, priorities and ease of use to reduce complexity of technology and processes. • Implement IT architecture improvements to support new PLM capability and ensure toolset performance.

Figure 23 The final framework to support the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) products

7.1 Enterprise Architecture

The structure of the framework for the implementation of PLM on ETO products has been influenced by Enterprise Architecture (EA). EA is used to manage the creation of information to describe the business strategy, model, objectives, processes and technology in an organisation. This allows the organisation to improve its decision making, communication and monitoring of both business and IT investments [144]. EA allows a business to manage a major undertaking, such as remodelling a complicated design and manufacturing process, by splitting it up into smaller elements [145]. These smaller elements are documented and their relationships captured, which enables an improved view and understanding of the relevant aspects of the business, thus supporting an improved decision making environment [146]. There is a strong emphasis within EA on understanding the 'as-is' problematic aspect of the business. This effort can be used to plan the 'to-be' target environment, therefore moving from a strategic to normal day-to-day business [146]. It also supports the communication of the as-is problematic aspect and the strategic environments to the key stakeholders [147]. This approach to transforming from an as-is, to a to-be environment supports the DMEDI research design by assisting with developing a detailed design, which ultimately supports the research aims which is to provide a framework for the implementation of PLM on ETO products.

The Information Management & Technology (IM&T) function of an ETO organisation has the task of relating the business objectives to technology solutions and making them understood by the stakeholders. The IM&T function have the responsibility of developing and maintaining the PLM system of systems and planning the evolution to support the business strategies. EA can be used to support this decision making process [148]. One of the key challenges with EA is the connection between the business requirements and the technology: the lack of a clear connection means that the full value of EA is not apparent to all of the stakeholders [144]. Unless resolved**,** this disconnect will impair the organisation's ability to use EA as a means to make strategic decisions across the whole enterprise. The lack of a coherent technology strategy which aligns with the organisational objectives can contribute to billions of additional costs and delays of years for major products [1]. Research has been undertaken to provide guidance on integrating business and technology architectures and also to validate the importance of aligning business strategy with technology investment [10] [12], but significantly, not in the context of implementing PLM on ETO Products.

The business architecture provides a focus on people and process, in order to meet the needs of the product or management of the product delivery, and encourages relevant requirements creation to support the move to an improved position. The technology architecture attempts to link the technology necessary to enable the requirements identified through the business architecture. In order to realise the business value required by the technology, the investment must ensure alignment between the organisational context and the technology itself [10]. Therefore the technology must support the strategic business requirements. EA supports the modelling of the as-is position and the to-be strategic target. The methodologies used, such as The Open Group Architectural Framework (TOGAF), supports the analysis of the gap to assist in determining the impact of the change and to help with the implementation [144].

This approach helps to support senior decision makers in being able to understand and assess whether the to-be position aligns with the organisation's strategy [146]. The transition from strategy to daily operations is supported through policies and meta-models which describe the main components of the architecture and how they interact, and is a critical communication mechanism [146]. TOGAF helps the IM&T team justify their architecture to the key decision makers through this improved communication [147]. As there are few technology changes which do not affect business process, they should be viewed as a business change [149]. This is due to IM&T being highly integrated into the organisation and, also, that the movement towards the to-be strategic environment is likely to be challenging involving both technical and social aspects [150]. Boddy et al. described three main parties which affect technology implementation as the general management, users and the IM&T management and staff [151].These parties' perceived failings relating to technology implementation are described in Table 11.

General Management Failings	Users' Failings	IM&T Management and Staff Failings
No clear business plan available	No clear expression of needs and expectations of information management technology	Inability to match information management technology to business needs
Inability to spot strategic uses of information management technology	Focus only on operational support; no strategic vision	Preoccupation with the technicalities of information management technology
Failure to communicate requirements to systems staff	Lack of appreciation of technical complexities	Lack of understanding of business environment
Lack of appreciation of technical complexities	No contribution to planning and policy of information management	Failure to market business successes of information management technology
Insistence on cost justifying all investments		

Table 11 Perceived failings from other parties' perspectives – adapted from [151].

EA can assist with overcoming these failings by providing a structure and clear communication route to capture and align the business need with the technology implementation. This approach will support the research aim for the development of a PLM implementation framework on ETO products, as they are highly complex with the gap between the business and technology architectures difficult to capture, align and communicate.

Svata stated there are many reasons for the gap between business objectives and the enabling technology [152]. This includes the challenge of aligning the enterprise goals with the technology implemented to realise the business objectives which may be due to the significant differences in perspective between business and technology owners. Svata provided an example of software engineering practices used by technology providers who use languages and modelling techniques that are not easily understood by the wider business community. Von Rosing stated there are missing links between the business model (strategic) and process landscape (operational) that are necessary for a successful Enterprise Architecture initiative [97]. Von Rosing continued by stating that this missing link causes a significant problem for the technology architecture which is required to provide an environment that satisfies both the strategic and operational needs of the business. Attempts have been made to manage this divide, including business process management [153] which focusses in optimising and organising processes in order to reduce costs, reduce time and to add value, especially in complex systems [97]. However, these need to be aligned with strategic objectives, information and technology.

Pereira and Sousa stated that Business, Information, Application and Technology are well understood components in most Enterprise Architecture Frameworks [154]. Figure 24 illustrates an integrated Enterprise Architecture where the business architecture is aligned with the information, software applications and technology architectures. This ensures that the business is able to deliver the product aligned to the objectives and processes and is fully supported by the technology.

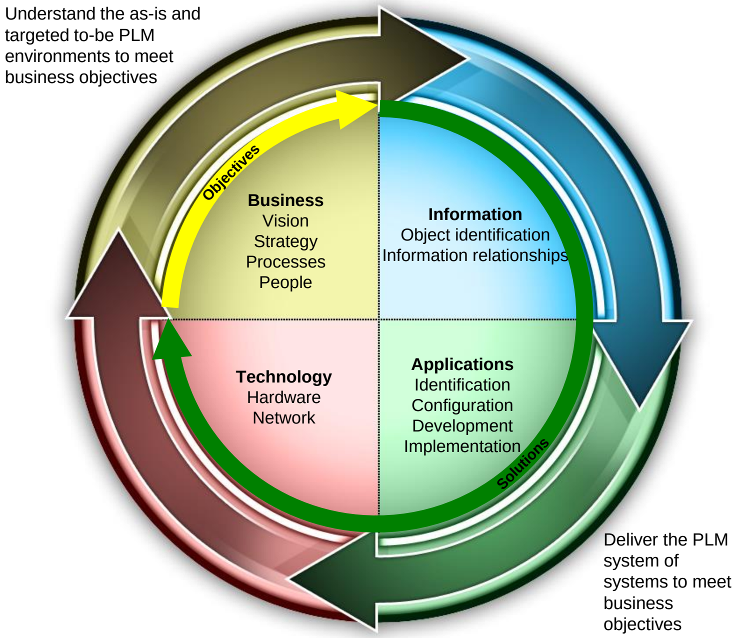


Figure 24 An Integrated Enterprise Architecture.

To leverage the EA approach, the PLM framework has been categorised into four dimensions these are:

- Information;
- Process;
- People; and,
- Technology.

The responses to the questions shown within Table 10across objectives, challenges and enablers were categorised using these four groups which not only helped to structure the PLM framework but also enabled the organisation to break the PLM implementation problem into small chunks and target areas for improvement relating to information, process, people or technology. This approach aimed to assist in supporting an organisation with prioritising and organising its implementation in specific business areas. For example an organisation may already have a well-established and effective PLM information approach, but requires specific focus on the people aspects.

7.2 The development of the structure of the framework

For each interview, the key points from the response to the questions were transcribed into Microsoft Word and imported into NVivo. These key points reflected a summary of the response to the interview question. This approach was designed to aid with future analysis by enabling efficient thematic analysis as discussed in Section 6.5, including codification and theme generation. A nodal hierarchy for the interview questions was then created in NVivo. The responses to each question for each interview was then analysed in NVivo. Each interview response to a specific question was given a code in NVivo which summarised the key point the interviewee was making. These codes were created the first time this key point was made for that question. Further similar key points made by the same or another interviewee had the existing code applied, for the same question. Using the same code for each question allowed the context for the code to be clear within the NVivo nodal hierarchy when further analysis took place. For example a code which applied to a question on objectives would not be misrepresented as a response relating to challenges. Similar codes could be applied but they would always be within the context of the question.

Once all the interview responses for all the questions had been analysed and coded, related codes were grouped together and a theme generated. A theme is a ‘particular subject or issue that is discussed often or repeatedly’ [155]. Each theme provided a summary of the topics being discussed which were represented by the codes. The themes and codes for each question were then categorised as relating to information, process, people or technology. An example of a theme generated by the codes in NVivo categorised as relating to people is shown in Table 12, this table shows a set of codes that have been applied to the content of interviews in NVivo.

Theme - Education, adoption and understanding value of PLM, and its relationship to quality		
Codes	**No of Interview sources**	**No of References**
People - new ways of working	2	2
People - ownership	1	1
People - stakeholder engagement	1	1
People - understanding why its required	5	5
What’s in it for me! - What are the benefits to engineers entering and maintaining the PLM data	1	1

Table 12 Example of a theme and supporting codes generated from Q4 - Describe the typical challenges you experienced with utilising PLM?

The number of times a code has been applied across one or more interview is shown in the ‘No of References’ column. The number of interviews where the code was applied is shown in the ‘No of interview sources’ column. This information was used to identify whether a point was being made by individual or multiple interviewees, therefore enabling the detection of key findings which have been triangulated across multiple sources. The ‘code’ column shows the names of the codes applied. These reflect a high level summary of the points being made by the interviewees. At the time of creating the codes the researcher was not aware of what the findings would be. Once all the interviews have been analysed, the codes for each question were grouped together into themes within information, process people and technology. A code could become a theme if it provided an adequate description which summarises another code. For example the theme ‘Education, adoption and understanding value of PLM, and its relationship to quality’ in Table 10 was also a code, the other codes where grouped with this theme in NVivo as they were making contributory points. This theme and codes were grouped under the people category, as they were related to personnel challenges in PLM implementation. The approach to generating the themes is illustrated in Figure 25 Structure created in NVivo to derive the research findings.

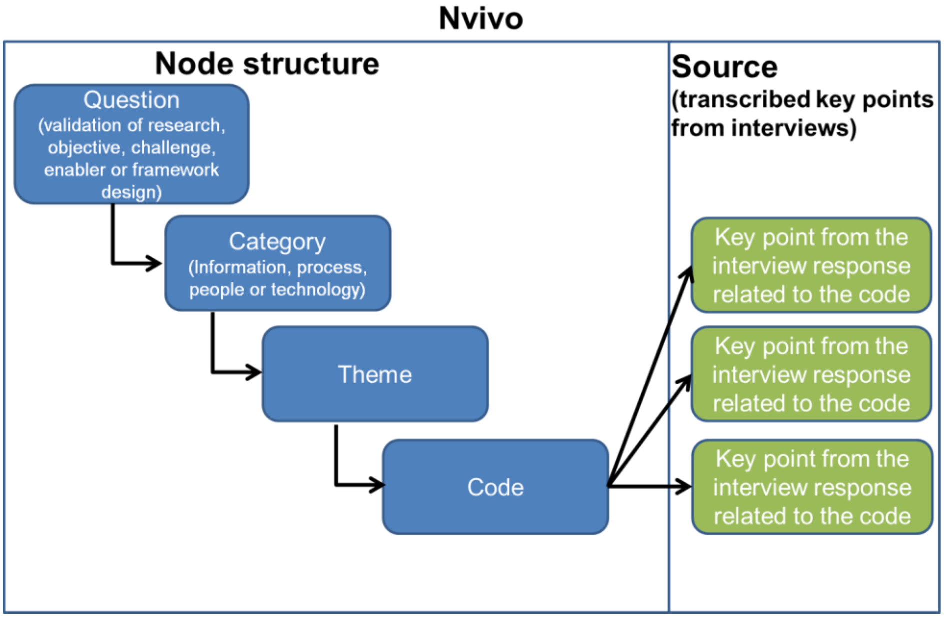


Figure 25 Structure created in NVivo to derive the research findings.

The interview questions were represented in the NVivo nodal structure and the key points from the interviews were transcribed and imported into the tool as shown in Appendix A. This allowed the transcribed responses to be analysed in NVivo with the relevant responses allocated a code under the nodal structure representing the question asked. These codes were then grouped into themes as shown in Figure 22 in Section 6.5. The themes and codes associated in NVivo with the question with which the response was captured, enabling a direct relationship between theme, code and key point from the transcribed interview. These themes were subsequently structured using the categories of information, people, process or technology. This process of mapping between NVivo coding, grouping and nodal structure allowed the derived themes in this section to have a direct relationship to the interview responses and to each key point in order to cross-reference to the transcript in Appendix A. This demonstrates a systematic approach to the capturing of the findings and traceability of each of the sections back to the interview responses.

The complete output of the NVivo nodal structure developed in the interview analysis is shown in Appendix C. The framework is therefore structured by information, process, people and technology with section headings of Objectives (Section 7.4), Challenges (Section 7.5), and Enablers (Section 7.6) which are directly derived from the interview questions in Section 6.2.

7.3 Confirmation of key challenges with PLM implementation on ETO products

This section describes the responses to Question 1, which was designed to further support the challenges with PLM implementation on ETO products discussed in Section 2.4. Following the feedback from the pilot interview, a set of PowerPoint slides (Appendix A) was created which was used to provide the interviewee with a lead-in to the follow on questions and to provide context of the research including:

- An overview of PLM;
- An overview of ETO products;
- The research aim;
- The characteristics of the problem of PLM implementation in ETO products as discussed in Section 2.4.2; and,

- How their responses will be used to generate the significant contribution to knowledge.

Question 1 was as follows:

> 'Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?'

The interviewees provided confirmation of the key challenges described in Section 2.4 which were captured in the interview responses in Appendix B. The following statements provide a summary of the responses:

1. 'I recognise a lot of these challenges particular in maritime', B.23.
2. 'You captured it well, you've put it in a cohesive manner; from my background and experience it is relevant and expected, I would note because of your background or research you touched on key points which would have occurred to me naturally', B.26.
3. 'It's an interesting way to look at it, the set of challenges that you articulated definitely apply to large bespoke projects - a lot of these issues apply in part to less complex projects - certainly the scale of the projects differentiates them from other system engineering projects', B.8.
4. 'In summary they are really good ones in terms of ETO and the different products out there', B.13.
5. 'All relevant, some taken as read - product complexity absolutely true, no brainier. Customer high risk, agreed', B.2.
6. 'I would agree with them, we've encountered all of them. Biggest being the level of customisation from programme to programme', B.27.
7. 'All sounds very familiar ', B.20.
8. 'Wouldn't remove any', B.25.
9. 'All relevant. An example is no prototype, key challenge as a business, something we have struggled with over my career', B.14.
10. Everyone I recognise', B.7.
11. 'Challenges are valid and have been encountered on many projects I have worked', 0.
12. 'The challenges are accurate', B.16.
13. 'Completely, particularly in our area, we design and continually develop while the manufacturing is ongoing, equipment would be six years old by the time we deliver the design if you choose COTS, hence why we evolve the design, develop and design while the ship is being designed/manufactured', B.18.
14. 'Yes I definitely agree with what you've said. What's comes to mind, as well as the project being long term and expensive, there are few organised businesses who can do this work', B.19.

The above responses provided confirmation of the key challenges with PLM implementation on ETO products. The responses to Question 1 provided confirmation that the challenges identified through the literature review were relevant to the industrial experience of the interviewees. These challenges are an important input to the research as it differentiates PLM implementation on ETO products from other product types such as ATO. They also provide an important context to the subsequent questions which identify more detail on specific challenges and how they can be overcome. These provide the basis for the creation of the framework as described in Section 7.

7.4 Objectives of PLM implementation within ETO

This section describes the literature and synthesises the interview responses in relation to the objectives of a PLM implementation to meet the organisational requirements. Literature is used to identify the objectives of PLM and to provide support or opposition to the interview responses. It will also support PLM objectives which may be taken for granted by the interviewees and not raised widely in the responses. The section describes in detail the objectives of PLM with the interview responses synthesising what aspects are important to the interviewees. This is not to state that those described in literature, but not highlighted in the interviews, are not important, but that they were accepted by the interviewees in a mature PLM environment. As shown in Table 10 in Section 7, interview Question 2 was used to contribute to defining the key business objectives. Question 3 was used to identify additional business uses of the PLM environment which were not necessarily key objectives of the individual being interviewed.

The following subsections were structured around the objectives of the PLM implementation framework with respect to information, process and people. The analysis of the interview responses did not synthesise technology as being an objective for the interviewees. Technology was identified as a challenge for PLM implementation on ETO products and as an enabler to overcome these challenges to meet organisational objectives. Therefore technology was not defined as an objective, but regarded instead as being the means by which to meet the information, process and people PLM implementation objectives of an organisation.

7.4.1 Information objectives

The management of information is a requirement of PLM in any NPD environment and this is reflected in literature which supports the information objectives in this section. The information objectives in ETO products differ at a detailed level as they must manage large volumes of information with various levels of importance which are not stable throughout the product's life phases. This section describes those information objectives for the implementation of PLM on ETO products which have been identified from literature and synthesised from the interview responses through thematic analysis. The results of this analysis are consolidated within subsections which describe the information objectives.

These include the through life capture, integration and management of all evolving product information from all stakeholders throughout the lifecycle of the NPD process. Ensuring that a single point of truth is used to capture evolving product information once, and used many times to reduce duplication and increase quality, was identified as an objective. The management of product configuration and emergent change was identified as an objective in multiple interview responses due to the impact this has on the NPD process on schedule, cost, risk and quality. The management of security, export and intellectual property was identified as necessary to ensure that the organisation responsibilities relating to legislation and commercial responsibilities are adhered to.

The management of evolving product maturity was a requirement on ETO products due to the long NPD lifecycle and the gradual development of the information to support the stakeholders. Ensuring that the information is up-to date, traceable, relevant, configured and can be accessed was establishes as an objective as this ensures that the information quality is maintained and that those who consume can easily interrogate and consume it. The information objectives in the framework are illustrated in Figure 26.

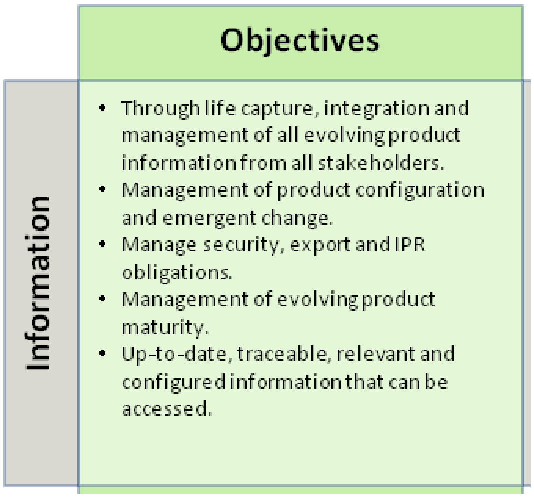


Figure 26 Information objectives

7.4.1.1 Through life capture, integration and management of all evolving product information from all stakeholders

Throughout its entire lifecycle, the evolving ETO product information from all the stakeholders must be captured in a structured way to ensure it can be understood, it adequately describes the product, the programme status including quality and any risks.

The literature described in Section 2 has established the importance of information management through PLM including Brunsmann and Wilkes who stated that the main goal of PLM was to provide an information backbone to the business [29]. This has been reflected in the interview responses including B.2 who stated the importance of BoM management as a key business requirement for PLM. B.25 discussed his role as understanding the performance of programmes from a design perspective, and that while he was in project management there was a huge focus on risk with BoM management and BoM Maturity. B.22 highlighted the importance of process to manage data including configuration, change and BoM integration and its flow into the production environment. A key objective of B.24 was not to track data but to understand the meaning of the information with regard to quality, risk and overall performance measures for the programme. Due to the large volumes of ETO information, it is important to understand what information is useful for what context and lifecycle phase. For example there will be supplier information, such as weight data, which provides important input into the overall weight management of a Naval Ship. This information is required to be captured and understood, while other data such as raw material information for pipes will not have the same value to the overall design.

The control of the BoM enabled through-life was identified by 0 as an objective with PLM enabling this through product structures and associated metadata. B.7 made a similar point when it was stated that it is important to understand how to structure the data by breaking it down into manageable chunks to support the build. This leads to the creation of the engineering BoM. The important information on ETO products consists of those internally generated within the programme and that provided externally such as from suppliers. This includes, but is not limited to, the BoM, documents, drawings, 3D model, which describes the product maturity and the configuration status of the product, and change management information.

B.18 stated the importance of PLM providing a means to integrate the information to product artefacts such as schematics to ensure that the design 'hangs together'. PLM enables the business to react to emergent challenges due to information provided by the supplier which helps the development of the product, 'the language of engineering has to be data'. B.23, B.22 and B.27 all highlighted the importance of PLM throughout the lifecycle, ensuring that it promotes integration of information through to in-service support and disposal. Therefore the information must be integrated to ensure it provides a complete representation of the product and assists the programme in understanding its status and for managing emergent challenges, such as information changes from suppliers which impact the design.

B.5 specifically raised the importance of how controlling data through the design and build phase enables the leveraging of this investment when in-service. B.10 stated the importance of being able to retrieve information on components once they have been installed in order to establish when it requires maintenance and also to replace the item with another with the same form, fit and function. The environmental information is also critical with B.10 having to consider the radiation that these components have been exposed to when planning maintenance. This establishes the importance of planning and managing the information through-life so that each life phase can be supported. As ETO products have a long-lifecycle there may be a focus on early phases such as system design to the detriment to later phases which may be years' later, such as manufacturing and in-service support.

7.4.1.2 Single point of truth to capture evolving product information once and use many times to reduce duplication and increase quality

Evolving product information throughout the NPD lifecycle must be captured and managed in a single point of truth to ensure that it is not duplicated in unintegrated multiple environments where there is a risk of misalignment and resultant quality issues.

A key objective, as described by B.3, is to capture, organise and share information to enable immediate response to business needs. B.7 stated that there is a need to collect data across the products’ lifecycle such as concept, build and commissioning as well as to review information captured throughout the products’ lifecycle which was supported by B.14. B.1 stated an objective is to source everything from their PLM environment through writing the data once, using many times, and having a single point of truth. The importance and challenges of information reuse is also described in literature including by Brunsmann and Wilkes, Baxter, Ball et al., and Sivaloganathan and Shahin [29], [34], [49], [51].

B.2 spoke of the importance of being able to trust the information and of it being from a single source. B.4 described the problems that their business faced with various in-house developed data systems and how they are currently moving towards a single integrated approach. B.25 spoke of his experiences with BoM misalignment across different PLM systems which were using the same information. He gave an example of where the procured BoM did not align with the design BoM. Each BoM through the evolving lifecycle of an ETO product is managed at a different level such as with the procured BoM being at the parent level but the design BoM broken down to levels to support manufacturing. When these become misaligned, such as due to design change, it causes quality issues and rework which has significant cost and schedule implications especially in build. B.7 stated that it has been recognised that there have been data quality issues across the systems used, but this is now being addressed with activities underway to improve alignment across the toolsets, including CAD, PDM and ERP. This integration of information, process and technology was identified as a requirement in the Type 26 case study as discussed in Section 5.4.

Gonzalez and Alonso discussed the importance of PLM systems integration with CAD and PDM in Naval Ship and Submarine NPD and how it improves quality and reduces costs [54]. Therefore where there is a requirement to share information through multiple PLM systems, these must be integrated to ensure that there is a managed gateway to share from the single managed source where quality is assured. This information must be trusted and easily accessible and retrievable to ensure an immediate response to business needs.

7.4.1.3 Management of product configuration and emergent change

Due to its long lifecycle and complexity the configuration of ETO products must be managed and baselines captured at appropriate points to provide assurance of completeness and correctness of the design. Lyon described Configuration Management as: 'a management discipline used to capture and control data', and went on to say that it is required for managing information in an extended enterprise but is challenging for people, process and technology [8]. CIMData described the importance of configuration management in ETO products as there is a high volume of change which affects large-scale, complex, products, resulting in a critical need to capture, understand, communicate and action change concurrently with the design, manufacture and support phases [5].

The capturing of the configuration baselines are aligned with the lifecycle phases of the ETO product such as when a design area has evolved to a level of maturity to enable it to progress. An example is when a design area progresses from the assessment to the demonstration phase as illustrated in Figure 8. The baseline will be captured showing the status of the design that was used as the basis for the stakeholders to make the decision to progress.

B.8 stated that a key objective was being able to control and understand the various engineering baselines and be able to refer consistently back to them. This configuration of the design as it evolves was also stated as a key objective of PLM by B.14, who also highlighted the importance of configuration management in the PLM environment due to the time it takes for the design to evolve through the lifecycle. B.11 described how the management of multiple configured baseline versions should be from cradle to grave. An example of this statement is to ensure that baselines are captured at each important design lifecycle phase and can be reviewed if there is emergent immaturity issues discovered at later phases. Another example is to demonstrate to the customer that the configuration of the design is being managed throughout the lifecycle phases, improving quality of the product.

Capturing baselines for evolving design areas at the relevant lifecycle phase enables change management to be progressively deployed. This approach supports control of the design when it has reached the appropriate maturity level to enable the next phase to use this information to further evolve the product, without uncontrolled updates by other stakeholders. For example the system design of an area of a naval ship cannot be updated without a formal change once it has progressed through the assessment phase.

B.8 described how configuration management supports coherence, completeness and correctness of the data with a key objective being an efficient design with the minimal number of iterations after the design is constrained into change management. The assurance of completeness was also stated as an objective by B.16. B.27 described that their PLM environment ensures the configuration management of their product is managed effectively. Effective configuration and change management ensures the customer has a design which has been agreed upon and any differences to the agreed baseline are subsequently managed through a robust process. This also supports the organisation with proving that they have an agreed evolving design with the customer. This is important due to the long lifecycle of the design where different customer representatives can be involved in the same design area across many years.

B.24 stated that tracing information and the implications in terms of measuring maturity, quality, risks and performance, is a key objective of PLM and B.4 stated that effective configuration and change management ensures the information delivered meets the customers' requirements, such as delivering a BoM which they can use to plan maintenance. B.11 noted the importance of configuration management in the context of variant and applicability management. Commonality is required to be managed across variations of products such as with a gas turbine room which could be the same for three variants of a product, however the weapon systems could be different. The Global Combat Ship (GCS) is a good example of this: they are based on the same product with the Type 26 being the reference ship, but the UK, Australia and Canada all have different radar systems. The differences in these design configurations are required to be managed.

Therefore, the PLM implementation must be able to manage differences across variants based on customer driven changes or obsolescence. As discussed in Section 3.5, change management is extremely challenging within ETO products due to the iterative nature of the new product development process and the emergent design changes this presents. Section 3.5 describes the long lifecycle of the development of the product and how the impact of change increases as the design matures; often these changes can be of a high volume which was raised by B.1. This was supported by the interviews, with B.23 emphasising the importance of managing engineering change, regardless of the size, and the consequent cost impact. Without the effective management of change the cost to the programme will be greater than that of the change management process. This point was supported by B.25, describing his experience with significant cost implications due to change, once production had started.

These cost overruns can be related to the level of change late in the lifecycle which result in rework in the manufacturing phase, for example, when there is a late or poorly managed change. Once the design is authorised that it is mature enough for manufacturing to begin, the design is configured into a baseline and locked into change control. After this point, the cost implications of any rework can be considerable, as shown in Figure 6, in Section 2.4.2. The reduction in rework is a business objective of PLM in ETO products.

B.2 and B.23 both highlighted the importance of a configuration management approach to manage the product with project management principles to manage the change process. This ensures that control mechanisms can be utilised to ensure downstream processes, such as detail design, planning or manufacturing, can be executed using stable information. It will support the understanding of the impact of change and that the embodiment of potentially large volumes of emergent change is managed throughout the lifecycle. It will also ensure that the customer agreement on the status of the product is agreed and captured.

7.4.1.4 Manage security, export and IPR obligations

The PLM environment must ensure that the information is appropriately classified with regard to its security, intellectual property rights and export with the access constrained to those with the appropriate rights. These PLM requirements are discussed in literature in Section 2.1 such as with Tauchen who stated that managing export information is a critical business objective with PLM being a key enabler for meeting these requirements [24]. Others such as Jarrett and Taylor discussed the regulations of those who operate in the defence sector that face heavy fines for breaches [23]. These regulations include security and export controls. Stjepandić et al. discussed the importance of managing IPR and the implication of it falling into the wrong hands [26]. ETO products have multiple organisations that operate across the extended enterprise. These organisations may be partners in the extended enterprise but competitors outside [2]. The management of export and IPR in ETO products increases when there are multiple variants, such as with the GCS. The UK, Australia and Canada have different security requirements resulting in careful consideration required when sharing information. Each country will also have their own IPR as will the supplier's involved in providing information of their products for integration into the systems of systems. Some of these products will also have export regulations, such as ITAR, which are required to be managed to ensure only those with approval can view the information.

B.23 highlighted PLM will help to manage the challenges associated with ITAR. B.20 described the importance of security and resilience. There were limited interview responses relating to security export and IPR due to the interviewees discussing the specific objectives they required their PLM environment to support. Security, export and IPR are standard objectives which are required across an ETO product such as naval shipbuilding. These obligations are a critical requirement of PLM especially in the defence industry where the existence of the business is dependent on being able to manage security and export regulations. An example is with B.1 who raised IPR as a PLM challenge but did not raise it as a PLM objective.

7.4.1.5 Management of evolving product maturity

Measuring the maturity of the evolving design is critical in ETO products. Maturity is managed to support decision making and to fully understand the status of the programme. This is due to the design evolving throughout the long lifecycle of the product based on the phased delivery of information from suppliers which is used to progress the design. Hicks and McGovern described maturity management as an objective of PLM in ETO products [9] and Lee et al. stated that PLM must be able to cope with the management of the evolving maturity of the product, especially as there is no physical prototype [38].

During design reviews, as stated by B.2, they use maturity levels of the information to understand risk; therefore, they can determine whether a level of maturity is sufficient to allow the design to pass the review, or whether it is deemed too immature to proceed.

The design maturity information is used by the programme to define the schedule, to measure its performance against the plan, to use as criteria for progress to the next phase of the programme, and to understand and mitigate risk. The maturity levels for the product are aligned to the programme schedule, so specific aspects of the product are identified as having a target maturity date for specific design reviews. This ensures that the evolving design supports the agreed manufacturing dates with the customer, and the programme risks due to immaturity can be identified and targeted for resolution. An example is the maturity of the propulsion system which must reach a level of maturity to allow other design systems to mature, such as HVAC requiring the mature wild heat data from the gas turbine. The maturity of the gas turbine managed in the PLM system enables the programme to reach a decision at the design review as to whether the programme schedule is at risk. The management of maturity to support the evolving product development and to manage the cost and schedule was also identified in the Type 26 case study as discussed in Section 5.1.

B.5 supported this link to maturity and programme schedule by stating that they use the PLM environment to understand the status of the developing maturity of the product, including all the information required for the next phase of the contract, including design artefacts, supply chain and the cost information. Managing maturity in the PLM environment was further supported by B.16 who stated the importance of establishing a maturity level to define a standard of completeness for entering the build phase. B.20 stated that they take a hard line on maturity before manufacturing; therefore the maturity status of the product must be fully understood by their programme management.

It is critical that when elements of the key maturity targets for the product have been reached, configuration management rules can be established to constrain the product into change control. This provides a mechanism for stability for the next phase of the programme. An example is between the system (assessment) and detail design (demonstration) phases. Once the system design has reached maturity, the relevant information is constrained to change control to allow the detail design to progress with the knowledge that any changes will be driven through the change process. The same principles apply for each phase of the programme such as entering the manufacturing phase.

The importance of maturity management was also highlighted by B.1 who described how maturity is raised in every programme discussion by senior management and B.24 stated that a key objective was the tracking of maturity information.

7.4.1.6 Up-to-date, traceable, relevant and configured information that can be accessed

PLM must ensure that the ETO programme can capture and manage product information and its provenance using a methodology which ensures it is configured, easy to access and understandable by all stakeholders in all geographical locations. Matsokis and Kiritsis stated that the PLM environment must capture information and provide traceability throughout the lifecycle of the product and also that it must be useful and not just a data dump [32]. Tang and Qian highlighted the importance of version and audit management of the product information [33]. Brunsmann raised the importance of being able to retrieve and understand the information easily. The interview responses support these requirements including B.2 who stated the importance of other business functions being able to access information provided by the owner. The example provided was manufacturing planning which uses the master information provided by engineering to plan activities. PLM must ensure that multiple stakeholders across the lifecycle have access to mastered, not duplicated, information and that it can be utilised at the point of need. This also relates to the configuration and change management objective discussed previously, where any changes to the information must be communicated to those who are utilising it for downstream activities, such as engineering changes which affect planned manufacturing activities. The captured history of the information in the PLM environment enables those who utilise this information to understand at what point it was changed and why, therefore supporting the impact of any changes, or design evolution, on their activities. The integration of the BoM, its level of detail to support all the business functions and its relationship to product change management was identified as a requirement for the Type 26 case study as discussed in Sections 5.2 and 5.3.

The stakeholders require efficient and easy access to information across the entire lifecycle and extended enterprise. These stakeholders within a naval shipbuilding context include the customer, engineering, supply chain, manufacturing planning, manufacturing, programme management, finance, safety, testing and commissioning, and in-service support. B.17 described the need for helping to enable geographically dispersed teams to collaborate, which is important in an extended enterprise such as Type 26 and has an even greater significance in the GCS where the stakeholder will be in different time zones. B.3 stated that capturing, organising and sharing information to support immediate responses from stakeholders to new or updated information as the prime purpose of PLM. This is to ensure that new information is promulgated throughout the extended enterprise and its impact assessed and understood by all relevant stakeholders across the entire lifecycle. This is critical in ETO products due to the emerging information throughout its long lifecycle and overlapping phases in design, planning and manufacturing which if not managed will result in incorrect or out of date information being used with subsequent quality, rework, schedule and cost implications. Consequently, updated information is required to support evolving maturity but may also result in a quality impact which may have further repercussions in manufacturing rework. An example is a change to an electrical interface point on a gas turbine which results in the CAD model update of the part and the related electrical routing design. If this information is not easily accessible, the change not understandable and the impact clear to the manufacturing planning team then it could be overlooked. This could result in rework in the manufacturing phase where it is expensive to fix with the subsequent cost and schedule implications.

B.6 described how the ETO product is developed based on information provided by suppliers and that the PLM environment assists them with relating to unanticipated problems. Ensuring that all business functions communicate effectively through PLM was raised by B.15 as being a key objective. Consequently, when data is captured, it must be configured in a way that is understandable by all the functions. Examples of this are through the use of metadata against the part which defines its key technical parameters and are used by numerous stakeholders in the design and manufacturing of the integrated product.

Having easy access to the relevant information is also important to not only allow the customer to interrogate the product to determine alignment to their requirements but also to demonstrate that there is a robust approach to information management, which is an important enabler to customer satisfaction as raised by B.26. B.5 described how this also helps to sell products as it provides evidence that information is managed which improves cost control and lowers price. This was an important consideration with the success of the GCS as the Australian and Canadian customers clearly expressed that the management of the product information was a key requirement. B.14 stated that the PLM environment supports design collaboration across a wide range of stakeholders and is the repository of information across the lifecycle of the product, and which again was an important factor in the GCS bid.

7.4.2 Process objectives

Effective PLM business processes are important for any NPD and those objectives identified in this section are supported from literature which can relate to ETO or other product types. ETO products differ due to the complexity and uncertainty throughout the lifecycle which requires these processes to be adapted to support these differences. This section describes those process objectives for PLM on ETO products which have been identified from literature and synthesised from the interview responses through thematic analysis. This enabled subsections to be created which describe the process objectives.

These objectives include supporting the design and build for product safety and environmental considerations. Enabling quality through right first time to reduce rework is an objective due to the lack of a physical prototype which would otherwise mitigate build issues. Processes to support product development and build collaboration across all stakeholders in ETO products is important, as is ensuring that the schedule and cost is managed to maximise profit, to reduce risk and provide value for money for the customer. As ETO products are highly customised, identifying and enabling standardisation in design and build is another objective discussed in this section. The process objectives in the framework are illustrated in Figure 27.

Figure 27 Process objectives

7.4.2.1 Support the design and build for product safety and environmental considerations

The design, build and in-service support of an ETO product must ensure that Safety, Health and Environmental (SHE) obligations are managed. PLM will support this objective through providing processes which enable the necessary SHE information to be captured and managed throughout the product's lifecycle. As discussed in Section 2.3, PLM supports NPD in relation to meeting SHE regulations. Stark stated that not only will PLM assist in capturing and formatting information to meet SHE regulations, but will also provide audit trails as why decisions were taken [27]. Duque et al. and Barreto et al. discussed how PLM supports green manufacturing and sustainability by tracking materials used in the product throughout its lifecycle. This is supported through the interviews such as with B.1 who stated that PLM provides evidence with regard to the management of information to support product safety. Providing evidence of design for product safety is an important element of NPD and PLM could provide this evidence when required. On investigation of previous product failures such as with the Nimrod crash, a lack of evidence of design for product safety has been identified and included in recommendations for improvement [57].

The challenges specific to ETO products described in Section 2 require robust PLM processes relating to SHE such as ensuring correct data formatting and attribution, but as stated by B.24, PLM also supports involvement from the product safety team to ensure they can influence the design. This is achieved in a number of ways including access to the emerging product information across the extended enterprise throughout the lifecycle. As the data is structured in a configured way with a full audit history displaying how the data evolved, then it makes it considerably easier while undertaking the business processes to understand any SHE implications. B.20 also stated that safety considerations are a key business objective for PLM. This enables the NPD stakeholders to support and monitor the evolving product development ETO products throughout its long-lifecycle and provide SHE reports directly from the PLM environment. It will also provide evidence to the appropriate regularity bodies that SHE legislation is being met.

7.4.2.2 Enable quality through right first time and reduction in rework

As discussed in Section 2.4, ETO products lack a physical prototype and have overlapping life phases with design areas reaching maturity as different times with emergent product development behaviours impacting the programme. Hicks and McGovern stated that ETO products are subject to product change through the lifecycle of the programme [9]. These can result in quality issues which can have a significant impact on the programme schedule and cost due to rework. The cost of quality increases as the programme matures, with resultant cost, schedule and reputational damage.

Quality is a topic which was consistently discussed in both the literature and in the interview responses. The literature in Section 2 highlighted the role that PLM has in improving quality and reducing rework throughout the lifecycle of the product. B.2 and B.25 raised a key objective for PLM to support the reduction in rework due to improving quality, therefore reducing cost to the programme. B.12 provided the example of lifed items, which are those components which have a specific life then they are required to be replaced, e.g., hoses connecting equipment items. The information and related processes must be managed effectively, including item description, location, fitting date and maximum life span before replacement.

In ETO products, these components number in the many thousands, so a poor PLM implementation in this respect, will result in considerable cost in the manufacturing phase as the programme stakeholders attempt to understand what items need replacing and when. B.10 and B.20 both stated that in hazardous ETO environments such as a nuclear facility or a particle collider, the quality considerations are critical as rework has a considerable cost: once an item has been fitted in a radiated environment it cannot be easily removed. PLM supports improving quality and reducing rework by managing the evolving design, build and maintaining the product in-service, and assists with the management of emergent product development behaviours throughout the product's lifecycle. This includes identifying the implications of these behaviours to ensure that quality is not impacted and rework is reduced.

Using PLM as an enabler to meet quality objectives and reduce rework allows organisations not only to better protect their cost and schedule, but also to protect against reputational damage associated with poor quality and cost and schedule overruns.

7.4.2.3 Enable product development and build collaboration across all stakeholders

PLM is required to assist with the mobilisation, integration and collaboration of stakeholders throughout the lifecycle of the ETO product. Due to the scale and long-lifecycle of the ETO product there are thousands involved who have various skills and functional objectives. They will be in different geographical locations and from different organisations. This objective has increased in importance for the GCS, as Australia and Canada will integrate their specific product requirements into the Type 26 reference design. As discussed in Sections 1 and 2.2, enabling collaboration throughout the NPD process is a widely considered and fundamental objective of PLM in the literature. Gomez et al. highlighted how PLM removes traditional problems of silos of information and will enhance collaboration across the extended enterprise [35]. The ability to mobilise disparate and physically dispersed stakeholders towards collaborating on a design was also captured throughout the interviews by B.14 and B.17. Examples include the integration of engineering processes with those of manufacturing planning to ensure that the design can be effectively built. This also allows manufacturing planning to have visibility of the design to allow them to undertake their planning processes earlier, therefore reducing the lifecycle of the programme and as a result reducing risk. This was raised as a specific requirement on the Type 26 case study as discussed in Section 5.5. The same can be said for other business processes such as collaboration with engineering, product safety and the commissioning of the build as raised by B.2. The interviewees did not widely raise collaboration as an objective of PLM considering its importance and relevance. This may be due to collaboration using PLM being a fundamental requirement for their organisations and accepted, similar to security, export and IPR requirements.

The PLM processes deployed must ensure that each stakeholder understands how to achieve their deliverables including the interfaces with the processes used by other business functions. These processes may be used by thousands of stakeholders across multiple geographical locations. ETO products will reply on PLM to support understanding of the emergent process behaviours such as product change, and its impact on the various business function processes.

7.4.2.4 Cost, profit, risk reduction and value for money

There is a history of significant cost and schedule overruns in large scale complex projects as described in the literature in Section 2.4.1 and illustrated in Table 2 in Section 2.4.1. These overruns include public and private financed projects. An objective of PLM is to assist in the management of risk through processes which enables the capturing and presentation of the programme information. This supports the management team in identifying and reacting to programme performance.

The need for cost management as an objective for PLM was also captured within the interview responses. B.22 stated that PLM must support profit for the business providing more for less, and supported by appropriate metrics. B.5 stated that information is the building block to drive and sell your product, and that if you can control your information, you can better control cost and therefore your price. Without PLM there would be no effective approach to the management of the programme cost and schedule. The importance of profitability to an organisation is raised by B.26 as a key objective of PLM. This is due to the ability of PLM to reduce rework and as a risk reduction for exposure to warranty costs. B.26 stated that PLM is a key resource for customer satisfaction through providing value for money and improved assurance that the product meets the customers' requirements. B.24 stated that PLM helps to understand customer risks; therefore, they can be managed more effectively which will drive risk reduction. Therefore PLM will also assist in managing the programme performance and for providing assurances to the customer that they are receiving value for money by proving appropriate metrics on programme performance, such as with the design maturity against the plan or the status of identified risks.

7.4.2.5 Enable standardised design and build

As described in Section 3, the literature on PLM for ETO products is sparse. The objective of providing standard design and manufacturing processes to the design and build of large-scale, complex products given their unique challenges is not widely discussed. Pulkkinen et al. discussed how PLM can enable the standardisation of manufacturing processes, but also commented that further research was required in order to achieve this [156]. PLM enables standardisation of processes such as with the Siemens Process Framework [157] but these do not provide guidance on the challenges of ETO products and the difficulties with standardisation. These challenges include the highly customised nature of ETO products as discussed in Section 3.4. This results in difficulties with standardising design and manufacturing processes. The lack of a physical prototype as discussed in Section 2.4.8 means that design and manufacturing processes cannot be refined using prototypes. Due to the highly customised nature of ETO products and the lack of a prototype, there are a significant number of processes which are non-standard and therefore not repeatable, especially in the build phase. This leads to inefficiencies and risks to quality and safety due to the limited opportunity for continuous process improvement. A requirement was identified in the Type 26 case study for repeatable standardised manufacturing processes as discussed in Section 5.8.

An interviewee captured that a key objective of PLM was to enable standardisation in the design and build. B.12 stated that there was a need to introduce standardisation as the whole product could not be prototyped; instead prototyping aspects of the product, examples include identifying repeatable manufacturing processes in build and relating back to the design process. This is discussed further in the Type 26 case study in Section 5.8. Therefore an objective of PLM is to assist in the identification and management of processes which can be standardised, with the resultant opportunities for continuous improvement. These improvements can be used to influence other stakeholder processes, such as improving design for build or support.

7.4.3 People objectives

For a PLM implementation to succeed on any NPD those objectives which relate to its people must be understood. The people objectives described in this section are similar to those in other NPD projects but there are specific differences with ETO products compared to other product types which require the objectives to be tailored to meet the ETO product’s needs. This section describes those objectives for PLM on ETO products which relate to people. These have been identified from literature and synthesised from the interview responses through thematic analysis resulting in the creation of sub-sections.

The people objectives include enabling collaboration across multiple-sites when the ETO product has many thousands of personnel interacting across multiple geographical locations who have different skillsets and experiences. Demonstrating to the customer that the product meets requirements is another objective as the ETO product is highly customised to meet the needs of one or a few customers. This is also important as there is a long design and build lifecycle and neither the customer nor the organisation responsible for delivery can wait what could be many years before the product is complete, to determine whether it meets requirements. Supporting organisational knowledge management and learning is important as the programme personnel will have different skillsets and experience which will require PLM to support the integration of their business functional output with that of others. Using PLM to support the improvement of decision making is another objective in ETO products as this can be difficult due to the multiple business functions and the large volumes of information which without PLM would be difficult to manage and interrogate. The process objectives in the framework are illustrated in Figure 28.

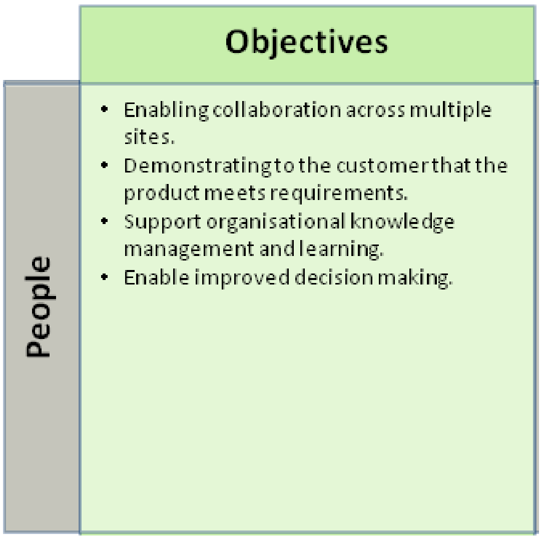


Figure 28 People objectives

7.4.3.1 Enabling collaboration across multiple-sites

The increase in globalisation has resulted in the growth of engineering collaboration [158], and ETO products are no different. ETO products require significant facilities for build and highly skilled personnel which are difficult to obtain. To gain access to these resources results in stakeholders being located in geographically dispersed locations with many thousands collaborating, include industry, suppliers, the customer, and the user. There are benefits for ETO products but the difficulties are considerable because of the unique challenges of ETO products as discussed in Section 2.4. This geographical dispersion of facilities and personnel, such as with the GCS who have resources throughout the UK, Canada and Australia, can result in disconnects such as with new information through the evolving product or change, and communication between engineers in the design process. These disconnects can occur throughout the lifecycle of the programme, as those involved do not engage in physically interaction or are separated by time zones to progress the design and build, identify issues and resolve problems.

PLM supports collaboration across multiple sites through capturing and sharing the right information at the right time in a structured way to those who have permission, resulting in improved and more accurate decision making [158]. This does not replace the personal interaction that is required between stakeholders but rather is a foundation to provide appropriate and effective support for information and process oriented collaboration. Examples of collaboration can be on 3D models where visualisation technology has improved product development across locations both nationally and internationally [159]. An example of this is with 3D CAD visualisations being used by the GCS to improve design reviews by reducing travelling and giving stakeholders access to the CAD model in a 3D environment. These CAD models are enhanced by relating engineering and manufacturing metadata such as attributes [158], related documentation or change information. These reviews can engage non-CAD specialists due to the high performance but low network bandwidth visualisation tools which allow interrogation of the 3D CAD model integrated with the BoM. These are packaged in most industry-leading PDM systems, such as Windchill and Teamcenter [158]. ETO products such as the GCS benefit as hugely complex spatial CAD models can be shared in lightweight formats with stakeholders across the globe, improving collaboration in the design, manufacturing and customer acceptance processes. This collaboration will differ depending on the objectives of the stakeholder; it may include capturing and sharing of information to progress the electrical design, to support design reviews, for progressive customer acceptance, or for collaborating on 3D CAD development.

7.4.3.2 Demonstrating to the customer that the product meets requirements

PLM must provide the customer with the assurance that the product development meets their requirements and that it will be achieved to cost and schedule. ETO products are highly customised and must ensure that it meets requirements before the product is complete, which may be many years after contract award.

B.24 described a key PLM objective was for information to confirm that the solution being developed meets the customer requirements and that it will be achieved to time and budget. This is particularly important with ETO products that are often government funded as they require evidence of taxpayer value for money and that they meet the strategic needs of the nation. This is important as they are often scrutinised carefully by politicians and the national audit office. The requirement of providing evidence of taxpayer value for money was also identified by B.20 as a key objective for PLM.

B.18 indicated that requirements decomposition and management is a key PLM objective. PLM can assist with not only requirements decomposition but also relating the design solution to the decomposed requirements assisting with customer acceptance. Relating the design to enable customer acceptance was stated by B.25 as being a key objective. It was stated that the design definition as managed and presented by the PLM system of systems, when handed across to the customer, should help to maintain the product through life. This is a key requirement for any ETO product whose design for support and in-service support is hugely expensive. B.25 also stated that this design definition will help to be internationally competitive for export bids. Staying ahead of competition is a considerable benefit given the major export bid wins for the GCS which had competitive bids by major Naval Shipbuilding companies for the Canadian Surface Combatant (CSC) [160] and the Australian SEA 5000 programme [161]. However B.25 also warned that it must be efficient and not adding cost for no return.

The relationship between the requirements and the design supports a quality product with customer satisfaction and aids in customer acceptance and concluding contractual obligations as raised by B.21, B.26 and B.27. Customer acceptance is challenging in ETO products due to their highly customised nature, long-lifecycle and complexity. Industry would prefer a progressive acceptance process as early in the programme lifecycle as possible, as this mitigates a considerable risk of the customer rejecting elements of the finished product. Rejection of the finished product is an extremely difficult and expensive problem for industry to resolve. ETO products have a considerable amount of customer interaction in the programme lifecycle as discussed in Section 3.3. Relating their requirements to a customised product is extremely complex. PLM can mitigate this by progressive acceptance using the 3D CAD model and the integrated design information providing evidence of requirements being met. This can be achieved before manufacture commences which mitigates expensive rework in build. The results of acceptance can be captured in the PDM system and related to the requirements system, with the appropriate approvals, years before the actual handover. This approach lessens the risk at customer handover which may be ten years after the design is agreed and where different personnel may have different perspectives on the requirement, design and finished product. It will assist with monitoring the design and build which provides ongoing evidence to the customer and enables lifecycle phases to be passed. This evidence based approach is important due to the long-lifecycle of ETO product development where personnel will change and agreements otherwise potentially misinterpreted or forgotten. This progressive acceptance will contribute to the customer having the necessary mechanisms for them to maintain the product through-life, as any support issues can be identified earlier in the product lifecycle.

7.4.3.3 Support organisational knowledge management and learning

PLM must support the capture of knowledge within the organisation and enable its reuse to improve business performance. The huge investment in the ETO product means that efficiencies in sharing knowledge can enable significant benefits through improvements directly to the product itself or indirectly through enhancing the skills within the business.

This reuse of product knowledge with PLM enables product knowledge capture and sharing across the programme's lifecycle [162]. An example is with product change management which is used to drive improvements through correcting identified differences from the baseline design. Implementing improved methods to the product development process to capture knowledge using PLM will bring benefits to the product development process by capturing, structuring and processing information that is generated and therefore transforming experiences into knowledge that can be used by the business stakeholders [163].

B.6 described how PLM can be used to capture and configure knowledge from the engineering environment, in order to support manufacturing. The PLM environment will provide mechanisms, such as the change management process, to capture and manage improvements to the ETO product design, build and support. As ETO products start manufacturing before the design is complete, there is inevitably a risk associated with the volume of product change to the configured baseline. This may be due to corrections to resolve issues identified later in the lifecycle, or it may be to include additional maturity information which requires the design to be updated from what was agreed through the design reviews.

The knowledge used to manage changes can be captured and reported through means such as attribution and relationships to the affected product artefacts. As ETO products have emergent challenges throughout its lifecycle, capturing why these changes occur will help with their resolution and for future avoidance. This knowledge should be used to directly enhance processes and information management approaches. These may be within specific functions, such as with manufacturing planning, or capturing knowledge from manufacturing back into the design through quality queries or formal change management. This will improve the quality of future build sections where engineering has not yet completed due to the phased lifecycle of the ETO product, i.e. manufacturing starting before the design is fully complete.

7.4.3.4 Enable improved decision making

PLM provides a managed and structured approach to present configured information which can be trusted. This enables the stakeholders to make informed decisions on the ETO product. The information must be captured from the various business functions and have appropriate reporting mechanisms based on the requirements of the stakeholders. Sääksvuori and Immonen stated that PLM improves decision making and decreases approval time by capturing and sharing information in a structured way [17].

PLM provides accurate information from the BoM which includes supplier delivery lead times which is used to leverage the market for the best possible deals, as highlighted by B.17. This also supports the customer value for money PLM objective in Section 7.4.3.2.

PLM enables multi business function integrating across detail design, supply chain, manufacturing planning and system design by publishing the physical design for review by these stakeholders as stated by B.14. The more informed decisions that can be made by these stakeholders using the information managed in the PLM environment as the greater the benefit to the ETO NPD.

B.24 raised the importance of generating and using reports from the PLM environment to integrate the design and enables an improved understanding of programme status. PLM can assist with reducing decision making and approval timescales by leveraging the structured information through the reports to provide an immediate, up-to-date status of the programme. B.24 went on to highlight that identified issues can be used at the gate reviews, and used to evaluate the design and agree whether the product is at a level of maturity to progress to the next phase.

7.5 Challenges of PLM implementation within ETO

This section synthesises the interview responses in relation to the challenges with PLM implementation on ETO products. As shown in Table 10 in the Section 7 introduction, Question 4 was used to capture the typical challenges faced by the interviewee when utilising PLM. Question 9 was used to capture any further challenges which the interviewee believed would impact the transitioning from an as-is PLM environment, to one which incorporates the improvements they require. This approach was designed to capture any further challenges that the interviewee may not have considered in Question 4 as they had not yet been asked and considered what improvements they require in a PLM environment to meet their business objectives. Questions 10 and 11 were used to prioritise their challenges in terms of impact and effort if there were more than one challenge identified. This was used in the thematic analysis to determine what challenges had the greatest significance.

The following subsections are the challenges of the PLM implementation framework and are structured by those which relate to Information (Section 7.5.1), Process (Section 7.5.2), People (Section 7.5.3) and Technology (Section 7.5.4). There are related to the challenges with PLM on ETO products as described in Section 2.4.2 but are captured at a more detailed level based on the experiences of the interviews.

7.5.1 Information challenges

There are information challenges relating to PLM in any NPD environment but those which relate to ETO products differ at a detailed level as they must manage large volumes of information with various levels of importance which are not stable throughout the various life phases. This section describes those information challenges for the implementation of PLM on ETO products which have been synthesised from the interview responses through thematic analysis.

These includes identifying, managing and presenting emergent complex information for management decision making where there are large amounts of information which have various levels of importance throughout the lifecycle of the product. Another challenge identified was integrating complex product information through-life across multiple toolsets where the same information is used to support a business objective in different technology environments by different business functions but can become misaligned due to the evolving design or through product change.

The management of product information maturity and its relationship to change, configuration, schedule and cost was identified as a challenge. This is due to the maturity of the product information being used to understand the status of the programme but is required to have configuration management and change control applied to provide stability to the design. This presents difficulties due to design evolution and emergent change resulting in additional work-scope which had not been planned or costed. The information challenges in the framework are illustrated in Figure 29.

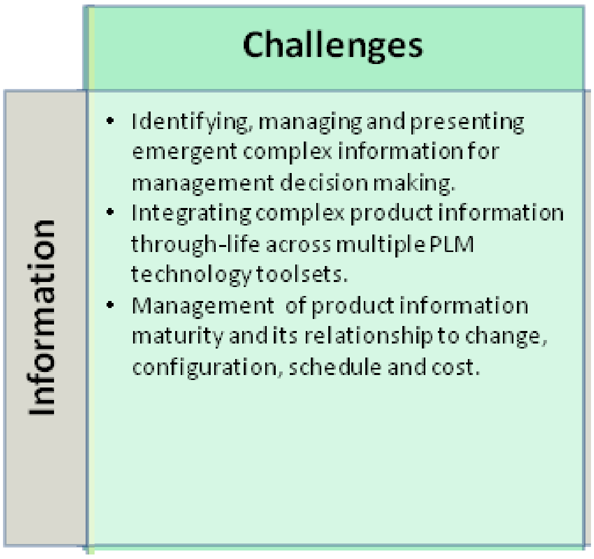


Figure 29 Information challenges

7.5.1.1 Identifying, managing and presenting emergent complex information for management decision making

There will be difficulties with the identification, management and presentation of product information in the PLM environment for management decision making in complex ETO products. This is due to the information which can relate to areas of significant programme importance but are difficult to identify within the large volumes in the PLM environment. The importance of information will also vary as the programme progresses through the lifecycle phases. For example, information on the 3D detail design CAD model will be of minimal importance in the system design phase of a Naval Shipbuilding programme, but will become increasingly important as the programme progresses.

As highlighted by B.6, there is a challenge in understanding the status of the programme and the identification and resolution of product issues which may impact the programme. With ETO products, the schedule is aligned with the product development lifecycle phase. Therefore if there are emergent product issues such as for example, the identification late in the design phase of a gas turbine cooling requirement for the HVAC design on a Naval Shipbuilding programme which requires rework, then this will have a direct impact on the schedule.

B.26 stated that there were different approaches to supply chain procurement across partners within their project, which impacted production activities; the simple example used was bolts not fitting nuts. Therefore, if information relating to supply chain activities is not managed effectively, and the issue is not identified through the PLM environment, then the consequential impact to the programme can be considerable, with the impact increasing later in the programme lifecycle, as shown in Figure 6 in Section 2.4.2.

Identifying what information is important to the programme is challenging when there are such large datasets with thousands of personnel interacting with them. B.5 stated that turning data into management information is problematic and that they are better at capturing data as opposed to turning it into management information from which they can make decisions. This is due to a lack of understanding of what information is important to whom and at what point in the lifecycle.

B.13 described that their product is data rich and people often lose sight of what is important. He went on to state the challenge of identifying when data becomes useful information; otherwise it’s just data with limited value and with a big overhead to maintain: ‘Seeing the wood from the trees’ is difficult. Measuring the programme performance is based on progressing product development but the large volumes of information and the emergent product issues impact the schedule. The later the emergent issues are identified the greater impact to the programme. Identifying what information will impact the programme is difficult due to the large volumes and the thousands of stakeholders interacting with it.

The PLM environment can capture the information but identifying what is important and presenting it to management for decision making is difficult. The PLM environment can become information rich but finding what is important at the specific lifecycle stage to identify and resolve emergent issues is challenging.

7.5.1.2 Integrating complex product information through-life across multiple PLM technology toolsets

There will be challenges with integrating the ETO product information throughout its lifecycle. The huge volume of information is constantly evolving and changing including at the point when it is required to be consumed by the large number of stakeholders from multiple business functions at various points in the programme's lifecycle. The information is required to be integrated from the authoring environment to the various systems which require it for their specific requirement. Examples are engineering data in the PDM system which is required for planning and procurement in the ERP system. Section 2.4.3 described the levels of complexity involved with ETO products which results in challenges associated with providing an integrated information environment across the programme's lifecycle. B.5 stated that their single biggest challenge was providing a single point of truth at any one time, whilst B.18 explained that she can query the functional and physical design, but requires to see an overall view of the product development across multiple PLM technology systems such as how the design in the PDM system is supporting the safety case in that system. Due to the significant information volume and the multiple technology systems where duplicate information is utilised by the programme, there are difficulties with understanding where the single point of truth is. The information is changing in one technology system but is being concurrently consumed in another. Examples are engineering data changing in the PDM system but this information is being used for procurement in the ERP system.

As identified by B.12, the challenge is how information flows from the engineering environment to the ship build, and how information is utilised throughout the lifecycle of the programme. He stated the example of the codification of parts in the design lifecycle which is understood by the engineers, but within the build it becomes difficult to understand what the information means. This may be due to design engineers possessing a different mental model of the product than manufacturing engineers. Therefore, as information evolves throughout the lifecycle of the product, those who use the information are from different business functions and may not understand what the descriptions mean. B.12 provided the example of High Pressure Sea Water system which was coded as HPSW in the past and was understood by the build team. However, as the codification changes to meet other business needs this has an impact downstream.

B.15 stated that there is a challenge with integrating in-service support requirements into the design in the PDM environment as there is a focus in their business on the engineering lifecycle.

As the engineering lifecycle phase can be close to a decade in duration, there is a challenge with identifying and enabling information management strategies for downstream activities such as manufacturing planning, build and in-service support. This is due to the uncertainty in the programme's lifecycle where information is constantly changing. B.24 stated that not only is it difficult to understand each other's data, but this gets harder as the team grows in size, and when you have a team of 1000 people split over a number of sites, it becomes very difficult. Ensuring that downstream requirements are captured in the engineering phase is difficult, especially if the engineering programme has cost and schedule challenges. Any quality issues or additional requirements that are identified by downstream information consumers, such as in the build phase, has a significantly greater effect than if it was identified in earlier phases as it will require rework with resultant engineering schedule and cost implications.

B.4 stated the challenge of reducing duplication within PLM, and cited the importance of using a common shared parts library. Duplication is a challenge of PLM in ETO products due to the large volume of data and the long lifecycle of the programme. Duplication can occur due to the same or similar information being incorrectly created more than once. Using the part library as an example if one engineer requests a particular part to be created, e.g., a valve, and another engineer creates the same part, there is duplication which will result in quality issues as both may become misaligned due to the differing technical attribution applied. This can also cause issues with the supply chain as the same part is ordered twice. Another example is with incorrect information used by manufacturing planning causing rework in the build phase, with the considerable expense this causes.

With ineffective information management and integration, there are many other instances where duplication will occur through the life of the programme, as there will be thousands of staff creating and consuming large volumes of information over many years, such as 15 years for a first of class Naval Ship build. 0 discussed the problems of data accuracy on previous programmes, but believes that the correct integration across CAD, PDM and ERP will assist in eliminating manual translation and data integrity issues. B.16 described the challenges of misalignment between CAD and PDM, and the significant cost involved with aligning data if not correctly managed. CAD and PDM can easily become misaligned on ETO products as the engineering phase includes years of design with the phases overlapping, as shown in Figure 6. In the system design phase, the information is mastered in the PDM system, which is then utilised by the detail design teams in the CAD system to create the physical 3D model. If the PDM system is updated, such as through emergent change and the CAD user is unaware, then both the system and physical designs have become misaligned. This leads to problems such as poor engineering quality, resultant significant cost increase and a schedule impact to the programme. Controlling the integration of product information, whilst a key challenge, is also a key objective as discussed in Section 7.4.1.1. This is supported by B.14 who stated that a key challenge of utilising PLM is data alignment across the CAD, PDM and the ERP systems.

7.5.1.3 The management of product information maturity and its relationship to change, configuration, schedule and cost

ETO NPD programmes have to ensure that maturity is appropriately managed to support decision making and to accurately reflect the status. It is also critical that when elements of the key maturity targets for the product have been reached, configuration management rules can be established to constrain the product into change control. This provides a mechanism for stability for the next phase of the programme; an example being between the system and detail design phases. Once the system design has reached maturity, the relevant information is put under change control to allow the detail design to progress with the knowledge that any changes will be driven through the change process. The same principles apply for each phase of the programme as illustrated in Figure 6 in Section 2.4.2.

Whilst configuration management is a well-practised discipline in many product types including ATO product providers such as Airbus, there are specific challenges with ETO products. This is due to large volumes of data having a variety of interconnection across various systems which are subject to increased 'velocity' of changes [11]. This is due to information changes impacting the product real-time which affects the management teams' ability to understand the maturity status, and therefore the status of the programme schedule. Therefore there is a challenge with providing stability and control mechanisms without impacting the progression of the design and build. The interview responses provide further information relating to these challenges. B.25 stated his belief that his programme over-complicates maturity, including in the system and physical designs. He also stated that maturity management adds value but stated that the progressive refinement of a system design does not necessarily mean that it is immature, just that the system maturity is progressively increasing.

There is a risk that the maturity approach can be overcomplicated resulting in configuration control too early in the programme's lifecycle with the further consequences of approved change management tasks required to update the design. This will result in additional burden to stakeholders who are trying to improve the maturity of the design and an increase in unnecessary change on the programme.

What may seem a simple change to one system may have a significant impact on another. This was supported by B.18 who described how technology cannot be used to understand the impact to product relationships and how they have been affected, therefore manual investigation is required. This is due to engineering effort being required to understand the impact of a change, technology can help to identify the relationships but knowledge is required to understand the impact to the programme.

The timing of applying configuration control is important as while the impact to the evolving design should be considered, it is important to understand the effect of product updates on the various interconnections of the design systems. This is a difficult challenge as if a design is deemed mature enough to pass the stage gate to go into the next phase of the programme, then a level of configuration control should be applied. However when additional information is added to the system design, then the formal change process should be applied. This is due to the level of complexity in ETO products where it is difficult to quickly establish the impact of a design update to the various interconnections throughout the lifecycle of the product.

0 stated the challenge is with how and when change management is implemented in the product's development, as inadequate information which was used to resolve design and immaturity issues has resulted in change. The relationship between what is design evolution and what is change was also stated by B.16 as a challenge with PLM. His perspective was from programme management where there is a team size agreed and the appropriate budget and schedule decided. The engineering schedule is linked to the maturity of the product and there are difficulties with identifying what is valid design evolution and what is a valid change which requires additional time and budget. As emergent changes affect the design the agreed schedule and budget is impacted as work which was deemed complete, then has to be updated. Therefore the challenges of maturity, change and configuration management is not just with developing the product but also with ensuring that the product can be delivered to cost and schedule.

7.5.2 Process challenges

This section describes the challenge of creating processes that meet business objectives and are not overly complicated. This challenge was synthesised from the interview responses through thematic analysis and was the only processes related challenge for the implementation of PLM in ETO products. The analysis of the interviews identified that creating processes to meet business objectives was required but that it is difficult to align this with processes which are manageable, flexible and easy to understand due to the level of complexity and uncertainty in ETO products. The process challenges are illustrated in Figure 30.

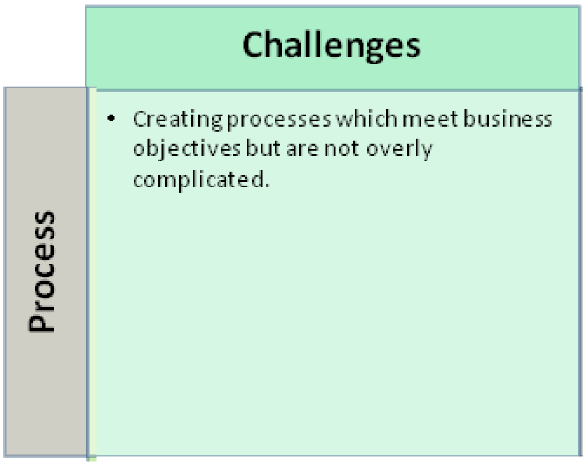


Figure 30 Process challenges

7.5.2.1 Creating processes that meet business objectives and are not overly complicated

There are numerous examples from the interview analysis where PLM processes which were developed and implemented to meet ETO business objectives have been over engineered. B.2 stated how they incorrectly made their electronic process workflows in the PDM system overly complicated and prescriptive, resulting in difficulties when something went wrong and needed to be fixed. The result was that they had to reengineer their workflows to make them simpler. The creation of complicated processes, including those which are replicated in the PDM workflows, is understandable given the complexity of ETO products, but flexibility is required to manage emergent product process behaviours such as change. Also, an objective of PLM in ETO products is to manage security, IPR and export obligations as discussed in Section 7.4.1.4, and these require PLM processes with multiple stakeholders and strict rules which if breached can have significant consequences.

B.1 stated the difficulties associated with identifying IPR information that cannot be shared across different ETO programmes. He used the example of a diesel generator which might have information embedded in the detail which cannot be shared with other programmes. A consequential failure to implement processes to manage obligations may result in a breach of security, IPR or export controls.

Another example of the challenges of managing process complexity is with non-recurring activities. ATO products typically have repeatable processes that can be refined and improved after many uses, with considerable learning reused in the next generation. B.16 highlighted the difficulties associated with planning for non-recurring tasks that are typified within the novel nature of ETO products, where the processes may be defined and used for the first time. He spoke of the difficulties with creating a programme plan if processes are at a high-level and cited the example of managing product reviews.

The challenge is therefore to achieve an appropriate balance between overly complicated processes that lack flexibility, and processes which are too simple and do not support the business objectives. Processes should also not be constrictive due to the level of uncertainty in ETO products. B.17 discussed the challenges related to the focus on schedule adherence when implementing improvements on the programme, one of which was not enough attention paid to realising strategic objectives. This balance between having the right level of process detail to manage uncertainty in the programme and having processes which can be applied to accomplish programme objectives and to measure cost and schedule adherence, as well as the overall programme performance, is a challenge that needs to be addressed.

B.12 discussed how their business is building a bespoke product which is tailored to meet customer requirements. He goes onto say that their requirement is more unique compared to other similar products, this necessitates tailored business processes. B.12 introduced new processes to identify products that can be manufactured repeatedly. This was a new approach with a greater level of flexibility, required in order to adapt their business processes as they learn through the ETO programme lifecycle. Ensuring these processes are not overly complicated is difficult when they have never been applied before. Another difficulty with ensuring processes meet the business objectives is guaranteeing that all the many stakeholders in the ETO programme are using the same approach. Differing, non-standard processes result in a significant impact to ETO product delivery. B.26 cited an example where partners in his programme have different specifications for testing, resulting in constant rewrites of the test specifications to meet business objectives.

It is also important to adhere to processes that have been agreed. B.2 described a challenge for the successful use of PLM is with process documentation, as people often work around processes, tailoring them to satisfy their need, and therefore problems or improvements are not captured as these workarounds are local and not documented. He goes on to say there needs to be more focus on processes adherence to support the PLM deployment. B.27 described a challenge with standardising processes is that they have a business model which was developed before their PLM implementation and the associated technology. He added that it is a challenge to standardise their business processes, not least because there are many different opinions across multiples programmes which go through different lifecycles. He stated that understanding what those processes are and what data is required to be managed is difficult, particularly for those who are new to PLM. Therefore, there is a challenge with integrating and standardising processes to meet the objectives of different programmes.

Overly complicated process will not only inhibit the ETO product design and build but will also lead to failures in meeting mandatory regulations such as safety, health, environment, security, intellectual property rights or export controls as onerous processes are bypassed. Where processes are bypassed workarounds are not documented and potential improvements are lost with problems not communicated to the responsible stakeholders. Due to the customised nature of ETO products and the lack of a prototype, processes may require to be created as the business objective or challenge emerges. This results in a novel approach which may have been used for the first time. Therefore there are difficulties with ensuring a process is fit for purpose before deployment, such as; managing security, maturity, design reviews or with business improvement initiatives in design or build. Other product types such as automotive manufacturing have repeatable processes which are proven and enhanced through testing on prototypes, and continuous improvement techniques such as Lean. There is also the challenge of ensuring that processes do not strip out necessary detail, and are therefore not fit for purpose, in an attempt to ensure they are not overly complicated. Processes should manage the uncertainty in the programme but also support the schedule and cost to ensure overall programme performance. This is difficult as each ETO product has differing customer requirements, such as an anti-submarine warfare frigate having a focus on managing underwater radiated noise, which results in tailored processes.

7.5.3 People challenges

This section describes the challenges relating to People for the implementation of PLM in ETO products and were synthesised from the interview responses through thematic analysis enabling sub-sections to be created. The analysis of the interviews identified that there were a significant number of challenges relating to people. These include education, adoption and understanding the value of PLM and its relationship to quality was identified as a challenge due to the difficulties with people recognising the importance of PLM to the business. Lack of expertise to enable and support PLM is difficult due to the various levels of skills required to ensure PLM is a success. Personnel's understanding of their obligations and through-life implications of their actions or non-actions in relation to a successful implementation of PLM is another challenge identified though the interview analysis. Understanding processes and toolsets and its relationship to through-life product information integration was also identified as a challenge, as were the difficulties with people working collaboratively across all business functional areas in ETO NPD. The people challenges are illustrated in Figure 31.

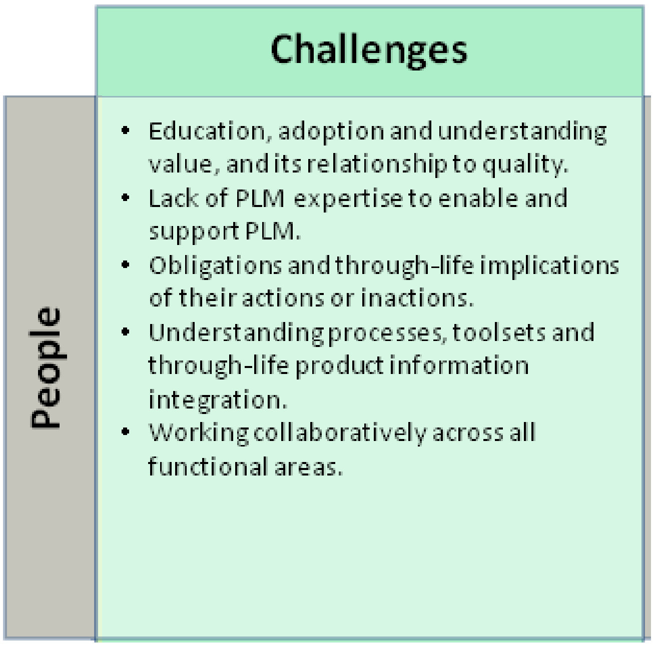


Figure 31 People challenges

7.5.3.1 Education, adoption and understanding PLM value, and its relationship to quality

ETO product design and manufacture are typically huge multi-billion programmes, where educating the necessary stakeholders and ensuring the adoption of PLM is a significant challenge. PLM means different things to different people and this lack of consistent understanding impacts the adoption of PLM. PLM can be perceived differently depending on the stakeholder and ensuring that the value of PLM is understood and is meaningful to the individual's role and objective is challenging. If this difficulty is not resolved there will be issues with data quality as the information in the PLM environment must be entered correctly and managed effectively.

B.23 highlighted that people's comprehension of PLM is a key challenge; they asked their employees if they understood PLM and discovered that it means different things to different people. He stated that getting an appropriate business definition was difficult. Therefore, ensuring that there is a unified and consistent definition of PLM within the business that employees can relate to and is aligned with the business objectives is critical. B.3 also stated that user adoption is a challenge when utilising PLM, as data quality is linked to user adoption as you need people to use it to ensure the information is current. If the stakeholders in the ETO products have not correctly adopted the PLM approach, significant problems will arise with its successful utilisation and this will have an impact on PLM meeting the business objectives.

B.14 described the relationship between people, data and quality as a challenge. He embellished this by stating that PLM involves getting the right quality measures in place as data is more important than ever, as you have more people manipulating it. He added that the biggest challenge is getting that quality culture into the organisation so they recognise that poor quality causes problems further down the programme's lifecycle. These problems are dependent on what information the engineer has been generating. Due to ETO products having a huge number of interconnections amongst their subsystems, these quality problems can have a significant impact on the programme. As shown in Figure 6, these decisions can incur significant costs to the programme, such as poor quality resulting in rework and the resultant cost and schedule impact to the programme, as well as reputational damage. Without full stakeholder understanding of their role within a successful PLM implementation and how this information is used by other personnel to enable the business objectives, there cannot be an effective data quality culture. Achieving this business understanding and quality culture is challenging due to the scale of ETO products, the high level of change and the large numbers of diverse multi-skilled stakeholders interacting with each other's processes and information. The long lifecycle of ETO product design and build also contributes to these challenges as it can be difficult for stakeholders to understand other personnel's requirements for the information throughout the lifecycle. Examples of this are relationships to data sources, for example early design information to manufacturing drawings, or with information required by the support team that was not provided in the design phase. These interconnections through-life can impact stakeholders' understanding of what their responsibilities are and can cause quality issues such as rework in the build phase with the related significant reputational damage that causes.

B.6 discussed the challenges relating to the amount of metadata at a part level and how this can be used to determine when an engineer has 'done their job'. She added that there are difficulties in providing support to engineers when some are traditional and others are integrators. Therefore there are those within the organisation who will work in a traditional unintegrated way to progress their objectives and there are others who will integrate engineering design. Different stakeholders in the ETO product development have diverse roles, such as a radar systems engineer who is responsible for the functional system design and another 3D CAD detail designer who is responsible for integrating this design into a physical CAD model. There needs to be shared situational awareness with clear, consistent and agreed understanding of what information is important, what the interconnections are, and what rules are required to measure the data quality.

B.8 expressed a clear understanding of the importance of PLM and of providing technical Suitably Qualified and Experienced Personnel (SQEP) and technology. However, he added that the value of PLM is not widely understood and that it can be undervalued and not seen as an enabler to the design intent. He also stated that, for a non-specialist, it can be seen 'as smoke and mirrors' and that perhaps what is being done, and why it is important, is not explained. This includes the importance of underlying data quality checks which some may see as an overhead. He discussed the balance between the time and expense of PLM with the return in this investment, the 'payback'. These include benefits in manufacturing with better quality and accuracy than could be achieved in a less constrained environment. He also linked the importance of people adopting and recognising the value of PLM to overall quality of the product.

The benefits to overcoming these challenges are improved quality throughout the lifecycle of the ETO product. This includes the multiple disciplines who are involved with creating and consuming the information at various points in the lifecycle. Examples are supply chain procuring material based on information created by engineering or a CAD detail designer modelling based on information provided by system designers: these activities can be separated by years.

B.4 raised business change management as a key challenge and cited the importance of incremental implementation with initial deployments followed by the next challenge. These incremental steps should assist with demonstrating value to those who are required to successfully use the PLM environment rather than with a large single deployment which takes longer and can have difficulties in showing value early. B.13 stated a key objective of PLM should be linking it with how users intend to use it. He says there are some in engineering who understand PLM, but there are those in other functions who do not, such as within manufacturing engineering or in supply chain. He cited an example of the supply chain team who purchase parts based on the information from the PLM environment. He stated that the business do not always equip their personnel with the skills to ensure they are integrated with PLM and that people often see it as a toolset, but policy, process and people are key requirements. This was supported by B.15 who stated that a challenge is including all the functions in the programme and having them working with the same process. He added that process is key, and it does not matter what toolset is used but you have to convince them of the importance of PLM.

B.4 stated the first and biggest challenge is that individuals do not understand the concept of PLM and they see it as a configuration management solution. He added that there is no effective education as to what PLM is and what it can do for them – the individuals that should be engaging with PLM are not sufficiently educated in it. B.19 described a PLM challenge is that the teams are disconnected, with the 3D detail designers' toolset is not integrated with the system designers' toolset. He added that the teams sometimes do not see the benefit of PLM and they need more training. The CAD team are those who undertake detail design with the 3D CAD system. The PDM team are those who undertake the system design within the PDM system. The main activities of these two teams can be separated by years with the system design being undertaken first, then at an appropriate maturity, the detail design phase is undertaken. Due to the size and complexity of ETO products, these phases involve many hundreds of individuals and are undertaken over several years.

0 stated a challenge with utilising PLM is one of people and ownership within engineering with B.27 also stating the challenge of changing organisation culture and trying to convince the company to use PLM. He added that they are new to PLM and it is difficult to change the business model. B.1 commented that educating staff is a key challenge, and he additionally described that there is an assumption that everyone understands top level PLM, and are motivated to populate it with information. He asked, 'where is their reward' and cited an example of a part owner who was required to populate data and asks 'what is in it for them', as the data was consumed by others. He stated that there is an assumption that everyone has bought into the benefits of PLM and its adoption, but he is not always convinced. Therefore, people are required to be educated so they fully understand what PLM is, what the value is to them and the organisation, and what is required from them to achieve these goals. This is a challenge given the scale and complexity of ETO products but developing and implementing an education and business management approach is critical to the success of PLM.

B.12 discussed the challenge of changing the culture to remove working in silos but warned against 'organisational thunderbolts' where there is enormous change within the business which needs to be managed effectively. There needs to be a balance between cultural change, and being able to undertake the programme effectively. Major business changes will cause disruption to the programme impacting schedule and cost as people are trained, which takes them away from day to day activities, also that it takes time to become experienced in the new approaches. B.15 described the importance of managing transformation and that a major objective is to win the hearts and minds of the people. He added that the various stakeholders typically do not understand each other's activities and challenges due to the size and complexity of the programme. He used the example of those in the manufacturing phase who do not understand the information used in design. This design information is high-value and requires changes to work practices which have to be managed effectively, which is why transformational projects take between three and five years. The cultural changes described by B.15 are difficult to overcome due to the size, long lifecycle and complexity of ETO products, which make it difficult to convince thousands of stakeholders why a change is happening, and what they are required to do to support it. Often these changes have implications which are not well understood at the point they were initially implemented.

B.1 raised a cautionary point with regard to providing education to the stakeholders. He believes the level of understanding should be appropriate to the needs of the programme to ensure that people are not overloaded with information. He elaborated that the programme assumes that there is integration and understanding across all the areas, but the product is so large that people only understand their part in the process. This challenge was also raised by B.2 who stated that as they have such a long product lifecycle, people cannot understand the whole integrated flow.

B.8 raised the challenge of people undertaking the same activities for years, and when transitioning to a new PLM environment, the PLM architects must be able to answer the 'what's in it for me' question that is typically asked. He added that to sell it, you have to satisfy self-interest by explaining either what the advantage is to the individual, or how it is not a disadvantage to them.

B.14 stated that a key challenge to realising the benefits to the enhanced PLM environment is the behaviour aspects, and the requirement of commitment from major stakeholders to ensure the implementation is successful. He embellished this point by stating that it is important to ensure that key individuals are exhibiting the right behaviours, as it is easy to take a negative view. This correct behaviour is required to support PLM information management, processes and technology approaches. B.23 also identified the challenge of business change management in implementing the PLM environment to achieve business objectives. He discussed the importance of ensuring that the message to the stakeholders is correct, as his experience was that PLM implementation is commonly seen as an IT project, and stakeholders subsequently wait to be told what to do by the IT function. This experience by B.23 requires a planned implementation of PLM to include ensuring that this is a business-wide change and not an IT driven activity. PLM must be viewed not just as a software system but as a means to manage processes, information and technology to enable people to function effectively to achieve business objectives. Programme personnel must be educated at the appropriate level to support their day to day activities. This is required to ensure they understand the part they play and the value of PLM in ETO products. This will be challenging due to other priorities, diversity of skills, personnel in different geographical areas and the long-lifecycle of the programme.

B.1 raised the challenge of getting commitment from stakeholders due to other competing priorities in the programme, for example when there is a lack of attendance at workshops and less than optimal engagement then this can weaken the programme. He added that if these stakeholders are not engaged, then they will later question aspects with which they were not initially involved. This problem of conflicting priorities is a challenge. Careful consideration is required regarding how to ensure engagement and buy-in to the PLM implementation. B.2 discussed his experience with having commitment and buy-in early in a PLM implementation project. However when mistakes or other challenges emerge, people will typically revert to old ways of working especially with underestimating the cost and schedule of the project which may result in an impact to the programme, such as with meeting a payment milestone based on a date. This is a challenge also raised by B.14 who stated that overlaying PLM implementation on top of a challenging programme schedule will result in objectives which are not always achievable. PLM implementation objectives may become less of a priority if the overall ETO programme has issues relating to quality, cost or schedule. B.2 supported this by stating that it is easier for the PLM team earlier in the implementation project as all the personnel in the programme have had communication sessions from senior management and are committed to the transformation project; wanting to do things earlier with enthusiasm. He states that you can make rapid progress that is best achieved with a small group of people that can communicate easier. He then described how the next phase is more challenging with programme personnel becoming disillusioned making the implementation more difficult.

At this point within the implementation, there are more stakeholders and it becomes harder to communicate. This challenge becomes even greater as more people join the ETO programme from previous programmes, where there PLM environment on which they may have been working on for many years may be very different. These stakeholders will also not have been involved in the initial communications, meaning that they are not familiar with why the PLM initiative is being undertaken, and also that the process and technology will also be new. These differences culminate in resistance from the stakeholders. B.2 then described the current state of their PLM implementation, where it is hoped that people have realised that 'resistance is futile' and it is all for their own good.

B.24 described that there can be focus on driving an integrated approach through processes and toolsets, but there is a clear requirement to focus on people, as they have different needs. He elaborated that there is a need to get the right balance to understand where people fit in to the approach. He also stated that since there is less focus on downstream activities than those upfront, there is a tendency to focus on those that are needed now, not later. He described how as the team attempt to implement the solution, they discover further business challenges. The complexity and long lifecycle of ETO products means that creating a holistic view of a PLM transformation project is extremely challenging, especially as improvements are implemented concurrently with the actual product development. This provides additional challenges where resource pressures exist to support the implementation project but also to ensure the programme schedule is maintained. The delivery of PLM business change and education cannot be a one-off and should be embedded in the business culture or people may resort to old ways of working.

7.5.3.2 Lack of PLM expertise to enable and support PLM

Due to the complexity of ETO products, it is difficult to ensure that suitably qualified and experienced personnel are embedded to ensure the success of the implementation and ongoing use of PLM to meet business objectives. B.14 stated that they have very limited resource within the organisation of those individuals who have the knowledge and experience of the PLM processes and toolsets. He added that they can get other resources, but questioned whether those appointed fully understand the details such as the processes and the challenges. He highlighted the challenge that this is not knowledge which is held externally due to uniqueness and complexity of their product. The skills required for PLM in ETO products are significant due to the large number of processes and supporting technology in use. As PLM is an integrated system of systems, then each element within PLM will have an effect on the others. An example of this is with the product change process which, due to the emergent issues with ETO products, means change management is critical to the programme.

B.16 stated that they have hundreds of changes that are agreed but are late in being embodied into the design. He stated that the change managers do not prioritise from an internal customer perspective, and typically do not recognise others' needs. He used the example of understanding change management and what it meant to others in engineering and build. The consequence of change to engineering and build are significant as this may require rework with the resultant effect on the cost and schedule. If there is sufficient understanding of the PLM processes and toolsets and how they relate to the wider business stakeholders, then this will significantly impact on the success of the programme. Not only are there limited personnel who understand PLM and its use on ETO products, those who do are in great demand across the entire programme. B.14 highlighted the challenge of skilled PLM resource available to support the PLM implementation. B.20 expanded on this by explaining that the expertise challenge is also with the suppliers who have to be convinced to invest in the development and training of their own personnel.

Due to the complexity, scale and long-lifecycle of ETO products there are a large number of processes, information objects and technology systems required to support the programme. Locating SQEP who understand these elements and how they relate to other business functions and the business objectives will be difficult.

The example of the large amount of product change which the ETO product will experience and the importance of the resources understanding the implications of this change on other business functions is significant. These resources must assist with the successful embodiment of the changes and also ensuring that they are correctly prioritised. These skills have traditionally been built up through experience by undertaking the roles defined by the business, as opposed to defined training on PLM in ETO products. For a new PLM implementation there will be challenges with leveraging these SQEP into the PLM team, as they will be required to undertake their day to day roles and there will be restrictions on their availability. Convincing the various business functions involved in the programme to invest in their team's PLM skills development will be difficult.

7.5.3.3 Obligations and through-life implications of people's actions and inactions

There will be challenges with ensuring that programme personnel understand what is required from them to ensure a successful PLM implementation. They must also understand the implications of their actions within the PLM environment or when they do not fulfil their obligations. Due to the challenges of ETO products such as with scale, complexity and the number of interconnections throughout the long lifecycle, entering, integrating and maintaining the required information to a high quality standard is vital to the success of the programme.

The Interconnectedness of information provided by the programme personnel is complicated to manage and the implications of incorrect, out of date or missing information can be significant. B.16 stated that whilst there are technical challenges with PLM, the behaviours, interactions and judgements of the individuals using it are important. B.1 highlighted stakeholder buy-in and education as challenges, but ensuring that all understand what is expected from them is difficult. He went on to say that it is important to ensure that the thousands of people involved in the programme understand maturity management and that it is the language of the programme; this has taken two years and that they are still not yet there. Therefore linking business change, education and what is expected from the project personnel is important, as is explaining aspects such as how maturity management provides the management team with the information to gauge whether the programme is on schedule or not, and how their inputs are critical to this process. B.12 stated that the first challenge is with policy development to create a vision that people can understand and follow, such as design for manufacture. B.5 described that a challenge is how people like him and others do not understand what it takes to design and implement the PLM environment. In addition those who do understand the associated challenges typically do not understand what his needs are. He finished this point by asking whether these dichotomies can be brought together.

The implications of incorrect, out-of-date or missing information can be significant and the longer this continues in the programme's lifecycle without resolution the greater the impact. It is difficult to ensure that people understand what is expected from them, especially when there are thousands on the programme who all have different roles and responsibilities. An example is with maturity management which is used to manage the programme status on a naval shipbuilding programme through its lifecycle. Maturity management requires programme personnel to populate their maturity status for the various information objects on the programme, such as BoM and drawings. This information is then reported to provide a status of the programme. Therefore each person who populates and manages this information requires an understanding of how it is used in the ETO NPD and what the implications are for not providing the correct and up-to-date information. Another example is with providing information used to evolve the design, such as electrical information from a navigation system equipment owner which contributes to the overall electrical design. If the information is missing or incorrect this will impact the design of the ETO product.

7.5.3.4 Understanding processes, toolsets and through-life product information integration

The successful delivery of the PLM implementation will be impacted by peoples understanding of the relationship between information objects, processes and enabling technology. B.11 raised a key challenge as being not understanding the PLM toolsets due to the level of customisation employed which has overly complicated the PLM technology. B.7 highlighted that a typical challenge is ensuring that people work correctly within the PLM environment. Ensuring that people use the PLM processes and toolsets correctly to support through-life information integration to meet the needs of the programme is challenging. People are required to understand how the toolsets support the business processes and the information objectives.

B.17 stated that ensuring that configuration management works effectively across people and process to manage the BoM is a typical challenge he has experienced with PLM. B.6 discussed how many personnel operate by ensuring that they have done their technical task, for example entering the BoM for their design, but that is not enough. She added that individuals must be made aware of the relationship between their tasks and the overall business objectives. She also stated that as the personnel only understand their own scope of work, the chief engineer has the challenge of the overall integration. The scale and complexity of ETO programmes means that there are highly complex information integration requirements which are required to be supported by integrated technologies and associated processes. This is a requirement from the Type 26 case study as discussed in Section 5.4, primarily for the integration of the PDM and CAD systems, but also for an interface between the PDM and ERP systems. People are required to understand how the toolsets are integrated, such as with CAD and PDM and how the information relationships function. They also are required to understand the processes for ensuring that the integration functions correctly. This should not be just for their specific activity but also how it relates to overall programme objectives, such as when to publish from the CAD to PDM systems and how it is consumed downstream in manufacturing planning in ERP.

The success of the integration is impacted by the long-lifecycle and overlapping phases of ETO products, for example the design to manufacture life phases can be spilt across physical design areas at different times. This is further complicated by the programme personnel having to understand the relationship between information integration and configuration, change and maturity management processes.

B.10 supported the challenge of personnel understanding the processes and toolsets and its implication for through-life integration. He explained that people focus on their own work scope areas and gave the example of electrical designers where they believe that as PLM functions well for them, then it should work for others. This highlights a lack of understanding of PLM process, toolsets and information and how it used to support business objectives.

7.5.3.5 Working collaboratively across all business functional areas

Due to the complexity, long-lifecycle, no prototype, high customisation, various geographical locations and scale of ETO products, there will be challenges with ensuring that the personnel work together effectively. There are numerous business function roles which in many cases become more important at various points in the lifecycle. This results in business functions recruiting different skills at various phases of the programme. For example there are more system designers earlier in the programme lifecycle compared to manufacturing planners, who become more numerous the closer to the start of build.

B.17 stated a challenge within ETO product development is that people with varying skills have to work effectively together. There are large numbers of people working together in organisations across the world but, as discussed in Sections 2.4.5and 2.4.8, ETO products are highly customised, so there is a limited number of repeatable process and no prototype. It is therefore difficult for collaboration to be improved through continuous improvement of the same repeatable tasks with the same personnel.

As ETO products have these unique challenges this means that personal have to react to frequent emergent challenges and are required to work collaboratively to resolve these issues. These challenges include where immature supplier-provided designs have to be integrated with other supplier systems and then incorporated into a 3D physical model, all of which have to meet the customers’ requirements for cost and schedule. Those who are required to work collaboratively can be across geographical boundaries with various skills and experience resulting in the increased potential for personnel to work in silo’s where information is not shared. Impacting design evolution, problem resolution, change impact assessment and change embodiment. There will be continuing emergent challenges which require addressing by the various stakeholders. This requires collaboration and it will be difficult for each functional role to understand and address the needs of other stakeholders to resolve the issues. Examples include where 3D CAD data is created by detail designers to provide information for manufacturing planning and build, which can be subject to product change due to supplier updates. All of which has to be understood by the programme planning team to manage the cost and schedule commitments.

B.25 stated that they have a lifecycle phase defined boundary between people within the programme. He uses system and detail design as an example where there are lifecycle gates within the programme to manage the transition to configuration control to enable stability on downstream activities. An example of this is when the system design will be brought under configuration control, once the maturity criteria has been reached, to allow detail design to commence with a degree of stability as changes to the system can only be undertaken by the change process. B.25 added that the data handover between disciplines is not well integrated. He provided an example where the CAD team demand information from system designers, whereas a more appropriate mechanism would be for them to get involved themselves. He regarded these as organisational barriers. Therefore, the lifecycle phases, introduced to support the management of the programme, have presented organisational boundaries which are negatively impacting collaboration across the programme. Without effective collaboration the business objectives for PLM described in Section 7.4 cannot be achieved.

Introducing configuration control across these lifecycle bounded phases results in the need to use change control to update the design. Therefore the attempts to introduce stability through the lifespan of the programme using lifecycle gates, configuration control and change management are required to be understood to ensure they do not result in additional impact onto the programme and restrict the ability of personnel to work collaboratively.

7.5.4 Technology challenges

There are challenges relating to technology when implementing PLM on ETO products which are described in this section. These challenges were synthesised from the interview responses through thematic analysis enabling sub-sections to be created. The analysis of the interviews identified that the challenges included those relates to the technology robustness and longevity to support long-life a design and build which can be measure in decades. Another challenge is ensuring that throughout this long-lifecycle there is a balance between the complexity and simplicity of the technology to ensure that it meets business objectives including ease of use by the programme personnel. The creation of a PLM system of systems through technology integration and rationalisation to support business objectives was also identified as a challenge. The technology challenges are illustrated in Figure 32.

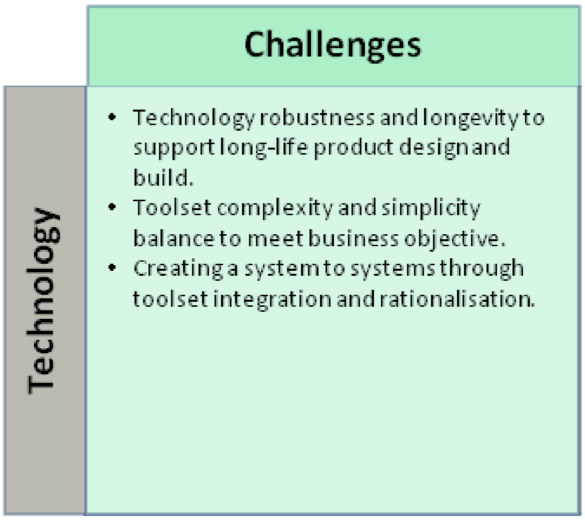


Figure 32 Technology challenges

7.5.4.1 Technology robustness and longevity to support long-life product design and build

This section describes the challenges to a successful PLM implementation faced by ETO products due to the long-life of the programme and its relationship to the supporting technology. ETO programmes have a long design and build lifecycle which relies on PLM technology providing support to the management of complicated process and the information. This technology must be robust enough to ensure that the functionality and performance meet the needs of the programme. It must also evolve throughout the programme's lifecycle to ensure that it does not become obsolete and can be upgraded with the latest functionality and IT architecture. The same core PLM technology systems such as CAD and PDM are used throughout the design and build programme which can be decades in some instances. Building a class of Naval Ships for example can take 30 years with the first of class alone typically 15 years. There are business-critical technologies which are extremely difficult to replace within this lifecycle, therefore, it must be maintained and aligned with technological advances and an upgrade strategy from the vendor. A well-established example is with the CAD system where migrating from one CAD system to another is extremely difficult due to the proprietary data models limiting conversion from one CAD tool to another [164]. Moving from one CAD version to another can have also have significant implications to the programme due to the data model differences incorporated into the version which may have unknown implications. An illustration of this challenge is with the failure in the Airbus A380 programme between version 4 and 5 of their CAD technology, Catia, leading to significant delays and billions of lost revenue [165]. Therefore there is a reliance on the ETO programme for PLM toolset vendors to have long-term commitment to their products and also that they have quality control relating to version management. If PLM toolsets are changed for any reason, such as commercial difficulties with the vendor, quality concerns or toolset obsolescence this would result in costly and risky translations into a new format.

B.12 provided an example where they migrated from one CAD system used on a previous ETO programme to a new system for a later programme, and they found that the machines used in the production environment had compatibility difficulties with the CAD systems. B.3 specifically highlighted the challenges between transferring data between CAD systems in ETO products. He elaborated the challenge of accessing data many years later and importing this legacy data into their latest product development systems. Other examples include those stated by B.26 where they would make a design change, then often found it difficult to export the information properly into customer or partner systems due to their in-house, customised, proprietary toolsets. B.20 also highlighted this point stating that challenges can commonly be related to version consistency across the supply chain's IT systems. B.11 spoke of the difficulties of moving to new technology due to the level of customisation employed in their legacy toolsets, and how they are now no longer supported by the vendor. ETO products can be significantly affected by PLM toolset vendors changing or retiring their products while they are being used to support long-term complex design and build activities. It is extremely difficult for an ETO programme to change toolsets during its lifecycle. PLM toolset issues can have a significant effect on the ETO programme due to the risk to the schedule, information quality and resultant cost implications.

B.19 stated the importance of flexibility within the PLM technology to ensure it can be configured to meet the emerging needs of the programme and the objectives of the business. He added that it must be adaptable to support the new ways of working which people have not thought of yet. B.19 supported this need and used the terms 'adaptable and flexible'. These are important points as the level of customisation of the technology must be kept to a minimum or it further restricts the flexibility of the toolsets to support the programme. An example is that upgrading to the latest versions of PDM software becomes more difficult with more customisation. Another example includes when customisation of ERP software has impacted the maintenance of the toolsets [166].

B.2 described the challenge with integration between the CAD and PDM systems which was identified as a key element of their transformational PLM implementation. He stated that when they implemented the integration, there were lots of errors when the data was published from CAD to PDM. The reasons for these errors include data quality where the technology interface will reject CAD data which does not meet the criteria for use within the PDM system. Due to the large volumes of CAD data in ETO products such as equipment, steelwork, piping and HVAC, the publishing of information across the interfaces can be extremely challenging. These challenges include implementing IT architecture to manage the large volumes, capturing, understanding and resolving the publishing failures and managing the updates and republishing caused by design evolution and the emergent changes in the design.

B.23 identified one of the biggest challenges they faced is a demand for customising the toolsets to meet their objectives, which is a massive overhead. He emphasised the importance of building stability into the technology. B.10 explained that software providers do not have sufficient understanding of ETO businesses to provide solutions that satisfy all of the functional requirements of the ETO programme. He elaborated that the solutions the software providers propose are not appropriate for complex environments. The challenge of external PLM software providers not understanding the ETO products requires those in the internal ETO business to configure their processes and the technology to meet the business objectives. This requires working with the software providers to balance their toolset capabilities and to understand the needs of the programme. This includes toolsets that are stable, easy to use and have the necessary performance to manage large datasets.

The robustness and longevity of the PLM technology is important to ensure that business performance can be maintained. When the technologies are integrated to support business objectives, such as with CAD and PDM, the sharing of information from these toolsets must be efficient. Due to the scale of ETO products, the evolving maturity, and emergent change, sharing of information across technologies will involve huge quantities of engineering data which constantly changes. Therefore if the technology is not robust and this sharing fails, it will have a significant impact on the programme schedule and therefore increase costs. The causes of these failures, such as IT infrastructure not coping with volumes or information quality issues resulting in errors, must be understood and mitigated.

7.5.4.2 Technology complexity and simplicity balance to meet business objective

There is a risk that to support complex ETO products, the technology implemented becomes excessively complicated to be used effectively by the personnel on the programme. ETO products are complex and as a result have a business architecture which contains thousands of processes, policies, standards and other guidance used to meet the business objectives. The PLM technology such as CAD, PDM or ERP must have functionality that supports these business activities and as a result will have a scale proportionate to the size of the programme. Therefore it is expected that ETO products will have a technology infrastructure which will be large-scale, manage significant volumes of information and used by many thousands of stakeholders from various business functions throughout the long-lifecycle.

B.11 described how the output from their PLM environment to their customer is more complex than it needs to be. B.3 described a challenge he experienced when they refined the toolsets to specifically satisfy their requirements which resulted in a more complex environment. This complex environment is a result of implementing technology to support the complex NPD of ETO products. There are large numbers of personnel from different business functions who require the toolsets to support multiple processes and information management requirements which can result in technology implementations being overly complex. B.26 discussed how the size of their programme was a challenge with different variants and design streams which needed to managed from the same PLM systems. He used examples of international export orders for their ETO products which all have to be configured differently for their specific requirements. Variant management in ETO products is difficult due to the complexity of the products. Each requirement change for a baselined design has consequential implications which are difficult to understand and manage due to the scale of the information, its interconnections and the complexity of the design. B.26 explained how this will be managed in their PLM environment which will have to be configured to suit these objectives. Consequently, balancing simplicity of the PLM environment with that of a complex business environment is challenging. There is an additional challenge relating to adapting the toolset to meet business objectives which is due to the emergent development challenges of ETO products. When there is a new PLM implementation on a customised, large-scale ETO product, there is inevitably new functionality which has to be introduced at short notice which may not have been captured in the PLM strategy. Therefore when these technological improvements are introduced, procedures must be in place to ensure that they meet the business objectives and are not knee-jerk reactions to solve emergent programme challenges, which may lead to customisation and complex toolsets. B.19 stated that the cycle time of change within the toolset is not aligned temporally to meeting business needs and added that they need to improve the agility of the development, rollout and testing.

There is a danger that the PLM technology environment becomes excessively complicated as the technology providers attempt to meet the requirements of the business. If programme personnel cannot understand how to use the technology due to it being overly complicated, they will adapt and bypass the toolsets such as capturing and managing information in offline spreadsheets. This will result in information being out-of-date or unavailable to other stakeholders. The effect on the programme can be considerable as up-to-date information is necessary to support the schedule. This will have further impact if there is a variant of the ETO product which is being designed concurrently as the variant will rely on the emergent information from the reference design being up-to-date. Therefore there is a challenge with balancing the supporting of business technology requirements, with ensuring that the technology remains simple enough for the programme personnel to use.

7.5.4.3 Creating a technology system of systems through integration and rationalisation

The objective of reducing information duplication and increasing quality as discussed in Section 7.4.1.2 relies on technology being integrated. A PLM environment should have a minimum number of toolsets which are integrated in order to remove stovepipe software which promotes information duplication, manual translation and misalignment. Whilst a minimal number of PLM technology is advantageous, there will also be a core set of software which performs specific functions during the lifecycle. No one PLM toolset can provide all the functionality required by the ETO programme. The minimum toolsets include, but are not limited to, CAD for 2D drawing creation and 3D modelling, PDM for managing the product information and ERP for managing planning, supply chain and manufacturing execution.

ETO products require technologies which must manage millions of data items, many of which are utilised across toolsets throughout the lifecycle of the programme, as shown in Figure 3. B.13 stated that when managing the definition of the product, there are always different toolsets and they are specialised for different reasons, all of which must be understood. In addition, as it is not possible, or preferable to have a single monolithic tool, it is necessary to understand the interfaces. He also stated that their PLM systems are challenging and ever changing and that they struggled to define them at the outset and to manage it accordingly. He elaborated this stating that they do not manage and align those expectations and, as a result, there is a level of frustrations directed at IT support and integration to the point the toolsets are retired.

0 stated that a lack of appropriate integration would cause data accuracy issues and cited an example of a major ETO project he was involved with where there was a lack of integration across key technology systems which caused significant problems. He also stated that he has seen improvements recently with integration between CAD, PDM and ERP systems eliminating manual translation and reducing data integrity issues. B.16 also described experience of a lack of system integration, specifically with CAD and PDM misalignment and how they incurred significant cost to create a team to align the data. This was further supported by B.14, who described experience with data alignment across CAD, PDM and ERP and how that was a typical PLM challenge for them.

Many of these systems were created and evolved for different product types which present difficulties with their integration. B.11 described how their current environment is an amalgamation of different systems and while work gets done, it is not integrated and there is a considerable amount of manual effort required. B.19 stated that for their CAD and PDM integration, they are linking two tools which were not designed to work together so the software vendors have developed a solution which 'sits on top' because the design principles which a CAD tool has, may not be compatible with the PDM system. He added that there is always a compromise in how the toolsets are integrated.

These toolsets are specialised and have been designed to perform specific functions throughout the lifecycle and cannot be achieved with a single solution. Often these technologies are from different software providers and are long established in the ETO business, so have not been designed to be integrated. There will be difficulties with ensuring that the PLM technologies are viewed by the business as being as a system of systems to support the ETO programme objectives, and not as independent toolsets performing specific functions.

CAD and PDM integration is common amongst many product types, but ETO products have different information management requirements due to the large-scale design. The information includes structural steelwork, large systems of pipework and HVAC. They also have sophisticated customised equipment with integration requirements which are often unclear during the design phase, such as immature power or cooling requirements. Specialised CAD tools are utilised, which often do not have a pedigree beyond the CAD design elements of ETO products. For example they do not manage configuration and change effectively, and do not integrate well with systems that do have this functionality, mainly the PDM system. Therefore, when seeking to implement a PLM system of systems, there is the challenge of integrating technology which has not been designed to be integrated.

B.15 stated that it is not just CAD and PDM toolsets which requires integration, but other technology systems across the lifecycle of the programme. B.18 supported this view stating that there should be a PDM system, a tool for requirements management, another for the functional modelling of the design, a performance modelling toolset for the product development, and a design-for-safety tool. These toolsets have differing integration levels which have to be understood and mapped. She added that there is good integration between some, and less so for others.

The level of integration between the technologies should align with the needs of the programme; as some ETO products require a greater degree of integration than others due to the level of complexity of the product. B.22 highlighted that they have two FOC shipbuilding programmes, one of which is of far greater complexity than the other. The financial overhead one programme can afford in order to meet its objective is greater than the other. Therefore the levels of integration must be reviewed and agreed for each programme to ensure it has the necessary means to maintain the integration.

B.23 stated that they have suffered due to the effort and considerable time it has taken to move from their legacy toolsets to COTS technology, and that this is reflected in the cost and schedule estimates. He described the impact that this has resulted in them not being able to improve their new PLM capability as their resources are still focussed on the migration from their legacy environment. Therefore, there must be sufficient planning and controls implemented to manage the migration project to ensure that business improvement can be maintained. As ETO programmes have emergent challenges, mechanisms should be implemented to ensure that available resources are only working on technology initiatives that relate directly to the business programmes.

Understanding that the PLM technology is a system of systems is important; otherwise there will be a focus on individual toolsets as opposed to their overall integration. B.27 for instance, stated that they view the PLM environment as tool-centric and that for them it is the PDM system. He agreed that he knows it is more than that, but it is the capabilities of the PDM system which is important to him, such as the development of the product, document control and management of supplier information. This single

PLM system viewpoint is a challenge, because if the overall systems of systems approach including technology interfaces, information and processes, is not understood, it will encourage a stovepipe, disparate view of PLM resulting in difficulties throughout the lifecycle of the ETO programme. The integrated toolsets must manage emergent requirements where new information must be passed from one software system to the next. An example is with a new attribute in the CAD toolset which has been identified as necessary to allow manufacturing planning to schedule welding activities early in the design lifecycle before final equipment placing. This will require the interfaces to be updated to share the new attribute.

B.19 raised the challenge of forced, changing working practices due to the integration of systems as this dictated certain practices to be used due to the interfaces requiring certain criteria to be met before they will work effectively. B.8 highlighted that every business improvement they put in place can be enabled but also constrained by whatever toolset they have. This loss of freedom, which presents a challenge to the people, process and information approach to the programme, can also be used as leverage to force improved practices. An example is that, prior to the improved integration of technology systems, poor data quality or unauthorised immaturity may have been used in downstream systems, which may impact the overall programme. Therefore, technology integration may be an enabler and support the resolution of significant challenges with the successful implementation and utilisation of PLM to meet business objectives as discussed further within Section 7.6. Achieving an appropriate level of technology integration is challenging as ETO products require the management and sharing of millions of information objects. These objects will be broken down to various levels of detail by different stakeholders throughout the lifecycle of the programme to support different programme objectives. Without technology integration then these objects would become misaligned due to evolving design and emergent change. The large volumes of information and complexity of ETO products result in challenges with understanding the level of integration required. If the integration exceeds the limit of the businesses ability to manage the information, or is greater than the toolsets capability, then there will be an unsustainable level of overhead. This includes managing the information integration, the software interfaces and the IT infrastructure. Due to emergent challenges there will be new requirements for information integration that will be identified throughout the lifecycle of the programme. This may result in the technology providers having to respond quickly. There will be difficulties with understanding priorities of new requirements and ensuring that the technology providers can focus resources on appropriate business needs.

7.6 Enablers for PLM implementation on ETO products

This section synthesises the interview responses in relation to the enabler for PLM implementation on ETO products. As shown in Table 10 in the Section 7 introduction, the interview question 5 was used to capture what improvements the interviewee would make to their PLM environment and why. Questions 6 and 7 were used to prioritise the improvements in terms of impact and effort if there were a number of improvements identified by the interviewee. This was used in the thematic analysis to determine what improvements had the greatest significance. Question 8 was used to capture how the implementation of the improvements could be better enabled.

Question 12 was used to capture how the challenges which have now been identified by the interviewee could be overcome. This approach was used to capture any further enablers that the interviewee may not have considered in Questions 5, 6, 7 or 8 as they may not have yet identified all of their challenges with PLM implementation.

The following subsections are the enablers for the PLM implementation framework synthesised from the interviews using thematic analysis and are structured by those which relate to Information (Section 7.6.1), Process (Section 7.6.2), People (Section 7.6.3) and Technology (Section 7.6.4).

7.6.1 Information enablers

This section describes those information enablers for the implementation of PLM on ETO products which have been synthesised from the interview responses through thematic analysis. This enabled subsections to be created which describe the information enablers which include the development of policies to capture what information is required and how it will be used within an evolving complex product. Another enabler is PLM information integration, policy development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team. The development of a data quality and governance policy, team and adherence approach was also identified as an enabler, as was the development of configuration and Change Management approach across an ETO product and its variants. The information enablers are illustrated in Figure 33.

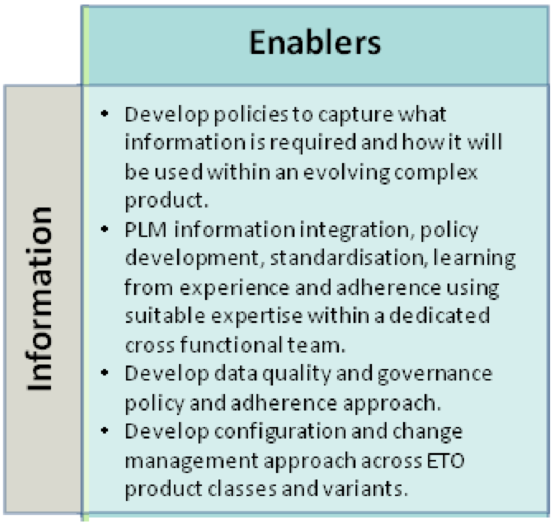


Figure 33 Information enablers

7.6.1.1 Develop policies to capture what information is required and how it will be used within an evolving complex product

ETO products have large volumes of information at various levels of detail which are used by multiple stakeholders throughout the lifecycle of the programme. It is important to understand what information is important and to whom. An agreed set of policies should be identified, created and managed for the information objects and their function within the programme. Clear ownership of the information and it's required to meet business objectives should be established. B.24 stated the importance of 'boiling down' the information to understand what is the status of the programme so that risk, safety and schedule status can be understood, and allow him to articulate this appropriately to his customer. He asserted that an improvement to their PLM environment would be to make the data more digestible which would allow better decisions to be made more quickly. He cited an example of a dashboard that shows the status of the information in terms of key risks such as with the schedule. To support this improvement, there must first be an understanding of what information is required amongst the volumes produced in ETO products. B.18 described the importance of understanding information and its impact on the programme. She provided examples of what appears to be a change to the product which initially has little impact but may actually have huge repercussions. She suggested that guidance is required to help people understand the implication of changing the information and its effect on the products. She provided another example of a weight related design margin where the location of an equipment item may have a significant effect, and that when an investigation of the impact of the change is undertaken, even though it has taken a long time, the results may not be correct. She added an example of a complex change where one team raised changes to electrical data. The electrical team then responded to say that there was not enough power. This in turn lead to a bigger change which had a major design impact, with the HVAC team stating that it had broken their design assumptions in an area. She commented that they did not have the prompts in the system to get a correct impact assessment, and that there is a need to improve the identification of the interconnections between the information impacted by the change. She stated the importance of being presented with the right information on the change, which would allow it to go through the change management system quicker and highlighted that, standardising the change impact approach would reduce the time taken to process it.

If a policy was created to capture the information that is important then this could be used not only to aid the stakeholders, but also to add valuable attribution to the objects within the PLM environment stating the importance of the specific artefacts. An example is with a part which is identified as an important element within a navigation system of a ship, which would aid identifying whether a change will have a significant impact or not. Attribution within a PDM system is common place, the key enabler is the policy which identifies what information is important.

B.18 also stated how reports are important to her to understand the impact of a change. If the information identified in the policy is applied to the technology, then report generation from the toolsets can be configured to provide the information required by the programme. B.17 identified product change and an accurate understanding of its impact on the supply chain as an improvement to their PLM environment. He added that they also need to understand what the supply chain business function is required to do in order to support the change. Therefore, the impact of change in the design will need to be understood across the programme functions. Supply chain have a particular challenge in that they need to go to the market to procure the materials required to support the product. As ETO products have challenges with procurement due to the bespoke nature of the product and the customer value for money restrictions, it is difficult to react quickly to a product change when the material cannot be easily sourced. Therefore, an accurate understanding of the product information and the change implication is critical, especially due to the bespoke nature of the ETO product. Consequently, the supply chain may have to seek concessions from the engineering community when material specified by the engineer cannot be sourced but a similar item can.

B.1 described how he believes that there is a disconnect between the engineering and supply chain business functions and that an improvement to the PLM environment is that of improved integration between these two functions in the programme. He cited an example: when supplier information is provided into the programme, he requires an understanding of how mature it is from a supplier's perspective, for example, is it used in other programmes or is it developmental and is therefore a risk to the programme as it may change. This can have a significant impact on the programme as this supplier information is used in the design and integration of the product and changes due to supplier immaturity can have a significant effect. Therefore, the policy must provide guidance on not only what information is required, but also guidance on maturity and how it relates to the interconnections across the programme.

ETO products can be hugely complex and, as described in this research, an understanding of what information is important and how it interconnects to each other is challenging. To enable the information objectives of the product and to overcome the challenges with providing this information, requires a policy to be created which helps the programme stakeholders understand what is important. It must also inform what it will affect and what is required to be presented to the stakeholders, such as through the change management system. B.5 supported the importance of identifying what information is important and provided an example of when there are a number of new occurrences in the BoM and how understanding what it means is difficult. Due to the large volume of BoM information in ETO products, understanding the implication of its growth is difficult. The policy should provide guidelines to the stakeholders about what information is important and any change needs to be articulated to those who consume the information and those who manage the overall design, cost and schedule.

B.24 described how important it is to understand what information other stakeholders require. He provided an example of the electrical design team requiring information from others on their electrical requirements. He also gave an example of the combat design team not understanding the implications of weight to the product design. He stated that they are effective at entering information into the PLM environment, but they do not put the right information in to help others in the programme. The overall programme team does not always understand what is missing. Consequently, not only will the policy help in providing information relating to identifying implications of a change, but it will also help in the design process to aid with evaluating what data is missing or insufficient to meet the requirements of the stakeholders. Therefore, the policy must be aligned with the information requirements of the programme, how the information should be captured in the toolsets, an appropriate business intelligence reporting approach and also a means to be able to measure and present the quality of the information.

B.5 stated how important it is to relate the capturing of product information with the programme management requirements to support its presentation in a form that the senior management team can understand and use. He questioned whether the product information and its use for programme management are close enough and whether they understand what information can be used for this purpose. He also stated the need for ensuring that the ‘lens’ on the programme is dynamic enough to meet the needs, not just of today but in a few months’ time, when the programme is at a different phase.

These policies will assist with establishing how the information will be presented to meet the needs of the programme. An example is to identify and report on the information which provides the management team with the cost and schedule status of the programme. Another example is to identify what level of detail is required in the CAD model to enable an Engineering Bill of Material (EBoM) to be created which can be have emergent change applied efficiently. Too much detail will impact the speed in which changes can be applied to the EBoM due to the time it takes to update large volumes of information. Understanding the information which is of value amongst the large volumes will assist with providing management focus to manage maturity and identify risks to the programme and technology can be applied to report on these high value items. Understanding the information ownership will help with assessing the impact of change on the design. It will also enable the impact assessment to be more efficiently processed by the correct personnel. What may seem as a simple change to one discipline, may have a significant effect on another. Examples are within the engineering teams where an electrical change on an equipment item placed in a physical location in a naval ship may have a significant effect on the overall electrical design for that area. This may result in a significant redesign and additional power generation required, which may have a consequential impact on weight management to meet customer requirements and spatial design where there may be no room for the additional equipment.

The interconnections between the information will include other disciplines such as manufacturing planning and supply chain where the impact of change can be significant. Therefore being able to have a thorough understanding of the information, how it will be used and its ownership will assist not only in managing the evolving design, build and support but with managing the information interconnections and emergent change. This understanding will also assist with educating the programme personal in providing updates to the information which is particular value to the programme, therefore assisting with understanding where there is missing or out of date information. These policies will enable a more effective business intelligence strategy as the reporting can be focussed on appropriate information at the relevant programme lifecycle, concluding current programme position and forecasting the status in the coming months and years.

This supports the need for a policy to understand what information is required, not only for product design and change management, but for all stakeholders in the ETO product throughout its lifecycle, including programme management.

7.6.1.2 PLM information integration, policy development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team

This section describes how a dedicated cross-functional team with SQEP personnel can be established to enable PLM information integration, information policy development and information standardisation. It will enable the learning of experience from within the programme, previous programmes, academia and from the wider industry to ensure that PLM objectives can be achieved and that related challenges in PLM implementation and utilisation can be overcome. It will also ensure that the information-related policies and procedures will be adhered to across the extended enterprise of the ETO programme.

0 stated that an improvement they would make to their PLM environment is to ensure the highest level of integration of information which is used by different business functions in different PLM technology systems. He provided examples of aligning common information which is used across the lifecycle of the programme, including CAD information, with that within the PDM system and that used in the in-service support environment in order to provide a through-life solution. B.15 agreed with the through-life approach to information integration but he stated that he would like to see improvements with downstream integration so that the focus is not just on the design, but includes the manufacturing and in-service support elements as this would provide improved customer satisfaction. 0 highlighted that the management of this master record is critical, and that this must be embodied in the technology systems to ensure that it is a cradle to grave solution with appropriate business rules and interfaces applied and that third-party software vendors are appropriately engaged. B.14 supported this view stating that an improvement to his PLM environment would to align the key data that the business requires with the relevant technology integration. He provided an example of a previous programme where there were information alignment issues which incurred significant cost to the programme, specifically between the CAD and the PDM system. This resulted in action to resolve the misalignment and resulting data quality issues as the information was passed to manufacturing. He described how there needs to be a more proactive approval to ensure the information is fit for purpose for manufacturing, and added that they have experienced significant ‘pain’ with understanding what the correct information is in what system.

B.26 stated how an integrated information environment would be a significant improvement for them, how highly he regards the BAE Systems iBoM, and how the information is captured from suppliers for improved population into the PLM environment. This is described further in the Type 26 case study in Section 5. B.10 stated that he would like to see an improvement in the way that PLM information is related to maintenance management. As a consequence, the information used to design and build the product, must also be used for maintenance both within the build lifecycle, e.g., for maintaining equipment fitted but not yet in-service, with that of the information provided for in-service support.

B.27 stated that an improvement to their PLM environment would be the upfront design of the PLM system itself – they have experienced problems in the past when not enough attention has been given to the design of the PLM environment. A dedicated PLM team with SQEP personnel from the business functions would enable these improvements and those described above to be managed effectively. The team should have the experience from previous programmes and across industry to understand the objectives and challenges to produce policies for the information as described in Section 7.6.1.1. They should also be able to understand the Learning from Experience (LFE) from within the programme, previous programmes and across industry and academia and will have the dedicated time and resources to undertake these activities. The team should be cross-functional to ensure a complete understanding of the interconnections of the information across the functions. They should be able to produce the requirements for the technology development and resultant reports to support the policies and ensure they are adequately tested and validated. Adherence across the extended enterprise of the programme should be ensured and support provided when there are issues with the information.

7.6.1.3 Develop a data quality and governance policy and adherence approach.

Quality of information has been raised as an objective in Section 7.4.1 and there are significant implications to the success of the ETO NPD if this is not appropriately managed. This is due to the large number of interconnections of the information which is created and used by multiple business functions throughout the lifecycle of the programme. To support this objective a policy to manage the quality of the data, its governance and also to ensure adherence of the policy is required.

B.2 raised data quality as an improvement to his PLM environment to meet their business objectives. He stated that when they went live with their integration between their CAD and PDM systems, there was a considerable amount of errors when the data was published. He described the rules in the interface which will stop data publication if there are non-conformances, and these should be validated at source. He stated that they should have put mandatory coding into the CAD system to stop the data being published rather than letting the interface deal with them. As ETO products have huge volumes of data items, including equipment, pipe spools, steel piece parts and HVAC, then problems arising from publication can take a considerable amount of time to resolve, impacting the cost and schedule.

CAD and PDM integration has an important business function to ensure alignment between the system design in the PDM system and its spatial integration in the 3D model on the CAD system. Due to the complexity of ETO products and their scale, if data quality is not managed, then significant issues will occur with the interface such as publishing failures between the two systems. This is compounded by the level of emergent change which will have a subsequent effect with CAD/PDM, for example, large volumes of data may have been published from CAD to PDM which may then have to be republished due to product change. A close relationship between data quality and the level of maturity of the product is required before CAD to PDM publishing commences, which should be captured in the data quality policy. 0 stated the importance of master record management with integration, which is important to understand where the master source of the data resides. As discussed in Section 7.4.1.2, there is a PLM objective to manage a single point of truth of information even though it is used in multiple PLM systems by various business functions. The master data is where the point of truth of the specific information resides.

B.3 stated that there is a relationship between data quality and user adoption as there are issues with quality which impact PLM toolsets and processes which will have an effect on its successful use. Due to the large volumes of data which require quality management, a team with the appropriate resources should be created to manage the approach to data quality. This team must understand the interfaces across the PLM systems of systems, and put in place a policy to ensure that data can be published to meet the needs of the programme. This policy should include where the master data resides and what form of validation should be enabled for successful publication and consumption by the programme. Appropriate business intelligence reports should be created in order to understand the success of the data quality publication and also to aid in the resolution of any issues. The team should also ensure that the policy is adhered to by the business such as with pursuing any quality issues at source and any IT issues relating to unsuccessful publication across the systems. The data quality team will assist in overcoming those information challenges identified in Section 7.5.1.2 and in enabling improved resilience of the key information required by the programme. The data quality and governance approach will be supported by the other enablers described in Section 7.6.

7.6.1.4 Develop a configuration and change management approach across ETO product classes and variants.

This section considers overcoming the unique challenges of ETO products by developing a configuration and change management approach which meets the objectives discussed in Section 7.4.1 and overcomes the challenges discussed in Section 7.5.1. This approach should include a single product and its design variants. Due to the highly customised nature of ETO products and the resultant evolving maturity and change which impacts the information, a specific approach to configuration and change management is required. Maturity criteria are closely linked to change and configuration management as there is an overhead to constraining the design into change management. When configuration control is applied and the design enters change management, any updates must firstly be approved by a change board. Due to the large volumes of data in ETO products and the emergent challenges which will occur, this can be a time consuming and resource intensive activity. Each change must be thoroughly investigated to determine its impact. This requires identification of the affected items which are related to the change objects. Typically, the market leading PDM systems, such as PTC's Windchill and Siemens Teamcenter, will have configuration and change management integrated with the product artefacts, enabling automatic configuration lockdown or unlock after the approval of the change. This has a further impact on the product development process; if mistakes are made, for example affected items being missed through the change lifecycle, then they will have to be revisited which will incur further delays resulting in schedule and cost implications.

B.18 stated how important it is for her to understand how the various design artefacts are affected by a change; this can often take days and how they are always missing things. She enquired whether there is a way for the technology to help a person understand what else could be affected; this could be very helpful if a solution was found. The challenge with this request is that while technology could identify the relationships of the objects within a change, it would be difficult to design technology which would understand the implications of the change in terms of its interconnections, as this would require some form of intelligence to replicate the knowledge required. There must therefore be a balance between technology, process, people and information management when applying configuration and change management.

B.13 described how the change process must be easy to use and achieve the balance between maintaining configuration control through change management. If it is overly complicated then it impacts the flexibility and speed of response from the programme. Therefore, developing a configuration and change management approach across the ETO product is critical. B.13 explained that the change process works until change is embodied into the product design. He stated that ownership of the end-to-end change process is required due to the multiple functions involved in its execution, for example engineering, quality, manufacturing and programme management.

B.16 stated that 60% of programme cost resides in the supply chain and a huge amount of data comes from suppliers. He added that it is important to understand that the design is integrated with the suppliers, and that the programme must ensure that they can manage and understand change across the business functions. Therefore, with configuration and change management, the approach must include ownership of the process and ensure that it provides guidance on the responsibilities and interconnections of change across all the functions in the programme. B.8 stated that managing multiple configurations of a product to assist with the design development and decision making would be very advantageous. The management of design variation is important not just in the context of a single product but also with the winning of new orders such as with export market opportunities. An example is with the GCS where there are UK, Australian and Canadian variants. This requires configuration and change to manage the evolving design and build across multiple variants in various geographical locations.

Whilst configuration and change management is a well-researched topic, ETO products have specific challenges which require careful consideration. The change and configuration management approach must align with the other enablers discussed in Section 7.6. For example, the policy regarding what information is required by the programme, as discussed in Section 7.6.1.2, will greatly assist in the successful execution of the configuration and change management approach by helping to identify important product artefacts and their relationships. The approach will also be supported by the process, people, and technology enablers discussed in the following sections. The approach must also ensure that the baseline point for configuration and change control supports the evolving product and does not constrain the programme into costly and time-consuming change management too early. An example is with a FOC naval ship which may require configuration control to be delayed later in the lifecycle phases than subsequent ships due to immaturity. This must be balanced with the risk of instability of the information impacting those who use the information in downstream activities. An example is with a pipework system in a naval ship build programme: the system designer is updating the functional design, the detail designer is updating the 3D CAD model to reflect these changes but the manufacturing planner is in the process of placing work orders for build based on the previous design.

7.6.2 Process enablers

This section describes those process enablers for the implementation of PLM on ETO products which have been synthesised from the interview responses through thematic analysis. This enabled subsections to be created which describe the process enablers. These enablers include the ownership of PLM business processes, their development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team. Ensuring guidelines and governance over process complexity to ensure they are simple and usable is another enabler as is mandating the utilisation of PLM processes internally, to partners and the supply chain. The process enablers are illustrated in Figure 34.

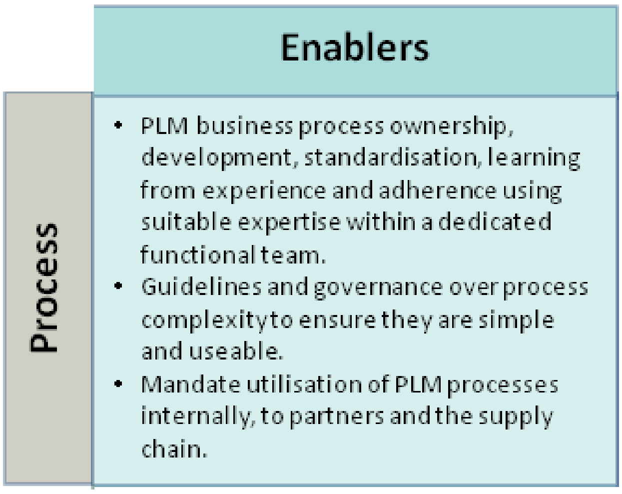


Figure 34 Process enablers

7.6.2.1 PLM business process ownership, development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team

The PLM business processes used to support ETO NPD should have appropriate ownership for development and maintenance to support the various business functional activities that they represent. The processes should also be standardised to support the various interconnections of the business functions to ensure that disparate processes which only support individual programmes or activities are not created. A dedicated cross functional PLM team representing the business functions will enable both ownership and development of the processes but also integration with the other business units. This team will also ensure adherence within their own business functions and target any disparate processes which do not support the PLM objectives of the business. Ensuring that learning from experience is captured from within the programme, any legacy programmes and across industry and academia will also be enabled by the team.

B.14 stated the importance of ensuring that the PLM strategy is not driven by an individual programme but spans all programmes within the business. He added that they have used PLM differently across a number of programmes as each is tailored to individual programme needs. They typically start PLM from 'scratch' for each programme with the resulting effect of having a slightly different PLM system for each programme. He stated that PLM should be owned by the business and not driven by the programme, but with a central function managing PLM. There should be standardised business-wide processes and technology which will drive consistency with the way people behave and will assist in eliminating data quality issues experienced by the programme. He provided examples of how, across programmes, people bring their own ideas which results in variations in the processes, technology and in the designs themselves. As a result of these variations, the business does not always get the benefits from translating design content from one programme to another and that, accordingly, people become frustrated. He provided further examples that if there is standardisation of PLM across the business then it would reduce the time to undertake tasks, resulting in improved schedule adherence and making the business more cost effective. He also described how the requirement for training would be reduced if there was standardisation across the business as more process variation usually means more training.

In order to ensure standardisation across the business, a cross functional PLM process team with the appropriate authority and SQEP should be created. This will include process development, ownership, ensuring adherence and also providing central communication to the technology providers to ensure that requirements meet whole business objectives and not just those of the individual programme. This will reduce technology variations across the business resulting in reduced customisation, lower risk to the programme and will enable the IT function to better focus their resources on the key business requirements.

B.13 described how an enhancement to their PLM environment would be to have improved team integration with different functions embedded within teams to advance the way they work together; this would also enable quick access to the right skillsets. The ETO product is complex so there are skilled resources which support the various processes across the functions, such as system design engineers, detail design engineers, supply chain professionals, programme managers, finance personnel, manufacturing planner, manufacturing engineers, test and commissioners and in-service support engineers. Having representation from these functions would assist with the success of the PLM approach by ensuring that the processes and enabling PLM technology meet the needs of all functions across the lifecycle of the product.

A central PLM team was also supported by 0 who stated that to resolve the issues associated with PLM delivery, it would be beneficial to have a centralised team to provide PLM administration, standardisation and ensuring it is consistently practicable. He added that they would provide economies of scale where the overall programme would benefit by utilising key resources centrally to leverage their skillsets to meet programme objectives. He also stated that this central team can be used to enable learning from experience and that; ultimately, centralisation would provide benefits which ensures that the same problems are not repeated, which has been the case on previous programmes. He cautioned that this may be seen as empire building by some, but that can be mitigated by gaining buy-in from across the organisation, not least by explaining the benefits centralisation will bring.

A.14 stated that they do not have a surplus of resources who have the knowledge and experience in the PLM processes and technology and that it is difficult to recruit SQEP due to the unique nature of their product and its complexity. He questioned whether external resources would understand the difficulties with their product and whether they would understand the processes. Internal skilled resources however have other demands placed on them to meet the challenging programme schedule and that they often rely on resources for the PLM implementation that have other responsibilities. Therefore there is a lack of dedicated focus on the PLM implementation from these skilled resources. He speculated that their organisation does not do enough to establish the relationship between the issues and the technology requirements, causing difficulties with implementing a solution into the PLM environment which addresses these requirements. The solution is typically implemented whilst undertaking the product development activities. Having a dedicated PLM team would enable the focus to be on the PLM implementation without being distracted by other activities. There would also need to be a balance between replacing these skillsets and building up experience in other team members.

B.10 described the difficulties with using the technology providers to assist as they do not understand the requirements of the ETO product, they have a very IT approach, and they focus on selling their products. B.3 stated that an improvement to their PLM environment that meets their business objectives, would be to use PLM earlier in the lifecycle, however it must be appropriate to the needs of the programme and be scalable to support business processes with the necessary control. The dedicated SQEP PLM team would provide this improvement by introducing repeatable processes and enabling technology proven in previous programmes. This team would have the necessary skills and experience from across the business. B.2 also supported the use of a dedicated PLM team. He stated that his organisation has process owners, but that they also undertake ETO product development activities, so will not have the capacity to create these processes. He added that they overcame this challenge by creating a central team which creates and maintains these processes, in alignment with the core PLM architecture and principles that can be explained to the business. The dedicated process team would be within the same PLM organisation as those described in Section 7.6.1.1, enabling integration with PLM processes and the information management approach.

7.6.2.2 Guidelines and governance over process complexity to ensure they are simple and usable

The challenge of ensuring that processes deliver business objectives but are not overly complicated was identified as the only challenge relating to processes, as discussed in Section 7.5.2.1. 0 stated the importance of ensuring simplicity with the processes, for example ensuring that electronic workflows in the PDM system are not technology driven with vendors directing the solution. He added that if a dedicated PLM team is created and there are integrated processes and systems with a master record approach, then this will assist with process simplicity. B.16 cautioned that the business should not be too prescriptive and that flexibility is required to assist with the complexity of the programme. B.7 described how there is a need to ensure that there are no local approaches to using PLM as that may result in quality issues resulting in a lack of information required to understand the root cause. He added that PLM can be used to mandate how the business operates.

B.14 stated they must not have processes which are too onerous, for example where electronic workflows are too complicated. He added that they keep the processes simple and endeavour to continue to do so. B.2 also highlighted how they made their electronic workflows in their PDM system too complicated and prescriptive as they believed that everyone would use the same workflow. This led to it becoming too large to support all the process variations and that if something went wrong in the workflow it was difficult to fix. He described how they had to completely reengineer the workflows to make them simpler and easier to support, with the key being to keep things simple. As shown from the interview responses discussed in Section 7.5.2.1, there was evidence to demonstrate that due to the complexity of the ETO product, processes are created which reflect this complexity, and subsequently make them unusable. A balance must be struck between ensuring that the processes are robust and meet the business needs but that they are also simple, usable and are easy to understand across the large number of personnel in the programme from various functions and backgrounds. This simplicity will also aid with ensuring that those electronic workflows, which are based on the business processes, can be maintained and are flexible to meet the emergent needs of the programme. Therefore, there should be guidelines and governance managed by the central PLM team to ensure that the processes do not become overly complicated when attempting to meet the business objectives.

7.6.2.3 Mandate utilisation of PLM processes internally, to partners and the supply chain

There is minimum advantage to the ETO NPD if PLM processes are created to support business objectives but these are not made mandatory for use by all those involved in the extended enterprise. B.21 used a supplier perspective to describe how important it is for suppliers to understand the programme's maturity management approach and the relationship with the product information they provide. The information provided by suppliers is used to progress the evolution of the design and often this is at various levels of maturity at different life phases in the programme depending on the level of customisation, as discussed in Section 2.4.5

He stated that, as a supplier they want more knowledge of the design systems their product will interface with across the ETO product and how they can help with the integration. This relationship between the supplier information and maturity management is an important enabler for a successful PLM implementation on ETO products as the suppliers provide technical information used to evolve the product development in the programme. To ensure a successful maturity management approach key suppliers, especially those for critical design systems, should understand how the information they are providing is being used by the programme to reflect the maturity of the product.

B.26 described how he would start from the beginning of the programme and ensure that the contracts have clauses stating that stakeholders and relevant suppliers must adhere to the PLM approach. He adds that it should be stipulated that they must use the same integrated environment and that they cannot subsequently create their own technology systems. This is an important point to assist with the objective of a single point of truth discussed in Section 7.4.1.2.

As there are many stakeholders in ETO programmes, having contractual obligations is important to ensure the prevention of disparate, unintegrated systems, with the resultant information quality issues. In conjunction with the contractual obligations, the stakeholders must also be supported by the PLM team who can provide support and help to ensure buy-in of the programme's PLM approach. The PLM team can also aid with assuring that adherence to the PLM approach is maintained.

As described by B.21, suppliers would be willing to support the PLM approach if they understood it. However, without the contractual obligations, as stated by B.26, there is a risk that when costs and schedule impact the delivery to the programme, the stakeholders may fail to follow the PLM approach. Having an appropriate balance between supplier engagement and overly constraining them by the PLM processes is important. B.17 highlighted the importance of allowing suppliers to innovate to assist with the product development process. This would also assist with the collaboration objective as discussed in Section 7.5.3.5.

B.20 stated that they would prefer long term collaboration with suppliers to build relationships and highlighted the difficulties with having to go out to the market for each new programme in order to meet value for money conditions set by the customer as discussed in2.4.4. He stated a preference for a healthy supply chain which is not reliant on their business. Since ETO products have a long lifecycle, there is a risk that if a supplier is too reliant on a single programme, they may become insolvent within the product development cycle. This would impact the information used to progress the product development as well as the final delivery of the hardware during the manufacturing phase. In addition to engaging with suppliers on their responsibilities within the PLM approach, monitoring the wider health of their business is important. Through this engagement, the skillsets of the supply chain and the wider stakeholders will increase, improving the understanding of PLM in the programme.

7.6.3 People enablers

This section describes those enablers relating to people for the implementation of PLM on ETO products. These have been synthesised from the interview responses through thematic analysis which enabled subsections to be created. These enablers include providing continuing evidence of PLM benefits to senior management to enable support and maintain sponsorship. Another enabler is developing and implementing a comprehensive business change initiative on PLM. Establishing a cross functional PLM education approach embedded within the core business training programmes which emphasises core values and objectives was also identified. Another people related enabler was the development of PLM objectives, education and support to the business using suitable expertise within a dedicated cross functional team. The people enablers are illustrated in Figure 35.

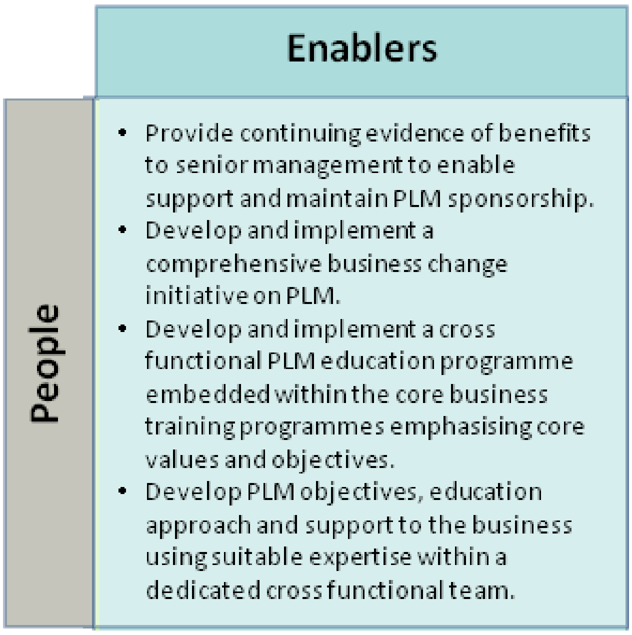


Figure 35 People enablers

7.6.3.1 Provide continuing evidence of benefits to senior management to enable, support and maintain PLM sponsorship

The section relates to the importance of ensuring that the senior management team is fully supportive of the PLM implementation through the lifecycle of its implementation and utilisation on the ETO programme. Without this continuing support the PLM implementation will be put at risk as people will by-pass polices and resort to old or non-sanctioned approaches.

B.8 stated that if management loses confidence in PLM then it can be seen as an overhead – the challenge is selling the investment and getting buy-in. However he goes on to say that senior management in his programme are always emphasising the strength of their PLM implementation and that the benefits will be realised downstream in the programme's lifecycle. This support from the senior management team is important as initial activities may provide the greatest benefit to other stakeholders later in the lifecycle. Without senior management team support explaining these benefits, there is little incentive for people who do not directly benefit undertaking the tasks. An example is with the identification of repeatable managing processes as discussed in the Type 26 case study in section 5.8. The engineers are those who are being asked to capture this information within the PLM environment, but the benefits will not be realised until the build phase which is years after the commencement of the design phases.

B.4 stated that it is important to be able to quantify the benefits of PLM and explain to the key stakeholders what the business is getting from the effort applied to its implementation and utilisation. The identification and communication of the benefits of PLM is required or people will start to lose faith in the implementation and resort to old way of working, or complain to the senior management team that they are not meeting their objectives due to time taken on PLM activities. B.19 described the importance of the senior management team understanding the architecture of the PLM environment and how it benefits the business. This will enable the senior management team to understand how PLM is utilised and where the business investment is being targeted to achieve value.

B.23 explained how it is important to gain sponsorship from the business and to have an owner from the senior management team: putting effort into winning the hearts and minds of the senior management team is worthwhile. He described the difficulties with their PLM implementation and that people in the programme see it as an IT project and someone else's problem, but explains that if it goes wrong then it can impact the programme. He stated that a designated PLM owner would help focus their organisational approach, is required to ensure a single methodology, and reduces the risk of disparate customised systems, simple processes and integrated information.

B.25 highlighted that PLM must provide efficiencies and should not be an added cost for no return. This is problematic as explained by B.8 who stated that the value of PLM is not widely understood and can be undervalued. An enabler for ensuring the continuing support from the senior management team is to provide evidence from across industry and LFE from other programmes of why PLM is important. The senior management team in ETO programmes are aware of the risk of cost and schedule overruns typical of these product types. They will require supporting evidence that the approach being undertaken is not high cost and risk with little return. The framework developed in the research is a good example of evidence which can be used to provide support to the senior management team of why PLM is important and how benefits can be realised and risks mitigated.

B.23 stated that they can use the approach undertaken by similar programmes such as Type 26 and this was supported by B.27 who explained that learning good practice from across industry will aid their PLM implementation. The success of the GCS export programme provides evidence of PLM practices which have provided value to industry.

The cross-industry benchmarking and LFE is an important enabler to gain the support of the senior management team. If the management team believe that their PLM approach is based on learning from across industry, then this will provide confidence to them that the risk of a failed PLM implementation on their programme will be reduced. The implementation of PLM on ETO products is a costly and complex project and, without the support of the senior management team, it will be difficult to receive the support from the rest of the stakeholders. It will also be difficult when the PLM implementation inevitably encounters challenges which require business focus to overcome. It is also important that once senior management have had buy-in, that this sponsorship is maintained throughout the lifecycle of the programme.

7.6.3.2 Develop and implement a comprehensive business change initiative on PLM

It is important that all the key stakeholders in the PLM implementation understand why the project is being undertaken, what they are required to do to support it, and to ensure that they are fully engaged and have a stake in its success. To achieve this objective a comprehensive business change management initiative is required to be developed, implemented and maintained as part of the core culture of the organisation.

B.6 stated that an improvement she requires in the PLM environment in order to meet the business objectives, is to develop the cultural elements including the skills and awareness of the importance of information. This was supported by both B.4 and B.17 who stated that business change management would be an improvement they would make to their PLM environment. The business change initiative will assist with overcoming the people challenges of understanding PLM value and the importance of their input as discussed in Sections 7.5.3.1 and 7.5.3.3.

B.8 stated that a weakness in their PLM implementation that requires improving is with briefing the wider programme team on the benefits and the necessities of what the business is doing with PLM. He added that he believes that the senior management have bought into their PLM implementation but he is not always convinced that those who interact with PLM on a day to day basis understand. He questions whether they see the PLM approach as a burden and that, if they understood the big picture, they would see it is worthwhile. B.27 stated that in his business, he had difficulty with ensuring that the senior management team understood the complexity of the PLM challenge, and that his experience is that the senior management team just want it done. He added that it is necessary to be clear upfront as to what is being undertaken. The senior management team must therefore not only understand the value of PLM to gain their support, but they must also be communicated as to the level of effort and resources required to support the implementation.

B.1 explained the importance of the programme stakeholders understanding the benefits of PLM and what is in it for them. He questioned whether people understand the benefits of their PLM implementation and the improvements it will generate for the programme downstream in the lifecycle. 0 also discussed the importance of people issues with improving the PLM environment. He described how it was possible to have a great system, but without buy-in, then there will be challenges. B.11 stated that an approach to overcome challenges with PLM implementation is to have a dedicated business change manager. He explained that, initially, he was sceptical but that he now sees the business benefits this brings. He added that the business change manager provides engagement and tested understanding and resistance levels of the stakeholders in the business. He also described how the business change manager identified intervention areas to bring people on the change journey and focussed interactions in these areas.

Not all ETO programmes with PLM implementations have had the same positive results with business change management as B.11. The experience of B.23 was that when they had cost issues and had to reduce the personnel involved in the PLM implementation, the business change initiative was targeted as it was seen as low value. The result was that those people who the change initiative was targeting then also see it as low value, impacting the success of the PLM implementation. He stated that he would put more effort into organisational change and ensure that they have the necessary resources to support the change initiative. B.8 explained that when implementing improvements to the PLM environment it is important to sell the benefits of PLM to those at the front end of the lifecycle. He explained that this is difficult as those who reap the rewards are often downstream, such as with manufacturing, and that it can be seen as a burden unless they understand the importance.

B.2 stated that with their PLM implementation they have changed to being much more information-centric than previous programmes, and added that people don’t understand that they have to work differently. In previous programmes it was CAD model centric and that was where people looked for the master data. He explained that it is now PDM-centric and the information is structured differently, including the materials used for manufacturing. B.24 mentioned that it is necessary to inspire levels of ownership within the teams and commented that on some occasions when in maturity management meetings he feels that people do not care enough about the importance of maturity information. He stated that it is necessary to inspire not just individuals but whole teams.

If project personnel have not understood the importance of maturity management, then this presents a risk to the programme to not only the criticality of maturity to manage the complexity of the programme, but also for understanding and adhering to the programme schedule and cost commitments. B.10 suggested that the way to win the hearts and minds of the stakeholders is to use success stories, whilst B.6 advised investigating the current culture and the level of understanding at information and technical level. This would allow for a targeted change management approach to focus on the areas that are required to support the PLM implementation. B.15 commented that overcoming difficulties with PLM implementation would be enabled by a top down and bottom up business change approach. Firstly the management team should be convinced it is the right thing to do, and secondly a bottom up approach should be undertaken. He stated that, in his experience, people have less resistance to change when you have their buy-in and they can then create pressure from the bottom up to contribute to the change. This he believes will help to convince the majority of stakeholders. He explained that they are attempting to use new mobile technology into the manufacturing environment to assist in improving the quality of the as-built BoM. He explained that this will improve quality as all the relevant data are inputted into the PDM system in the manufacturing environment and believes that this is where the business should be targeting. This approach to improved build completion activities based on PLM information was identified as a requirement in the Type 26 case study as discussed in Section 5.9.

Promoting business change management from the bottom up was also raised by B.22 as an important enabler to overcome the challenges with PLM implementation. He explained that change agents are important and that they can be used to articulate the benefits to the business and the individuals. B.14 also supported business change management as a key enabler to successful PLM implementation. He stated that the change should demonstrate the cost and the benefits to allow people to understand that the improvements will be realised on the programme.

There is a risk that the benefits of PLM introduced throughout the lifecycle of the ETO programme could be impacted if the stakeholders do not fully support the concept. If the manufacturing personnel do not embrace PLM and undertake the activities required to capture the build status against the engineering information then the management team cannot determine whether the huge volumes of artefacts managed through the design phase have been installed correctly. If not undertaken, this will result in significant investigation activities to ensure the build is completed to specification, prior to in-service and handover to the customer.

7.6.3.3 Develop and implement a cross functional PLM education approach embedded within the core business training programmes, emphasising core values and objectives

Embedding PLM education as part of the core business training programme will assist with ensuring that the personnel understand why PLM is important. It will also enable the stakeholders to understand how it must be used and what part they play in ensuring its success. This will assist with overcoming the adoption challenges identified in Section 7.5.3.1.

B.11 explained the importance of education in improving the PLM approach and described the steep learning curve for people when they must learn a new approach from something they may have been doing differently for over a decade. New programme personnel may transfer from other ETO programmes where they may have been performing a similar role over the lifetime of the design and build programme using different PLM processes and technology. This sustained duration of work commitment results in individuals possessing a clear and well-defined understanding of the PLM approach on the previous programme, which may differ significantly from the new ETO programme PLM approach. These differences are due to industry PLM approaches advancing over the duration of the previous programme, which can only be fully leveraged at the start of a new programme. This results in the business introducing improved PLM based on LFE which will affect the information management approach, processes and technology. Attention must therefore be paid to ensuring that new programme personnel understand the differences in the new PLM implementation. B.11 stated that if appropriate education is not undertaken, then the personnel may operate in the PLM environment incorrectly and pass sub-optimal practice on to other colleagues. B.27 agreed with education as an enabler to improvements with PLM. He explained that it is his intention to ensure that those who have a stake in PLM understand the importance of doing it right from the beginning, and that training can help with improving the processes and technology expertise. B.16 expressed caution that, when he first joined the ETO programme, he was given a good understanding of the importance of maturity management, but the programme then started to dilute the approach, and questioned the impact that this will have on the build programme. He was concerned that there is a danger that the management team will convince themselves that the diluted approach to maturity management will meet the business objectives, but they will end up with a negative impact later in the lifecycle as the new approach is not what they originally set out to achieve.

Therefore, a PLM education programme explaining business objectives, information management, processes and technology must persist throughout the lifecycle of the programme and not allow itself to be diluted if problems arise with cost and schedule challenges. The education approach should be adaptable to meet emergent needs but these should not conflict with the business objectives of PLM. B.22 stated that technology should not be the priority of improving PLM, but rather people and processes require focus to meet business objectives and customer requirements. Improving the skills of the programme personnel is important and that some people will understand PLM more than others and that there should be an approach to ensure there is an explicit understanding of PLM within the business. In addition, it should also be linked with business change management to ensure the behavioural aspects are addressed. He also described that when implementing an education approach it should be tailored to ensure that those involved are given the appropriate level of understanding required. He added that the business should identify those who can be taken to a higher level of knowledge and focus additional training for them as these could be the new PLM leaders. B.4 also raised education as an improvement he would make to his PLM environment. This is consistent with B.13 who stated that they need to spend more time educating people on what is expected, where it is and how to access it. This is again confounded by their PLM approach being different from other ETO programmes in his business and people need to be able to operate in the environment correctly.

B.17 raised the importance of the persistence of knowledge within product development as when people retire their knowledge is lost. He also stated that the more complicated the product is, the more difficult it is to make decisions due to the interdependencies within the product development lifecycle. He cautioned that, when improving PLM and leveraging knowledge, innovation should not be hampered. Therefore, while education to improve knowledge, skills and culture is important, the rules associated with effective PLM should not constrain the innovation process. B.1 described communication and training as improvements they would make to their PLM environment. Moving from a traditional document-based approach to one which is data-centric is not insignificant and should not be underestimated as it is a significant change for people. He provided an example of where their business' traditional training programme for engineers does not cover PLM which means that the engineers do not support his requirements. He explained that the business is ill equipping engineers to work within his programme. He explained that engineers must understand the relationship between maturity and programme management in order to correctly manage the product development. He continued by stating that there are disconnects across the functions in the business such as between supply chain and engineering. PLM is seen as being organised by engineering and perceived as being engineering-centric but it must be cross-functional and that an integration and understanding of the needs of each function within the PLM environment must be managed.

B.16 identified improvements that must be made to the way that the business functions within the programme work together including how the design provided by engineering integrates with the supply chain. B.26 described how they engaged with smaller partners in their ETO programme to help them understand and comply with their PLM approach and to assist with their integration into the programme. Educating the stakeholders in the use of PLM is important in meeting the objectives of the programme. Stakeholders, including the suppliers, must understand the implications of information that they either provide or consume. PLM training should be embedded within the core business education programme across all of its functions and stakeholders in the extended enterprise, and should not be seen a standalone environment for engineers. The training must ensure that PLM supports the business objectives of the ETO product. If programme personnel do not have PLM knowledge, such as the approach to managing maturity, then they cannot be expected to ensure that they understand the impact of the information they provide on the overall integration of the design and its relationship to the programme schedule.

B.24 also raised the importance of education in moving from traditional environments where CAD information was the focus to one which is product data-centric. He provided an example of a current ETO programme which has been in progress for decades where drawings were the main product artefacts for the product development and build. He stated that people need to understand data and why its quality is so important. He explained that if people understood the consequences of their information, it would encourage them to improve information quality. B.10 provided an example from his ETO programme where his colleagues do not understand the information architecture and that if this was addressed it would improve the success of PLM. This, he added, impacts people's ability to understand and work with the PLM system.

B.12 stated how they introduced a new approach for engineering to support the manufacturing requirements; however it was difficult to explain and transition to support this initiative as they were used to do something different. He explained that it is important that the needs of the various stakeholders are understood and that this is institutionalised within the business. He stated that to overcome these difficulties, it is necessary to train and coach people on the consequences of their actions, their cause and effect. He provided an example of someone designing equipment into the CAD model and how they should be considering how this would be installed, e.g., ensuring there is enough space to allow access for its installation. B.18 also commented on the importance of education and how helping engineering to understand what the consequences of their actions are. She embellished this stating that there needs to be education on what the effects are of actions and their impact to the overall programme. She gave an example of a decision which had a big impact on weight even when there has been documentation to explain what the weight guidelines are.

When developing and implementing a PLM education approach it must cover all of the requirements of the various stakeholders within the ETO NPD. Each of the business functions such as engineering, supply chain, manufacturing and programme management will have different objectives which are required to be supported by PLM. These requirements should be embedded within the education programme for the business to ensure that those required to provide the necessary support understand clearly what is required and why it is important. Due to the size and complexity of ETO programmes, this will be a challenging endeavour which will require the necessary funding from the business not only to create the education framework, material and trainers, but also to ensure that the many personnel involved are given the necessary time off their other commitments to undertake the training and gain the necessary knowledge.

B.8 described that, due to the long lifecycle of ETO products, it can be difficult for personnel to be able to track and understand the value of PLM on larger projects than it would be on smaller projects. He believed that there is an educational element to this, and added that large ETO businesses find it difficult to communicate to the teams due to their size, a problem which is less apparent in small organisations. Smaller organisations find it easier to understand each other's interactions and he suggests that, due to the size of ETO programmes, it is difficult to share knowledge and be part of a single team. He commented that his ETO NPD is, by far, the most siloed environment he has worked in, even for those within the same building. Examples were provided by B.8 of various disciplines within engineering who work within their own teams and do not interact well, and that there is a 'heads down' attitude, one which should be changed to where the personnel are sharing their experiences.

The education of the personnel must include the benefits of PLM and why it is important, even if some of these will not be realised for many years, for example within the manufacturing phase which could be a decade after the programme initiation. B.11 raised the point that an improved understanding of PLM will help people to overcome perceived difficulties and limitations with PLM, which will help to address the pursuit of sub optimal approaches. B.13 made the point that they don't equip their programme personnel to work effectively with PLM, stating that people often see PLM as technology but that it must include policy, process and people. The education programme should therefore not be exclusively technology-centric but must include all aspects of PLM. This should include the business polices and people and how the technology enables these aspects.

B.5 described the importance of understanding the developing maturity of the product and that this includes the design systems, supplier information and the cost model. He explained that this is important in not only understanding the current status of the programme but also in bidding for the next phase of the work. Due to the size of ETO programmes, funding is often released sporadically through agreeing phased contracts between the customer and the delivery business. An understanding of programme status will assist in helping to develop the bid for the next phase of work and agreeing cost, schedule and risk. It will also improve the relationship and confidence of the customer. An understanding of all of the information which relates to the programme status is important. This will be enabled through an education programme which covers all product information in the programme across all of the business functions, including engineering, supply chain, programme management, in-service support, manufacturing planning, manufacturing and IM&T.

7.6.3.4 Develop PLM objectives, education approach and support to the business using suitable expertise within a dedicated cross functional team

This section explains the importance of having a central team responsible for developing PLM objectives and how these relate to the overall business objectives. It also describes how this central team will provide education and support to the stakeholders.

The development of the PLM objectives and the approach to educating the stakeholders on these objectives is required. Ongoing PLM support to the stakeholders is also required to ensure they have the necessary guidance to deliver the objectives. As the stakeholders will be from various business functions the PLM delivery team should represent these functions.

B.6 explained that objectives must be made clear to the programme and each stakeholder's accountabilities must be understood. The PLM team will enable the development and integration of business objectives as well as defining how PLM will support their realisation. B.25 described how his business has recognised the need for centralisation of key capabilities across the business with members from these areas being embedded in the programmes. He stated that this assists with the utilisation of key resources with more focus on business value-adding activities, and would enable the cross-functional PLM expertise to be managed centrally and cascade the PLM approach to the ETO programmes. It will also assist with the utilisation of the scarce PLM SQEP which is difficult to recruit from other industries, due to the uniqueness of ETO products processes and information approaches compared to other products.

B.7 described how ETO products can have a 15 year design and build programme which means they can be a business within a business. Thus, there is a need to drive processes out across all the programmes and not just a single one. He explained that the business needs to be set up to support this and it will enable a standardised approach across all the programmes. 0 stated that standardising training across all programmes will assist with ensuring that LFE is driven across the business including leveraging previous investment. A dedicated team would address the concerns raised by B.14 on using resources that have other responsibilities in the programme, as they would be within the PLM team management structure. B.8 stated that his experience of a central PLM team has been positive, and that the level of facilitation this has provided in delivering PLM, has been better than any he has experienced. He explained that if you took this team away, then there would be an impact in the success of the PLM approach due to the challenges of large-scale projects. This PLM team will also have responsibility for those enabling activities related to information, process and technology described in Section 7.6.

7.6.4 Technology enablers

This section describes those enablers relating to technology for the implementation of PLM on ETO products. These have been synthesised from the interview responses through thematic analysis which enabled subsections to be created. These enablers include the identification and implementation of configurable PLM toolsets with minimal customisation. Driving the integration of information through toolset rationalisation was another technology enabler. Also identified was focusing toolset development on business objectives, priorities and ease of use to reduce complexity of processes. Another technology enabler was the implementation of IT architecture improvements to support new PLM capability and ensure toolset performance. The technology enablers are illustrated in Figure 36.

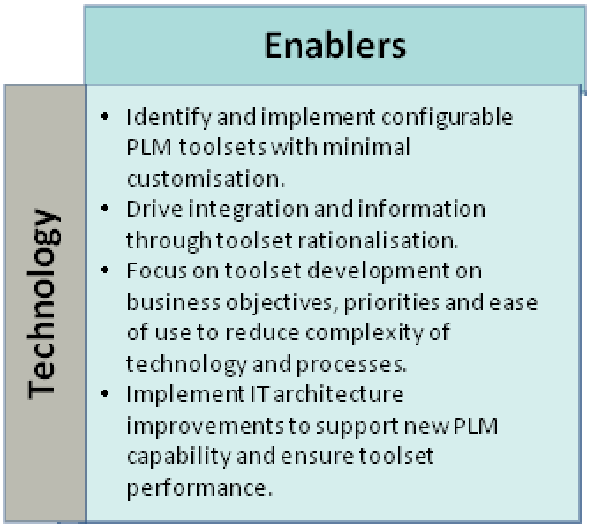


Figure 36 Technology enablers

7.6.4.1 Identify and implement configurable PLM technology with minimal customisation.

The challenge of ensuring that PLM technology can support the long life of ETO NPD was discussed in Section 7.5.4.1. Ensuring that technology customisation is kept to a minimum is an important enabler to overcome this challenge. B.2 described how they learned from a previous ETO programme which had highly customised technology and became difficult to support. They have now implemented technology which is the foundation for their programme and are COTS applications which have been configured to meet the needs of the programme and have significantly less customisation. In addition, he added that the lesson they learned was to go with COTS products and that this allows them to easily upgrade and keep the versions of the software current with the latest releases by the vendors. He also explained how these COTS toolsets have interfaces between CAD, PDM and ERP. Therefore, a lack of customisation allows for exploitation of out of the box capability for integrating the PLM systems, making them more robust and easier to support. In contrast to this, B.11 stated that their PDM systems are heavily customised, have approximately 20 interfaces, and as a result are not effective and make the use of the toolsets very difficult.

Customised software is difficult to upgrade as the vendors cannot use standardised upgrade methodologies due to the differences in the software compared to those which are non-customised. This results in expensive investigations and bespoke developments specifically to enable the upgrading of these complicated PLM technologies. B.11 stated the importance of not customising the PLM technology to ensure it maintains supportability and that when the software vendor brings out a new version they can quickly move to that. B.23 agreed with this, stating that on their programme, they are moving from a highly customised environment to that of one which is COTS. He stated that this is taking years, and they still cannot respond adequately to the emergent technology needs of the business due to the level of customisation and the resources applied to this project. B.20 also commented that they have elements of customisation within their technology but there is a drive to use COTS systems.

B.3 was concerned that attempting to meet PLM objectives could result in customisation, however B.19 commented that the PLM technology used in ETO products must be flexible to cope with business objectives. He added that there should be PLM capability to manage the understood requirements of the programme, such as managing the BoM, but it has to address new requirements to meet the emergent needs of the programme. He used the example of an ERP system to improve the management of build completion activities to illustrate this, and suggested that technology must be able to adapt to new ways of working which have yet to be thought of. The Type 26 case study described in Section 5.9 discussed how the PLM technology was configured to support build completion activities using master data from the BoM.

He stated that technology configurations should be managed within the business so that they do not have to go to the software vendors every time a new requirement is issued. He stated that the technology delivery team required more training from when the programme started to ensure they can configure the software to meet business requirements. If the approach of using an in-house team to configure the software is to be effective, then this team must have the capabilities to understand what the software can achieve and how it can be adapted to meet emergent business requirements. B.27 highlighted the importance of engaging with the software vendor will help to ensure that the technology is used appropriately. However he raised the concern of funding for using vendor personal for programme activities. B.17 also stated the importance of having technology that is flexible and provided the example of product change management which must work effectively to support the needs of the programme. Ensuring that configurable COTS software is selected for PLM programmes will assist with the reduction of customisation and also will exploit new business requirements such as those described in the Type 26 case study in Section 5.

7.6.4.2 Drive integration of information through technology rationalisation.

Information integration is an objective of PLM on ETO products as discussed in Section 7.4.1.1. PLM technology toolset rationalisation can assist with information integration as it discourages duplicate or disparate information due to them being managed in different toolsets. An improvement proposed by B.11 to their PLM environment would be to simplify it through rationalisation of toolsets, as they have a number whose functionality could be undertaken by a single PDM system. If they moved to a new PDM system, he believed that they could retire 12 out of 20 PLM toolsets. This would also reduce manual interaction on the information and toolset maintenance, and forecasted an associated resource reduction by utilising the functionality of a core PDM system.

B.26 stated that in an ETO programme, he experienced a customer paying multiple times for information changes due to it being in different systems and believed that a single point of truth is the key which should include the design and in-service support information. B.4 commented that they are implementing new PLM technology to provide a more integrated environment, part of which involved removing legacy toolsets and replacing them with a PDM and ERP system. He explained that this will reduce risk as there are a number of legacy tools that are not well understood by the business.

Whilst the problems that 0 had experienced on previous ETO programmes were due to unintegrated systems, the current programme with which he is involved has improved technology integration across the CAD, PDM and ERP applications which is eliminating manual translation of information and is improving data integrity. The requirement from the Type 26 case study provides an example of this approach as discussed in Section 5.4.

B.14 highlighted the importance of integration between the PLM systems and explains that they are endeavouring to improve the integration of the key business information. The rationalisation of toolsets across the ETO programme will enable information to be managed in fewer systems which will improve its quality and management. B.7 stated that an improvement he would make to his PLM environment would be to standardise the toolsets as this will drive consistency in the way people behave and also will assist in eliminating variation errors. A rationalised PLM system of systems will also reduce the complexity of the interfaces required to support the programme. This is due to the higher number of toolsets in the PLM environment and the greater need there is for passing information across the interfaces, which will lead to greater maintenance of the information including resolving information alignment and quality issues, supporting the data quality and governance enabler in Section 7.6.1.3. The rationalisation will also have the benefit of reducing the lifecycle and maintenance costs of the legacy toolsets and will enable a reduction in the IT architecture required to support these systems.

7.6.4.3 Focus toolset development on business objectives, priorities and ease of use to reduce complexity of technology and processes.

PLM toolset development should focus on business objectives and be prioritised accordingly. PLM toolset development should be managed to support a reduction in complexity not only in the technology but in the processes it enables. The importance of easy to use PLM toolsets was highlighted by B.3 who commented that while they have been focusing on PLM system integration they also have to be aware that it has to be useable. As discussed in Section 7.6.4.2, a reduction in the number of software applications used in the PLM environment has been identified as an enabler for improving the implementation of PLM by encouraging information integration, as the disparate sources of data are reduced. The core applications such as CAD, PDM and ERP are configured to replace the legacy toolsets and out of the box (OOTB) functionality from COTS applications must be used to ensure these toolsets are not customised. The OOTB functionality should also be used for the interfaces across the core application suite to ensure that the PLM System interfaces are supported by the software providers.

The reduction in the technology footprint in the business and the transfer of the functionality onto a reduced number of toolsets, such as CAD, PDM and ERP, will result in the information managed in these toolset increasing and the interfaces becoming more complicated. This may impact the ease of use and efficient maintenance of the technology and its information. Mechanisms must be in place to ensure that the priorities of the business such as technology and information integration are prioritised but also that the software applications do not become unusable. This dichotomy that simple systems are not always achievable was explained by B.10, as the toolsets have to be complicated enough to meet the needs of the business. Therefore, the development and implementation of the new capability must be carefully managed if the capability is to achieve the balance between the business objectives, usability of the toolsets, maintaining simplicity and managing the technology priorities.

B.3 stated that they should actively investigate how the technology is used and its ease of use. He explained that he gets feedback from engineers that, while working in the PLM software applications, they spent a lot of time doing what they see as administration tasks, as opposed to undertaking core engineering activities. He stated that they should make the applications more user friendly from an engineer's point of view ensuring that it is easy to put information in, and to get it out. He suggested that a way of achieving this could be through surveys or user groups into the technology improvements which will provide the greatest impact, but this can be anecdotal and takes time.

B.19 described the importance of managing workflows effectively and B.2 stated that they were able to configure their technology to make it easier to use and provided an example of electronic workflow simplification. Ensuring that the toolsets does not become overly complicated requires an understanding that technology should not replicate the complexity of ETO NPD, but support it. The example of the workflow simplification provides an illustration of technology supporting the processes without replicating it.

Technology should be scalable depending on the programme objectives as highlighted by B.13 who added that some programmes which are of a larger size and complexity may require technology which has more functionality than smaller programmes. Since the PLM technology solution for one ETO programme may not be appropriate for another, understanding the objectives, priorities and constraints are important. These constraints may be with the budget, schedule or the number of resources in the programme. An improved understanding of business priorities and scope will enable the Information Management and Technology (IM&T) team to focus their resources to deliver appropriate technology solutions.

7.6.4.4 Implement IT architecture improvements to support new PLM capability and ensure toolset performance

It is important that the IT architecture which enables the business objectives, including new processes and information management policies, will provide adequate functionality and ensure technology performance. There will be the larger volumes of data in the core applications due to system integration and the resultant reduction in the IT footprint as discussed in Section 7.6.4.2. The requirement for any PLM environment to have a robust and flexible IT infrastructure was proposed by B.17. This point was also considered by B.19 who explained that there is constant IT architectural change and stated the importance of keeping it up to date as people do not see the benefit until it is not there. B.19 added that the senior management team need to understand what the technology architecture is, and how it benefits the business, but creating a simple diagram which they can understand is difficult. He explained that there are new techniques in IT such as the cloud and virtualisation technologies but they need to update their toolsets quicker than they have ever done before to respond to the emergent business requirements. He provided an example where a PDM system upgrade project would typically take eight to nine months, but they now need to do it in three months to respond to the business objectives.

Introducing new capability quickly to meet the emergent requirements of ETO programmes is necessary to ensure that the product development lifecycle is not impacted. A reduction in the amount of customisation as discussed in Section 7.6.4.1 will contribute but there is also a need to implement new capability quicker than ever before and the integration of the PLM systems adds another complexity.

B.19 explained that, as the CAD and PDM systems are closely integrated, it was not possible to upgrade one application in isolation; both have to be upgraded in parallel. This adds additional complications to the IM&T departments who are responsible for the applications and the underlying IT architecture. More efficient practices for upgrading and introducing new capability to meet the needs of the business are required.

Aiming to fragment testing as they develop new capability in order to improve the time taken to implement into the programme was highlighted by B.19, but he added sometimes this is not possible. The translation of business knowledge into requirements for the software capability was discussed by B.4 using the agile scrum software engineering methodology to allow the requirements owners to see the evolution of the developments. He stated that it works well as it gives the business early insight into what the changes are and what it does before going live. This mitigates the risk of not meeting the requirements and non-acceptance, which in turn can result in further delays to the new capability introduction. He explained that the scrum approach also assists with the business change as it helps engage the business early on and gains buy-in before the implementation of the new capability. This was stated as being critical as these systems are live and manage years of data so there is a resultant large volume of data which requires migrating into the new system. The importance of testing the interfaces was raised by B.2 who described that, as the CAD and PDM applications work differently; they keep finding problems that require addressing.

Therefore approaches to quickly and effectively introduce new capability required to meet ETO programme requirements is important, as the product development process cannot be delayed to allow major IT upgrades. It is also important that the risk of failure of these implementations is minimised as any impact in the PLM environment will have a significant impact on the programme.

IT investment requires significant funding from the business and, if it is inadequate, the technology environment will not be able to support the PLM objectives which will impact the ETO product development, the programme and, ultimately, the business and customer. Securing this investment is necessary as is ensuring that it is enhanced as larger and larger volumes of data and user interactions are experienced throughout the ETO lifecycle. This is supported by B.13 who stated that a lot of time and effort must be put into the IT toolsets and interfaces as the user community will get frustrated if it does not work, and if it fails, people will be up in arms in five minutes. He explained that the technology is now further up Maslow's hierarchy of needs within an ETO programme context. Due to the importance of PLM technology in ETO programmes, if the applications become non-functioning or poorly performing then this this will have an enormous impact on the ETO programme's cost and schedule. This risk is greater with more information in fewer PLM toolsets and a greater complexity in the interfaces between these systems.

7.7 Summary

This section described the development of the framework to provide guidance for the implementation of PLM on ETO products. The thematic analysis of semi-structured interviews using codes and themes identified through transcribed interview key points in the NVivo software tool was the primary approach for creating the framework. This was supported by literature where appropriate. The interview questions related to objectives, challenges and enablers were identified and used to create the framework.

The codes and themes developed in NVivo enabled the grouping of interview responses allowing the related key points from the interviews to be described. To provide an audit trail to support the truthfulness of the findings, each key point was referenced to the transcribed responses in Annex B. The preparatory work to transcribe the key points, as well as the import and subsequent analysis in NVivo took considerable effort. The results of this preparation supported the development of the findings in Section 7 as each theme and related key points could be easily identified and described. Due to the substantial information provided through the key points from the interviews, and its importance in developing the framework, Section 7 is the most extensive in the thesis.

The framework themes are grouped based on whether the interview question related to an objective, challenge or enabler. This was to ensure that the context and structure of the framework was easy to understand. A further enhancement to the framework structure was identified through the use of Enterprise Architecture. EA is a well-established methodology to improve the creation of information to describe the strategy, objectives, processes and technology of a business. It also supports the transition from an 'as-is' to a 'to-be' environment by improving the understanding of the new environment and therefore aiding in the business change activity. EA influenced the grouping of the themes to improve the structure and understanding of the framework. This included the objectives, challenges and enablers contained within information, people, process and technology.

Each of the themes in the framework was described in detail and related to information, process, people and technology. These themes were used as sub-sections within the main section of objectives, challenges and enablers.

The next section describes the framework evaluation approach and findings.

8 Evaluation and Validation

Evaluation reflects the judgement or calculation of the quality, importance, amount, or value of something [15]. Validation provides proof that something is correct which in this context is that the framework contains the necessary elements for the implementation and successful use of PLM on ETO products [15]. Borrego et al. stated in relation to the aim of evaluation in qualitative research: 'the goal is to establish that the results provide convincing evidence sufficient to answer the research questions' [143]. Section 7 described the development of the framework for the implementation of PLM on ETO products. This chapter presents an evaluation of the framework which was undertaken using the following stages:

1. Preliminary evaluation through the presentation of the framework for initial feedback on structure and content. This was to gauge initial reaction to the structure of the framework to ensure it was easily understandable.
2. Main evaluation and validation through the presentation of the framework to selected participants followed by a questionnaire. The questionnaire contained statements to evaluate and validate the framework quality, structure and versatility.
3. The industrial application of the content of the framework in an ETO product. This section describes how the themes identified in the framework were used to develop the PLM approach in BAE Systems Naval Ships.

Each of these will be discussed in the following sections.

8.1 Preliminary evaluation of framework structure

Three presentations were undertaken to capture initial feedback on the structure of the framework to assess its ease of understanding and coherent layout. The presentation slides (Appendix A) were used to describe the research to provide context, followed by an overview of the framework developed from the thematic analysis as described in Section 7. As explained in Section 7.2, each of the themes were structured around people, process, information and technology, using objectives, challenges and the enablers. A first draft of the framework (Appendix D) was presented to the participants.

The first presentation took place on 23rd May 2017 with two participants with a significant interest in PLM implementation on ETO products from BAE Systems Naval Ships. These two participants had not previously been interviewed at any stage but were aware of the research. This approach was chosen to capture feedback from participants who were not involved with the research to gauge the content, structure and ease of understanding of the framework. The feedback was positive and both confirmed that they believed the framework would be of significant benefit to the implementation of PLM on ETO products. They questioned why the researcher had not established a relationship between each of the themes on the framework to more easily understand how an enabler could overcome a specific challenge to meet an objective. The researcher described the feedback from the interview responses as described in Section 7.2 that the framework is required to be flexible and scalable. The researcher added that specifying relationships between the themes may lead the guidance to follow specific routes and constrain its ability to be dynamic to meet various business objectives. They agreed that this would be necessary due to different programmes having different objectives and challenges. An example is where an ETO organisation is planning a PLM implementation where there are significant budget constraints, such as the UK Type 31 which is designed to be a less complex ship compared to the Type 26. It was also important to enable flexibility due to the emergent challenges in ETO products, for example there are programmes which require greater focus on people but may have a mature PLM technology architecture. The researcher stated that there was potential for future research to identify how they could be aligned, but with flexibility maintained. This has been captured in the further research in Section 2. They also highlighted that they agreed that 'enablers' would be a better description than 'improvements'. This was due to the themes describing how PLM could be implemented. They believed that 'enablers' better described that the themes were required to support the successful implementation of PLM on ETO products.

The second presentation took place on the 28th May 2017 with a participant who has a significant interest in PLM implementation on ETO products from BAE Systems Naval Ships. This participant had previously been interviewed. This enabled feedback from someone who understood the research aims and objectives and contributed to the findings. The participant stated that the themes and the framework structure were extremely valuable and would provide significant benefits to PLM implementation on ETO products. It was added that the 'enablers' were useful as they would support the development a new, more skilful, talented and technologically aware generation of engineers in the business. The participant described a desire to take the framework from inventive to exploitation and utilise it in an industrial capacity. It was additionally suggested that the framework and the background detail could be integrated electronically to aid understanding - a theme could be selected and the stakeholder presented with the relevant underlying information. The researcher agreed and stated that this would be an opportunity for further research as stated in Section 10.9.

The final presentation and discussion of the framework took place on the 7th June 2017 with one participant with a significant interest in PLM implementation on ETO products. This participant had previously been interviewed but was from an export customer. The feedback elicited was that the findings and the framework would provide significant benefits to their company and that it would steer the direction of their PLM strategy. It was opined that the framework provided a great presentation of the summary of the results, and a request was made for a document which described the overall research as this would help communicate this new approach to his business. The researcher explained that he would provide an academic paper, preferably in a peer-reviewed journal, on the conclusion of the research.

8.2 Main evaluation and validation of framework

Following the preliminary evaluation, a questionnaire was used as the main evaluation approach to capture the opinion of the senior stakeholders in ETO products who have an interest in the successful implementation of PLM. The questionnaire contained statements, which according to the Cambridge dictionary are actions used to express an opinion [15]. A questionnaire was chosen to focus the participants on the framework quality, structure and versatility using the statements shown in Table 13, the rationale for these statements is described in the following sections. Semi-structured Interviews were considered, however it was decided that they may result in conversations that were not related to the framework evaluation, and were therefore not pursued. The questionnaire enabled focused statements to be answered by the participants relating the evaluation objectives of the framework without the time necessary for structured interviews.

8.2.1 Development of the questionnaire structure

Section 6.2 described the interview questions used to develop the framework and why they were chosen. Q13 was created to address the following:

'Q13 - Would a framework assist with the transition from as-is to the to-be, if so how?'

This question aimed to investigate how a framework conveying the results of the research would assist in the implementation of PLM. It was also intended to capture the ways in which the framework would assist and investigate any potential enhancements in its design and use.

The framework content is structured using the thematic analysis of the interview responses described in Section 6.5. The key points from Q13's interview responses in Annex B confirmed that a framework for the implementation of PLM on ETO products is necessary, but the responses to Q13 also indicated that it must be easy to use, and should not mandate how it should be used and implemented. The interviewees commented that a framework should be flexible, scalable and easy to use. Therefore, the framework was designed to allow any combination of objectives, challenges and enablers which the ETO programme believe is most appropriate and which aligns to their business model. The responses contributed to the design of the framework but also to the evaluation objectives for flexibility.

The main objective was to evaluate and validate the framework quality, structure and versatility, measured based on the responses to the questionnaire. These opinions relate to the validation objectives for the quality of the PLM framework (Statement 1.1) which validates the research results in Section 7, in other words proof that the framework contains the necessary elements for the implementation and successful use of PLM on ETO products. The opinions also relate to the evaluation objectives for the quality of the PLM framework (Statement 1.1 to 1.3) and its structure and versatility (Statement 2.1 to 2.5). To enable this, eight statements relating to the evaluation objectives were used in the questionnaire, and the participants were asked to respond in terms of the extent to which they agreed or disagreed with these statements. The statements and the related evaluation objective are shown in Table 13.

Evaluation objective	Statement No	Statement
Framework quality	1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.
	1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.
	1.3	The framework is effective for the implementation and successful use of PLM in ETO products.
Framework structure and versatility	2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.
	2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.
	2.3	The content of the framework can be easily followed.
	2.4	The framework appears to be flexible in its use.
	2.5	I/we would use this framework to implement PLM on ETO products.

Table 13 Statements in the questionnaire related to evaluation objective

8.2.1.1 The Framework quality

Quality can be defined as how good or bad something is and that it is of a high standard [15]. Determining the quality of the framework is important to understand how well it will support the implementation of PLM on ETO products. There are three quality statements in the questionnaire and their reasoning to meet the evaluation objectives are shown below.

Q1.1 - The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.

The framework contains the themes derived through thematic analysis as described in Section 6.5. This question was used to investigate whether there were any elements missing which are required for the successful implementation of PLM on ETO products, including objectives, challenges and enablers.

Q1.2 - The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.

The objective of this question was to evaluate whether the framework provides guidance to support overcoming the identified challenges with the implementation and successful utilisation of PLM on ETO products.

Q1.3 - The framework is effective for the implementation and successful use of PLM in ETO products.

The significant contribution to knowledge corresponds to the construction of a framework which provides guidance for the successful implementation of PLM on ETO products. The question was used to evaluate whether this overall aim has been met.

8.2.1.2 The Framework structure and versatility

Structure can be described as how something is organised and arranged [15], which was important for the evaluation objective as the framework themes have been organised based on the enterprise architecture approach described in Section 0. Versatility can be as a characteristic of something, which allows it to be changed easily or used for different purposes [15]. The interview responses to Question Q13 reflected an opinion from the interviewees that they did not want a framework which constrained them into a rigid approach. They required a framework that is flexible and can be adapted based on their business objectives. Therefore, the versatility of the framework was another important characteristic of the evaluation. As structure and versatility are closely related, they have been combined in the evaluation statements, these statements and their rationale are provided below.

2.1 - Using information, process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.

The structure of the framework was developed to contain the PLM objectives, challenges and enablers across those themes relating to information, process, people and technology as described in Section 0. The objective of this statement was to evaluate the structure of the framework based on this approach.

2.2 – Information, people, process and technology across objectives, challenges and enablers covers all the categories for the implementation for the successful use of PLM in ETO products.

The objective of this statement was to evaluate whether the structure of the framework captures all the necessary elements required for PLM implementation, i.e., ensuring that the structure does not preclude any necessary elements which may be required but are missed or not clear due to the framework structure.

2.3 - The content of the framework can be easily followed.

For the framework to be effective it must be easy to follow, even though it is supporting the realisation of PLM objectives on new product development of complex products. The objective of this statement is to evaluate how easy the framework is to understand.

2.4 - The framework appears to be flexible in its use.

As described in the responses to Question 13 the interview participants asked for the framework to be flexible and not mandated to enable elements of the framework to be targeted dependant on the objectives of the business. This statement evaluates the flexibility of the framework.

2.5 - I/we would use this framework to implement PLM on ETO products.

The participants were chosen due to them being senior stakeholders in ETO products who require successful PLM implementation to meet their business objectives. This statement was used to evaluate whether they would use the framework to implement PLM on ETO products.

The participants were also asked to provide comments on the framework and/or and the research, and on the validation approach itself. This was included to understand any general feedback or motivation for the questionnaire response.

8.2.2 Evaluation and validation approach

The approach to the main evaluation and validation was constructed to consist of identifying participants who would attend a one hour workshop, either face to face, or via a teleconference with shared media. These participants were selected from business functional roles within ETO, or partner organisations within the extended enterprise. These organisations included:

- UK ETO design and manufacture;
- USA ETO design and manufacture;
- Canadian ETO design and manufacture;
- Canadian ETO customer;
- Australia ETO design and manufacture;
- Australia ETO in-service support; and,
- USA PLM ETO technology provider.

These organisations are involved in various multi £B ETO programmes and their products are global leaders. They are geographically dispersed supporting the triangulation of the evaluation to ensure that the framework is effective across different ETO products who may have different customer constraints, for example government practices.

The roles within these ETO organisations were selected to represent stakeholders who have business objectives required to be met by a successful PLM implementation. The participants were a mixture of those interviewed to generate the findings, those aware of the research but not interviewed and those with no knowledge of the research. The majority of those selected for the evaluation had not been previously interviewed; this was to support an independent view of the value of the framework based on the results of the thematic analysis. These roles include:

- F.1 - Head of manufacturing planning (not previously interviewed);
- F.2 - Engineering manager – in-service support (not previously interviewed);
- F.3 - Engineering manager – Design (previously interviewed);
- F.4 - Manufacturing planning manager (not previously interviewed);
- F.5 - Engineering manager – BoM (not previously interviewed);
- F.6 - Engineering manager – PLM (not previously interviewed);
- F.7 - IM&T manager (not previously interviewed);
- F.8 - PLM consultant (not previously interviewed);
- F.9 - PLM architect (not previously interviewed);
- F.10 - Design authority (previously interviewed);
- F.11 - Operations manager (previously interviewed);
- F.12 - Head of engineering (previously interviewed);
- F13 – Head of Enterprise Architecture (not previously interviewed);
- F14 – Head of IM&T (not previously interviewed);
- F.15 - Underwater systems specialist (not previously interviewed);
- F.16 - Programme director (not previously interviewed);
- F.17 - Deputy head of programme management (not previously interviewed);
- F.18 - Systems engineering manager (not previously interviewed); and
- F.19 - Engineering director (not previously interviewed).

In total there were 19 participants who responded and a further 6 who did not. Due to the risk involved with allowing the participants to respond after the presentation was delivered and questionnaire circulated, non-respondents were expected. The risk was mitigated by ensuring each organisation and business role targeted had at least one respondent. These participants were from various business functions but all are in senior positions and are stakeholders in the successful implementation of PLM in ETO products. The participants were engaged in the evaluation either on a one to one basis, or in small groups in a one hour session with the intention of communicating the research aims and methodology through a poster presentation as shown in Appendix E. The PLM implementation framework was then described using Appendix D followed by the questionnaire structure. It was decided that the one hour slot was utilised to maximise the time taken to describe the framework, and for the participants to subsequently complete the questionnaire in their own time following the session. They would therefore be able to re-read and complete the questionnaire in their own time [167]. This would enable then to reflect on the material presented and then complete the questionnaire. The participants were requested to rate their level of agreement or disagreement towards the statements using a five-point Likert scale. The range of options were: strongly disagree; disagree; neutral; agree; and, strongly agree. This approach and the wording of the statements was used in order to not lead the participant to a particular rating.

Following the briefing sessions the participants were sent the poster, framework, questionnaire and declaration form and asked to submit the responses to the questionnaire within two days. This self-completion approach introduced the risk of the participants not completing the questionnaire due to other commitments. This risk was acceptable to ensure the one hour sessions were dedicated to communicating the research approach, the outcome and the importance of evaluation using the questionnaire. The participants were a mix of those who had been interviewed to develop the framework, using thematic analysis as discussed in Section 7, and those who had not been involved. The approach was designed to ensure that there was a balance in the results from those who had been involved in the research and perhaps would see their input in the framework, those aware but not interviewed and those who had not previously been aware of the research.

8.2.3 Evaluation and validation results

The responses to the questionnaire questions relating to Framework quality, structure and versatility are shown in Figure 37.

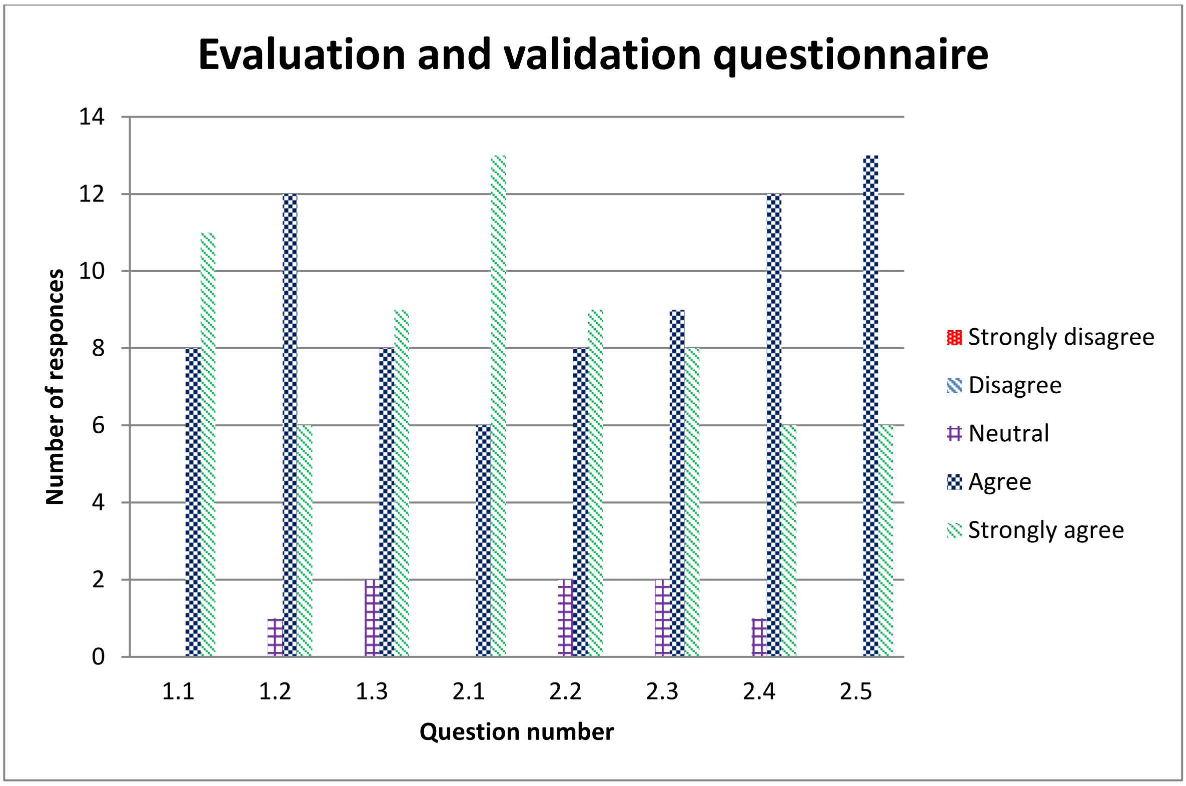


Figure 37 Questionnaire responces

As discussed in Section 8.2.1.1, Statements 1.1 to 1.3 were included in the questionnaire to assess the quality of the framework. For Statement 1.1, 42% of participants agreed that the framework contained the necessary elements for the implementation of PLM on ETO products with a further 58% strongly agreeing. For Statement 1.2, the responses reflect that 63% of participants agreed that the framework assists with overcoming the challenges in PLM implementation on ETO products, a further 32% strongly agreed, 5% responded neutral with no reasons given. For Statement 1.3, 42% agreed that the framework is effective for the implementation of PLM on ETO products and 47% strongly agreed, with 11% providing a neutral response. The comments from those who provided a neutral response for 1.3 related to the tailoring required to suit specific business circumstances and also that the detailed research behind the framework would be beneficial.

Section 8.2.1.2 described how statements 2.1 to 2.5 were used in the questionnaire to describe the structure and versatility of the framework. For statement 2.1 the responses found that 32% agreed and 68% strongly agreed that the framework structure of using information, process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework. Statement 2.2 had 42% agreeing, 47% strongly agreeing and 11% neutral response for the structure of the framework containing all the categories required for PLM implementation. The neutral response contained the comment that timescales are an important factor in PLM implementation and also that they would like to learn more about the framework. Due to the long lifecycle of ETO programmes and the constant technological advances, the participant highlighted challenges of aligning business operating timescales with technological innovation. This is discussed in Section 7.5.4.1 where upgrading or implementing new technology can be challenging for ETO products.

Statement 2.3 had 47% agreeing that the framework can be easily followed, with 42% strongly agreeing and 11% with a neutral response. No indication was given in the questionnaire comments why a neutral option was provided. The response to statement 2.4 had 63% agreeing and 32% strongly agreeing that the framework is flexible in its use, there was 5% with a neutral response. The neutral response related to a request to understand more about the research and the framework. Statement 2.5 had 68% agreeing and 32% strongly agreeing that they would use the framework to implement PLM on ETO products.

The responses to the questionnaire statements supported the objectives of the questionnaire for quality, structure and versatility as discussed in Section 8.2.1 with 95% of the responses either agreeing or strongly agreeing with the statements. The comments included within the questionnaire responses also supported the value of the framework. F.1 for example highlighted that in their experience there is an overreliance on technology to support PLM objectives and that it is the human factor that supports the successful implementation. F.1 added that it is refreshing to see this represented in the framework. F.15 commented that more emphasis on culture would have been preferred, especially with explaining the benefits of PLM to the stakeholders. This included: reduction in cost for through-life support, obsolescence management and rework; reduction in schedule risk due to rework; improved safety due to configuration management; and, a further risk mitigation for cost due to a reduction on safety incidents. It was explained to the participant that the framework contained enablers on improving culture and education, and that the researcher agreed the importance of business change to PLM implementation on ETO products. The focus that the framework gives to cultural change was raised by F.16 who stated that she appreciated 'the priority given to the cultural change required for a successful implementation'. She went onto state that she 'would be interested in exposure to the next level of detail'. F.17 highlighted that 'securing the support of the business is, and will always be, a key challenge and a very important enabler'.

The comments also highlighted the importance of versatility, with F.2 stating that tailoring was important, whilst acknowledging that the framework described their business challenges. F.11 stated that they were tailoring the framework to use on new programmes stating that 'the framework as specified is being tailored for use on a number of new/prospective programmes'. He went on to describe how the framework provided a scalable and tailorable approach for PLM implementation in a complex environment. F.14 commented that they are currently implementing PLM on an ETO programme and that 'this framework hit every aspect of the issues in the PLM install programme today'. F.16 stated that the framework 'would be useful to our organisation as we begin the implementation process'.

The framework was described by F.3 as being 'an invaluable asset to any business embarking on the implementation of PLM'. It was also highlighted by F.3 that the wide and varied research approach as a strength, which included different ETO products, and which recognised key themes that F.3 identified with during their PLM implementation. The systematic way with which the framework considered the key elements in PLM implementation was identified by F.6 and which was supported by F.9 who described it as robust and well considered and F.17 stated that the framework 'was well thought out'. This was further supported by F.10 who stated that 'this framework is clearly the result of a well-conceived and comprehensive fact-based approach. I applaud the author for providing a unique insight and synthesis of this complex material'.

F.10 highlighted that the framework structure is a 'noteworthy strength' citing the simple and intuitive graphical representation. He also stated that 'he has been in the business of producing ETO products for nearly 25 years and has not seen such a reasoned, thorough and rational presentation'. He went onto say that he 'can easily envision using this framework as a basis for establishing a PLM programme and providing direction to my team'. The framework structure was also highlighted by F.12 as a strength stating that 'the information, people, process and technology approach has allowed us to focus on the real areas of challenge in terms of PLM implementation, specifically cultural change and enabled processes. This was supported by F.13 who stated that it is 'good to see the objectives centred on people, process and information'; this comment supported the lack of technology objectives in the framework. The usefulness of the framework not just for ETO products but for other industries was raised by F.7 and F.9.

The quality of the research overview and framework posters was highlighted by F.13 who stated that it was a great presentation with the key points covered'. This was supported by F.19 who stated that the visual poster was good and the themes sound but are dependent on the codification validity. The feedback may be due to the lack of access to the interview key points and codes used to generate the themes.

0 stated that it is a 'very helpful PLM framework' and that the researcher 'consulted sufficient industry PLM companies/people to come to his thesis conclusions'.

8.3 Industrial use in an ETO product

BAE System Naval Ships has used the themes identified in the framework for the development of its PLM approach described in its iBoM strategy. This enabled PLM to support the objectives of Type 26 and to overcome the challenges related to ETO products as described in Section 2.4. The success of the naval ships PLM strategy was identified as a key business differentiator in the GCS export bids for both Australia and Canada. The understanding of ETO products compared to other product types enabled BAE Systems Naval Ships to explain the importance of PLM to achieve the objectives for the customer and how a specific approach to PLM is required. The PLM objectives, challenges and enablers relating to information, process, people and technology were used to convince the export customers that not only did BAE Systems Naval Ships have a superior product with the Type 26, but also that the PLM approach employed would support the development of the GCS export NPD. The iBoM strategy was also used to describe to the export customers how this would enable their required design changes to be incorporated into the GCS design through variant management. The Australian customer purchased the PLM approach as part of a transfer of IP to support their sustainable shipbuilding. The implementation of the themes in the strategy has established the business as leaders in the field of PLM in Naval shipbuilding. As the iBoM strategy is a commercially sensitive document it has not been included in this thesis.

8.4 Summary

This section has described how the significant contribution to knowledge, the framework for the implementation of PLM on ETO products, was evaluated. The preliminary evaluation was designed to capture initial feedback on the framework using participants who had not been involved in the interviews, those who had, and also feedback from an export customer. The results indicated that the framework content and structure was valuable but there is scope for further research to develop the framework electronically to help with communicating the detail behind the themes e.g. that described within Section 7.

Interview Question 13 asked: 'Would a framework assist with the transition from as-is to the to-be, if so how' with the aim of establishing whether a framework would assist in PLM implementation. The interview responses confirmed that a framework was necessary but also found that the participants required a framework which was flexible to enable the organisation to choose what elements of the framework were appropriate to meet their objectives. The response to this question influenced the main evaluation to establish whether this criterion had been met.

The main evaluation used a questionnaire to ask selected participants from ETO products for their opinion on statements related to the framework. These statements were used to capture the quality, structure and versatility of the framework using a Likert scale. They were worded to ensure that they were not leading the participant to provide a particular rating. The responses to the questionnaire statements and the comments supported the objectives of the questionnaire for quality, structure and versatility with the 95% of the responses either agreeing or strongly agreeing with the statements.

The Industrial use of the framework in an ETO product described that the findings from the research were used by BAE Systems to input into the Naval Ships PLM strategy. This enabled the PLM strategy to meet the related objectives on the Type 26 programme but also to establish PLM as key differentiator in the successful multi £B export contracts for Australia and Canada.

9 Discussion

This research has shown that a PLM implementation framework is required for the specific context of ETO products. This section discusses the thematic analysis findings from Section 7 and relates them to the research problem of PLM implementation on ETO products described in Section 2 and with the Type 26 case study described in Section 5. The structure of this section will focus on each of the categories of information, process, people and technology as shown in the PLM implementation framework. Although a specific framework in the context of ETO products is required, there is a significant contribution to PLM implementation research by other authors. The discussion chapter will relate where appropriate the relevant literature, albeit generic and not specific to ETO products, to the findings from this research and the Type 26 case study.

9.1 Information

The framework provides a number of information objectives, challenges and enablers that are required to support the ETO NPD. The thematic analysis captured the importance of managing the information provided and consumed by all of the stakeholders throughout the lifecycle of the programme. It also described the importance of ensuring that duplication was minimised in order to improve data quality. The thematic analysis and the information integration requirements described in the Type 26 GCS case study in section 5.4 explained how improved information quality will be enabled through the integration of the BoM information in the CAD, PDM and ERP systems. It also described how BoM quality is impacted by disparate unintegrated information. The requirement for integration of information as described in Section 5.4 is a significant challenge on FOC naval shipbuilding programmes. This is due not only to the information instability throughout the lifecycle but the necessary requirement for the programme stakeholders to consume the information to progress the NPD.

The PDM system used on the Type 26 case study will provide the master source of the system design BoM information to be integrated into the CAD model. The fully detailed design BoM is then published into the PDM system for digital planning, as described in Section 5.5. This presents challenges due to the significant volume of BoM information published across the interface which requires all of the information enablers identified in Section 7.6.1 to be applied. The timing of the publication across the interface is critical, as proceeding too early will result in large volumes of information being continually repeated due to product change, which in itself may be due to the evolving maturity of the product. The relationship between BoM publication, maturity management, and configuration and change management is important. The maturity of the information must be managed and understood, as described in the case study requirement in Section 5.1. This will assist with understanding when to apply configuration control to support a stable publication of the product information across the CAD and PDM interfaces.

If the product information is immature and publication between the CAD to PDM system is allowed to commence, then will this result in the publication process continually repeating to reflect changes due to the evolving product maturity. This will also impact the data quality measures in the programme as an understanding is required for what are genuine quality issues or those which are evolving BoM information due to immaturity. Therefore, it is difficult to understand the quality of the BoM due to continuing publication of the updated information across the PLM systems of systems.

The case study requirements, illustrated in the HOQ in Figure 14 in Section 5, require information stability. The downstream consumers of engineering information in the case study utilise the product information to achieve their objectives such as: digital planning (Section 5.5); design for support (Section 5.6); repeatable manufacturing identification (Section 5.8); and, completions management (Section 5.9).

If this information changes once consumed by other stakeholders then it may require rework and introduce quality issues if unnoticed.

Control mechanisms are required to be introduced to provide information stability at the appropriate points in the lifecycle. Stage gates can be used to provide control between phases, as illustrated in the CADMID lifecycle in Figure 8 in Section 2.4.6.

The framework, as described in Section 7.5.1.3, demonstrates that there are challenges with applying configuration control to the evolving ETO product. There is a balance between when to apply configuration control aligned with the defined maturity criteria to provide stability to downstream activities and the burden of applying change management processes. As illustrated in Figure 8 in Section 2.4.6, lifecycle review gates, which are aligned to maturity criteria and the programme lifecycle, can be used as decision points as to when to proceed to the next phase. This will assist in managing the evolving design of ETO NPD. The reason for applying configuration control is to provide stability for the next phase but, when it is applied, there is a change management overhead to the programme. Maturity management must inform the configuration management approach to ensure that the timing of constraining the design is appropriate. If the information is constrained too early and there is a change overhead applied to the programme but leave it too late and the stability of the design and build life-cycle is affected. BAE Systems has attempted to resolve this challenge by using lifecycle phase reviews at appropriate points in the lifecycle. Examples of these are shown in Figure 38 where there are a series of reviews focusing on the maturity of the design at various points in the lifecycle.

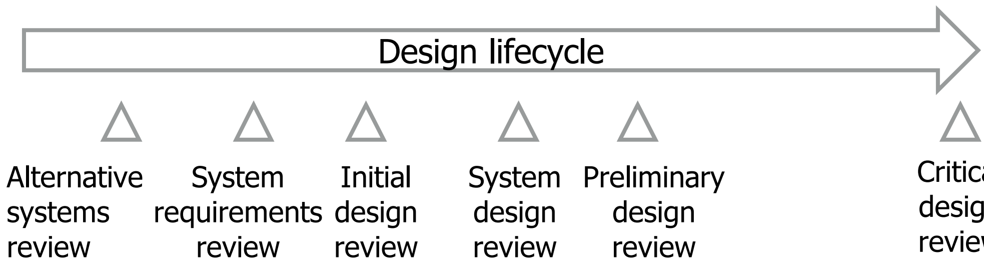


Figure 38 Design lifcycle phase reviews

These phase reviews evaluate the whole integrated design and if passed will result in design artefacts such as documentation, drawings and BoM, having baselines applied and the information being configured into change control. Further detailed reviews are required for ETO products such as Naval Ship NPD due to the size of the design and the long lifecycle which necessitates overlapping phases. These reviews will evaluate the maturity of specific design zones, enabling one zone to progress to the next phase while another can have a lesser degree of maturity. The reviews are often related to contractual milestones. Waiting until all the zones are mature before continuing to the next phase would introduce considerable additional time to the design and build lifecycle. Figure 39 shows the review lifecycle for individual design zones, where the reviews are aligned to the increasing maturity of the zone, they can also be linked to milestones.

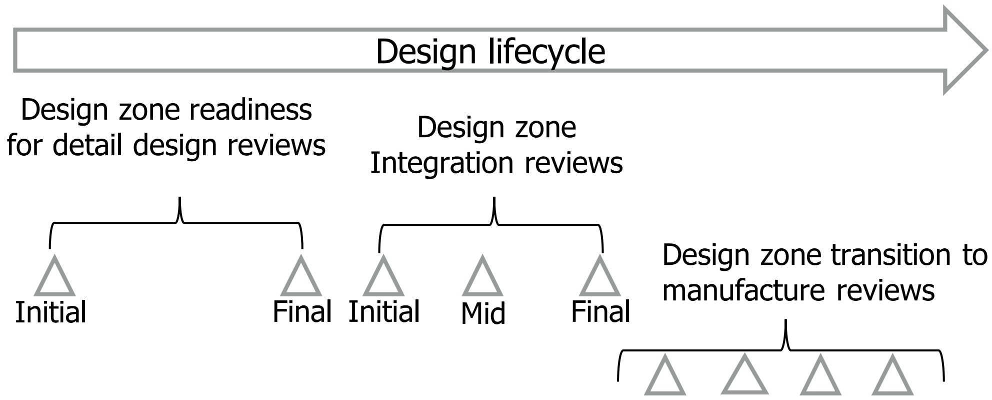


Figure 39 Individual design zone reviews

The detail design zone readiness reviews evaluate the maturity of the design for progressing from system design to detail design. The design integration reviews evaluate the maturity of the detail design for the zone. The transition to manufacture reviews evaluates the maturity for transitioning the design to manufacturing. There are multiple reviews of this type for each detail design discipline, for example structure and electrical can be ready at different times, resulting in an opportunity to pass one discipline while the other is able to focus on increasing maturity. This enables manufacturing to have a phased start for each zone. The approach on the RN case study was to apply progressive configuration control across its 12 design zones based on the maturity of each area. Once configured into change control the updates to these product artefacts can only be applied following approved change requests. The configuration control on a product artefact is automatically unconstrained once the change is approved. This is due to the relationship between the change object and the affected artefacts in the PDM system. The integrated design reviews and the individual design zone reviews are shown in the context of the CADMID, Shipbuild and configuration baseline lifecycles in Figure 40.

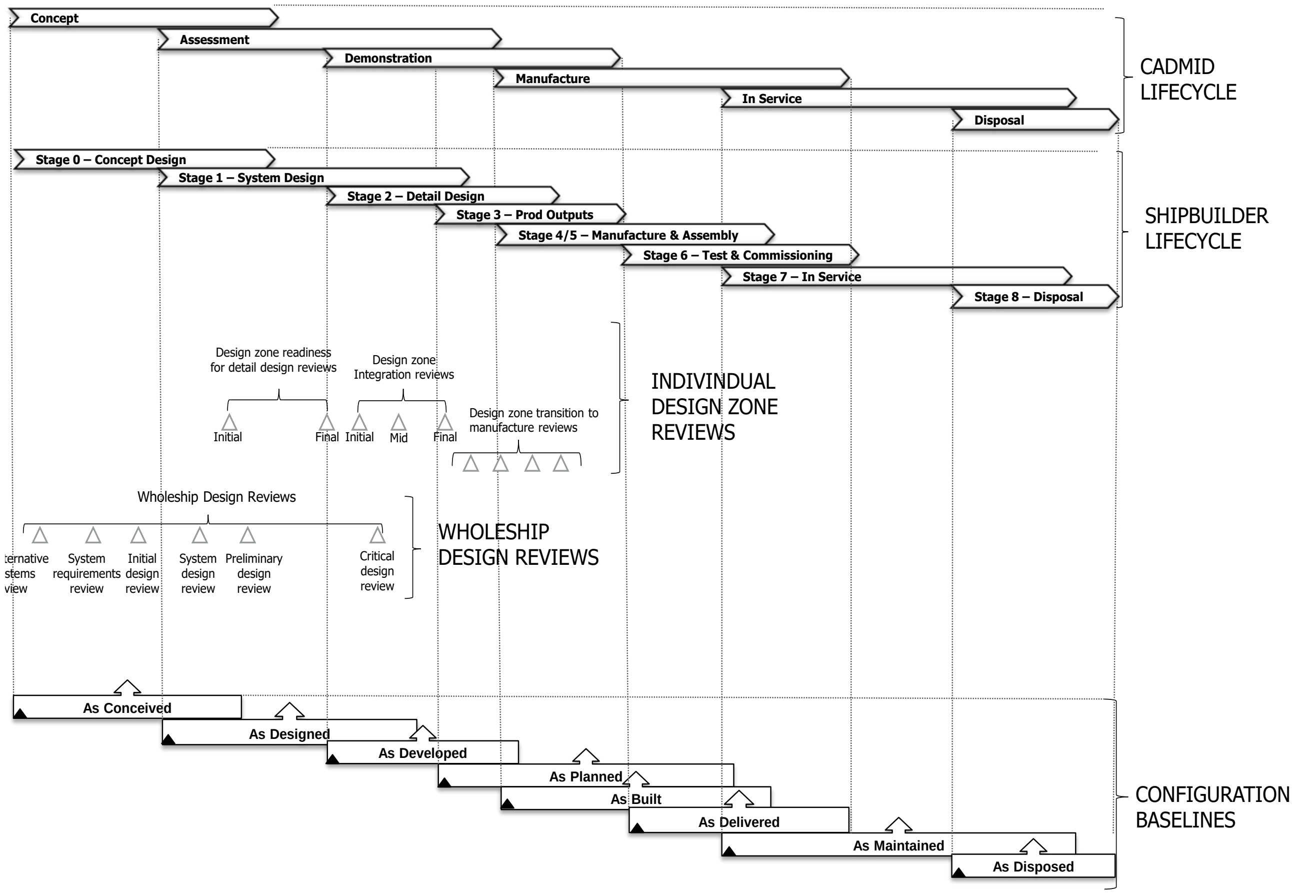


Figure 40 Lifecycle phases and maturity reviews

The selection of what product artefacts are chosen for configuring into change control is important due to the need to identify what is design evolution with minimal impact and what is a major product change. As stated in Section 7.5.1.3 once product information is placed under change control there is an overhead to the programme. This includes identifying the impact of the change which is difficult due to the interconnections within the design which may be affected. Once constrained the product artefacts require an approved change request to unlock the information from the configuration control rules applied in the PLM environment, which are typically managed through the PDM system. This is demonstrated in the RN case study where configuration control is applied to the BoM across the CAD/PDM/ERM interface through the requirement for the integrated PLM systems described in Section 5.4. The configuration control of the information also has a close relationship to the requirements for maturity management described in Section 5.1 and across the various product BoM hierarchies described in Section 5.2, which in turn have associated BoM elements as described in Section 5.3.

The scenario described in the figures below illustrates information integration and the impact of change on a Naval Ship NPD. Figure 41 illustrates how the BoM for the system design is populated in the PDM system based on supplier information, in this case 2D drawings. The system design bill of material is populated in the PDM system to reflect the information provided by the supplier, which consequentially is used to measure the maturity to support the zone readiness reviews as shown in Figure 39.

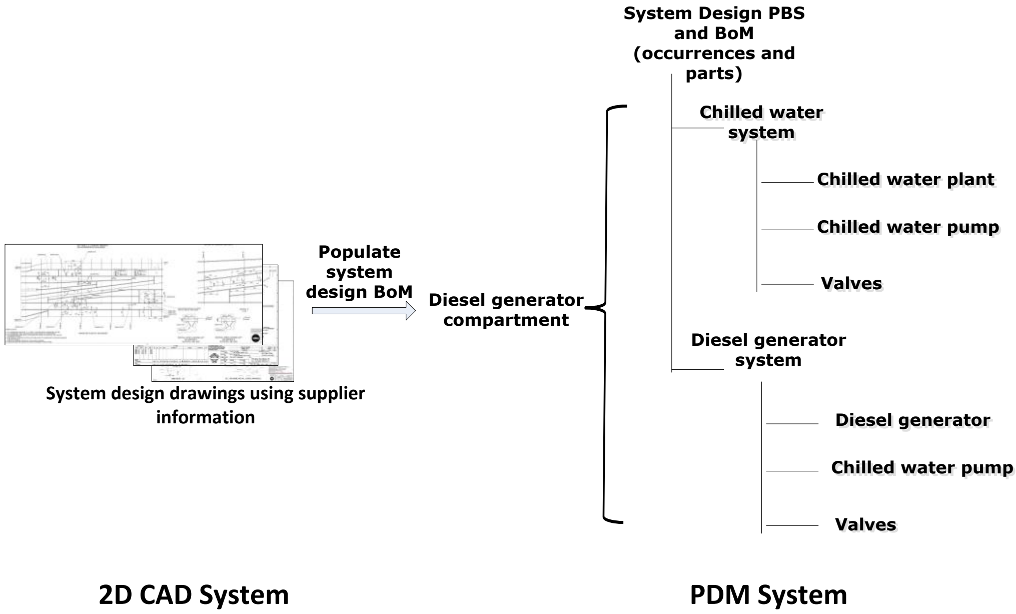


Figure 41 The system design populated in the PDM system based on supplier information

As the zone readiness reviews is passed, the system design for that zone is baselined into change control and the BoM is synched with the 3D CAD environment providing CAD/PDM integration, as shown in Figure 42. This enables the detail design to commence and the BoM for the compartment to be modelled in the CAD system.

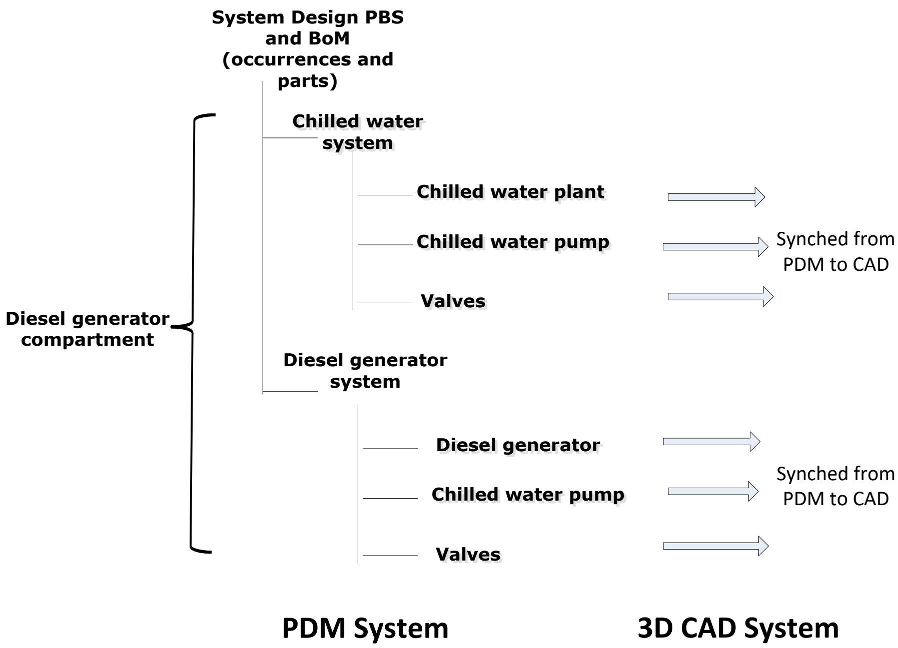


Figure 42 The system design BoM synched with the 3D CAD environment

The detail design team will not only model the 3D representation of the system design BoM, but will also produce product artefacts required to operate the ship. These include the structure, HVAC, electrical and pipe systems and resulting BoM, and any removal or maintenance envelopes or routes. Figure 43 shows a representation of a diesel generator compartment model with the system and design BoM at the final zone integration review.

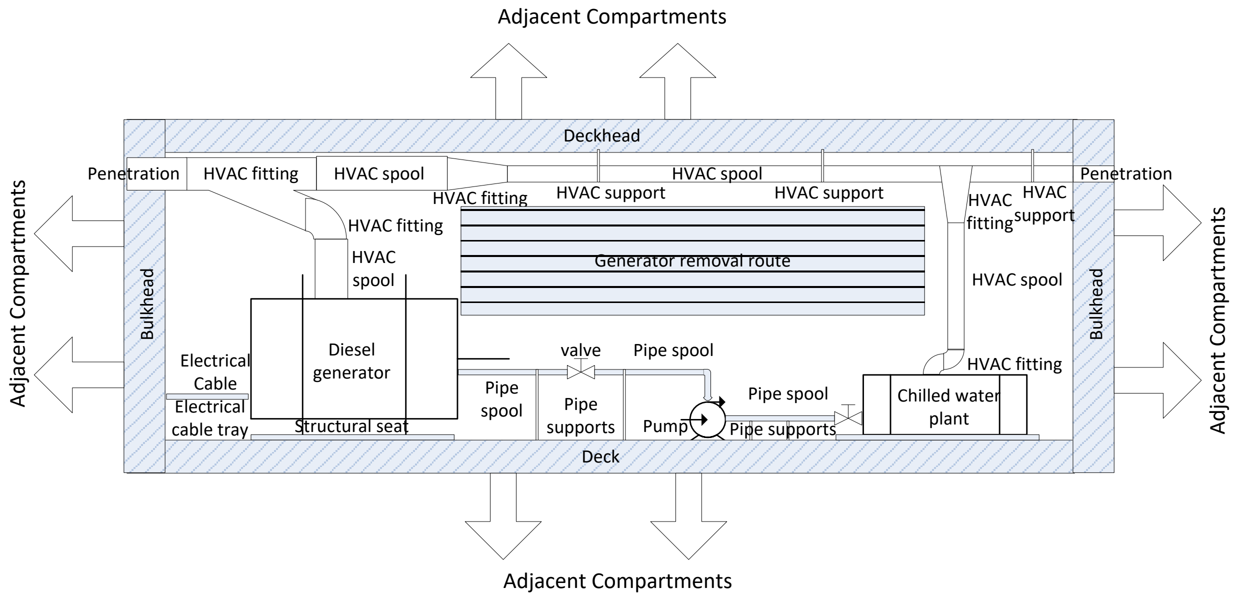


Figure 43 The detail design of the diesel generator compartment at the final zone integration review

When the compartment progresses through the final zone integration review the full detail design BoM for that zone is baselined into change control and can be published to the PDM system to enable downstream activities such as digital manufacturing planning, as shown in Figure 44.

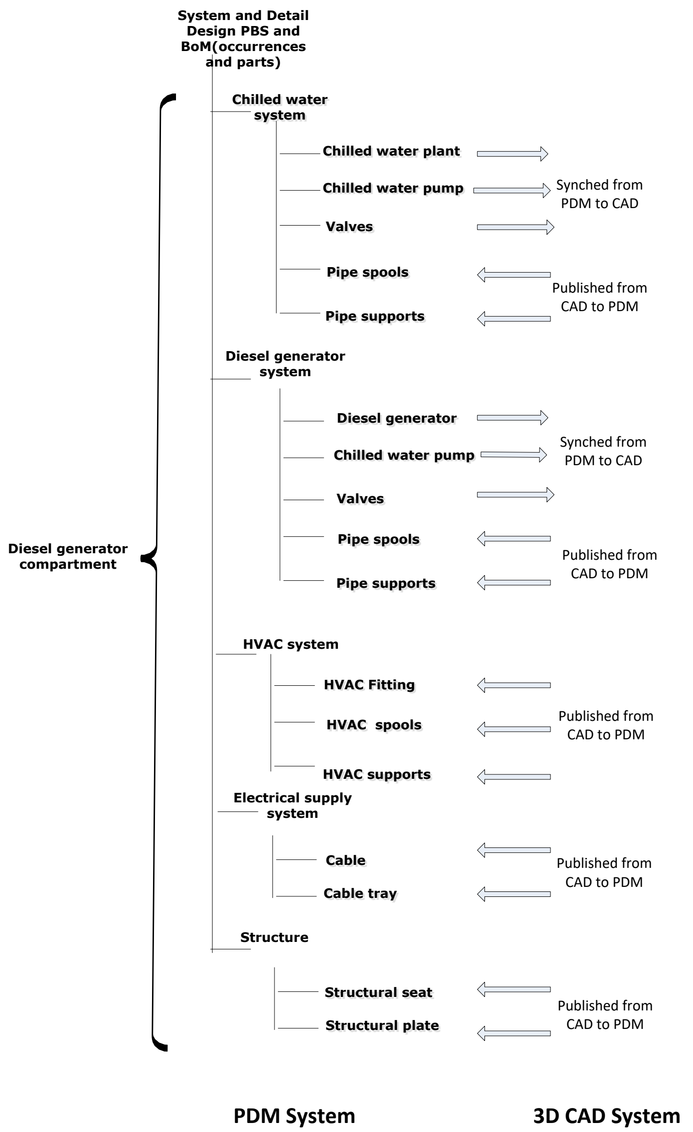


Figure 44 The publishing of the detail design BoM to the CAD to the PDM environments

With the design being assessed as mature the activities to transition to manufacturing can commence. The production drawings to support manufacturing are created directly from the 3D CAD system once the relevant zonal transition review has completed, as shown in Figure 45.

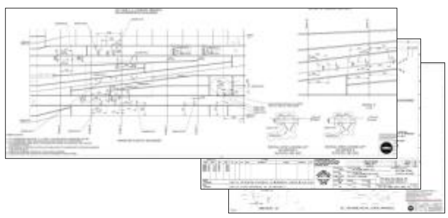


Figure 45 Production drawings outputted from the 3D CAD system

Manufacturing planning can also commence with the full engineering BoM published to the PDM system to enable the digital planning requirement described in the case study in Section 5.5. The relationship between the Engineering BoM and the work packages for manufacturing planning which are then transitioned to the ERP system is illustrated in Figure 46.

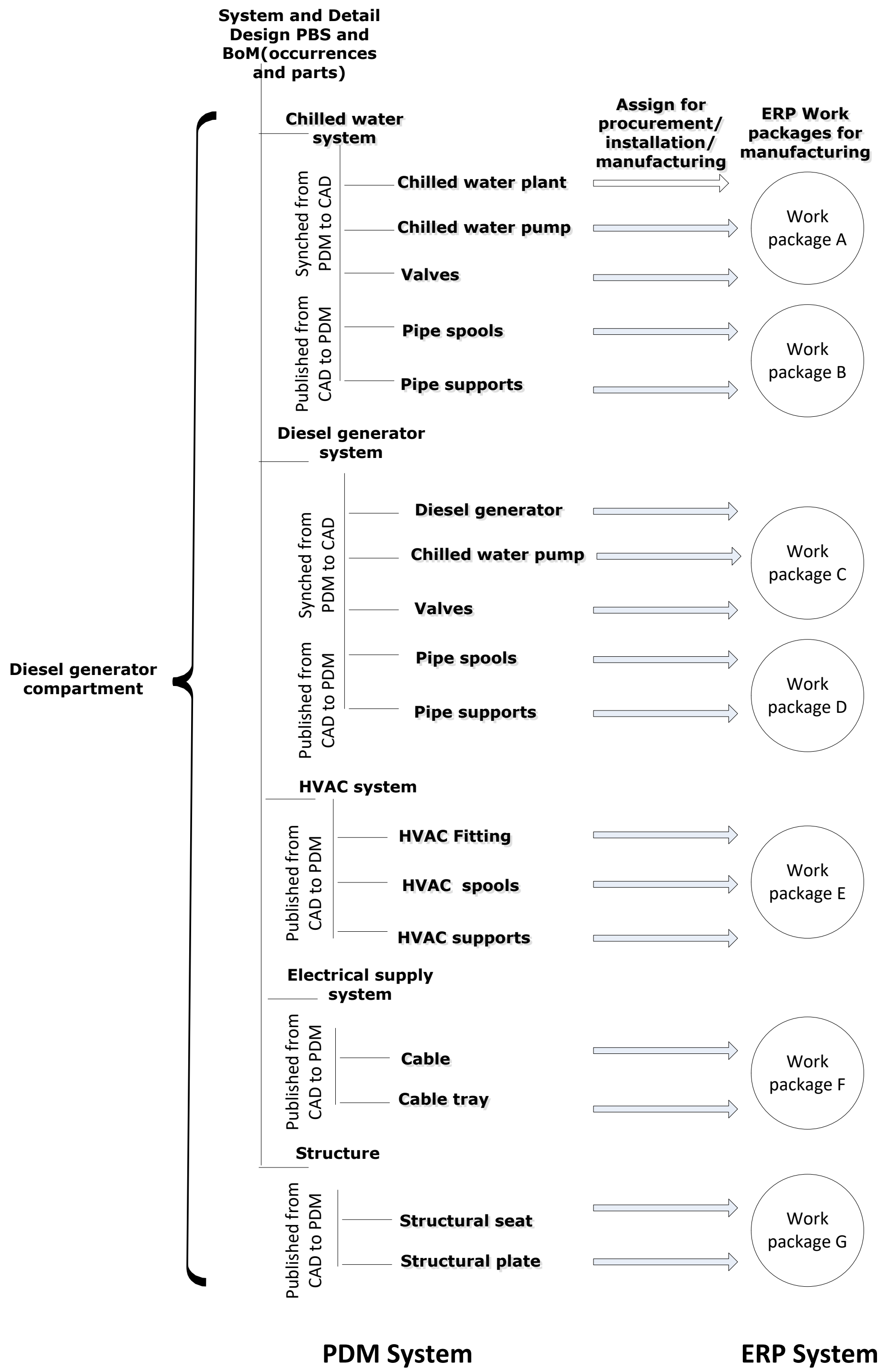


Figure 46 The Engineering BoM associated to workpackages to create the manufacturing BoM

As described in Section 7.5.1.3 the information challenges for the implementation of PLM on ETO products include the management of product information maturity and its relationship to change, configuration, schedule and cost. If there is emergent change such as with an update to supplier information then this may have a significant impact on the programme. Figure 47 illustrates the impact a supplier initiated size and weights change on the diesel generator to the compartment model and the interconnected BoM. This results in consequential change to the structural seats, electrical, HVAC and piping systems and the removal route for maintenance. There may also be an impact on adjacent compartments to accommodate the design change.

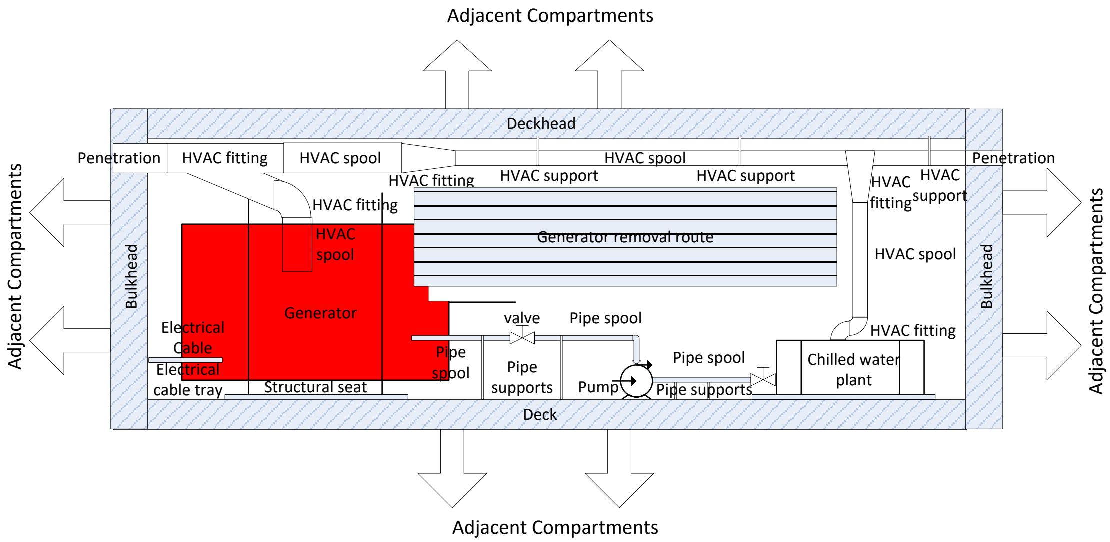


Figure 47 A supplier change to the size and weight of the diesel generator

The requirements in the case study for the improved BoM level of detail, Section 5.2, and the association of related BoM elements, Section 5.3, result in increased impact of the change shown in Figure 47. This greater the level of detail on the BoM results in more interconnections impacted by the change. This includes:

- The system design BoM being updated based on new supplier information, as illustrated in Figure 41
- The synching of the new information to the 3D CAD system, Figure 42
- Updates to the 3D model, Figure 43
- Republishing of CAD detail design BoM to the PDM system, Figure 44
- Production drawings being changed, Figure 45
- Planning activities having to be reworked, Figure 46
- Other rework such as with design for support, Section 5.6, Supply chain activities, Section 5.7, repeatable manufacturing identification, Section 5.8 and completions management, Section 5.9

Therefore the impact of the information change from the supplier once the maturity gates have passed, and the downstream activities have commenced, will have a significant impact on the programme cost and schedule. This includes not only updating the information but identifying the affected BoM items amongst the large volume which potentially may be impacted. These challenges are discussed in Section 2.4 and 7.5 and the findings described in Section 7.6.1 provide guidance on enabling information management improvements to overcome these difficulties.

Section 7.6.1.1 stated that a policy is required to establish what information is important, who owns it and how it will be used in the programme. This policy can support improved awareness of the status of the programme but it will also enable improved understanding of the impact of change. The greater the level of detail in the BoM then the greater the impact of change on the cost and schedule as more effort is required by the various stakeholders impacted, as illustrated in the diesel generator scenario. Some BoM items which when regarded independently should be simple, e.g. pipes or pipe supports. These inherit a greater significant due to the volumes which require updating due to design change. The policy should be developed by a cross functional team as described in Section 7.6.1.2 who include those described in the change scenario, such as system and detail designers, manufacturing planning, supply chain personnel and the support teams. This team must balance the information integration requirements with LFE to ensure that the level of detail in the BoM can be at as high a level as possible, to reduce the impact of change on the cost and schedule of the programme. This will also assist with managing data quality as described in 7.6.1.3 as the volume of information will be reduced enabling improved analysis, governance and reporting of information quality. The policy will determine what information is required to have its maturity managed in order to enable the development of the maturity criteria.

PLM will not solve all of the challenges on an ETO product, such as an immaturity, but will enable the programme to have consistent, valid and reliable information which can be used to make decisions on the programme. The case study in Section 5 represents a PLM environment which provides integrated information across a minimum number of software applications. Without the integrated information approach, there would be inconsistency of data throughout the lifecycle of the programme which would impact the ability to make informed decisions. This information is linked to the programme status such as with the product information located in the design zones which have programme milestones assigned to them. For example the wholeship reviews illustrated in Figure 38 or the zonal review points in Figure 39.

Therefore, the maturity level of identified product information artefacts is related to a programme schedule which is agreed with the customer. If the information management approach is not understood and is not managed in a robust PLM environment then the programme would not be able to understand its status against the agreed plan. The information management policy must also align with the change and configuration management approach as this will determine when, how and what information will be constrained into change management, as described in Section 7.6.1.4. The timing of baselines and the resultant configuring of the information into change control is an important enabler for PLM. The configuration and change management approach is important to ensure the integrity of the design is maintained, but this also introduces an overhead in the raising, assessing, approving and embodiment of the change. The approach should carefully consider the timing of introducing change and configuration management to ensure that the balance between what is change control and what is design evolution is understood. This may result in the zonal review points shown in Figure 39 being later in the lifecycle to allow increased maturity into the design prior to introduction of change control. The balance of this timing must be considered against the downstream consumers of the information and the demands of the programme schedule.

Having consistent information through a single point of truth is required to enable maturity and levels of correctness to be understood. The case study demonstrated that existing information can be used to meet programme objectives through integration as opposed to duplication, e.g. using the iBoM for completions management, digital planning, maturity management and design for support. These business processes use information mastered in their core systems, resulting in improved quality and an improved understanding of the programme performance. This enables the management team to make informed decisions. The reduction in information sources and improving their integration is an important enabler, but these must be supported by the appropriate information policies and cross functional teams as highlighted in the framework.

The lack of a prototype means that ETO products cannot test their PLM approach before initialising ETO design and production. The thematic analysis in Section 7.6.1 demonstrated that information integration is necessary to ensure right-first-time quality to support the programme. There are methods which can be used to assist with the development of an integrated information management policy such as Master Data Management (MDM). MDM is an approach to organise information to manage its quality, use and synchronisation to meet a business objective, e.g. customer information used across different business units [168]. Applying MDM will not solve the information challenges in an ETO organisation as this requires an understanding of the complex use of the programme artefacts and its interconnections, but it can be used to inform data quality and reporting activities once the ETO information policies have been created. As shown in Figure 48, a combination of information understanding is required including:

- What are the information objectives;
- What information is required;
- Who owns it;
- How it will be applied;
- How it will be measured;
- How it will be integrated; and,
- The alignment with the configuration and change management approach.

Investigating, documenting, agreeing and implementing this information approach will enable the information challenges identified in the research to be overcome.

Figure 48 An Integrated information approach is required to meet the objectives of all stakeholders

As described in Section 7.6.1.2 to ensure that information is not managed in duplicate environments there must be governance over where information is mastered. To achieve this, there must be SQEP personnel working within a cross functional PLM team who will have responsibility regarding the information detail, including:

- where it is mastered;
- what is to be published;
- when and where it will be published; and,
- monitoring its quality and publication success.

On Type 26 an engineering team was gradually formed over the lifecycle of the programme to ensure that the appropriate information policies were created, managed and had appropriate governance. These policies included the PLM (iBoM) strategy, CAD/PDM publishing, and maturity management to support the requirements identified in Section 5. Whilst this team has been a success in facilitating the cross-functional PLM requirements, the findings from this research have concluded that the team must include cross-functional representation. The findings also stated that the team must have ownership of the PLM approach across the business and not just within a single programme, or there is a risk that the lessons and investments will not be enabled to meet the overall business objectives, such as for the GCS export programmes where variant management is a key objective. This team must also include security, export and IP personnel to ensure the obligations described in 7.4.1.4 are met. This has proven to be important on the GCS programmes where the security, export and IP legislations differ across the UK, Canada and Australia and this must be reflected in the information management policy.

9.2 Process

The framework shows that the processes on ETO products have specific objectives, challenges and enablers that are required for a successful PLM implementation. Quality through right first time and a reduction in rework is a process objective described in Section 7.4.2.2 and in the demanded quality improvements to Type 26 in the case study, as illustrated in Figure 14 in Section 5. The ETO challenges described in Section 2.4 stated that there is no prototype to remove errors before manufacturing commences, therefore right first time quality is an important business objective.

Scheubel et al., using the implementation of a new PLM system within the energy sector as a case study, stated that the implementation of PLM will enable process optimisation, process quality and will also lead to cultural change [158] . They then described how the new PLM system will introduce initial process overheads and will result in opposition from the workforce. They go on to say that these overheads will be reduced through software improvements, training and enhanced skill levels. They also stated that enlarged electronic workflows will increase process quality as they are increasingly developed to align with the business processes. Careful consideration must be given to enlarged electronic workflows as the thematic analysis described in Section 7.5.2.1 described how overly complex processes are a challenge in ETO implementation. The interviewees gave examples of how they had enlarged their electronic workflows but these became unusable in their ETO products. This led to the enabler described in Section 7.6.2.2 to provide guidelines and governance over process complexity to ensure they are simple and usable. The findings described how enlarging workflows and adapting them to the business process will actually reduce the effectiveness of the PLM environment, and will be detrimental to process quality. Integrating processes into larger workflows in the PDM system will benefit less complex products. However, for ETO products the size, complexity and uncertainty in the product development lifecycle results in a requirement for flexibility in the processes in order to adapt to the constant emergent changes. If the processes are too rigid and inflexible and these are reflected in the electronic workflows in the PLM environment, then these will prove ineffective and will result in a reengineering of the processes. The processes must not be overly complex otherwise they cannot be used effectively to support the PLM business objectives. A balance must therefore be struck between processes which are of sufficient quality to support the complex programme development, and those which are flexible enough to manage the uncertainty.

As illustrated in Figure 49 and described in Section 7.6.2.1 there is a need to develop a cross functional team with suitable SQEP who will have PLM business process ownership, develop the processes and ensure they are standardised across the business.

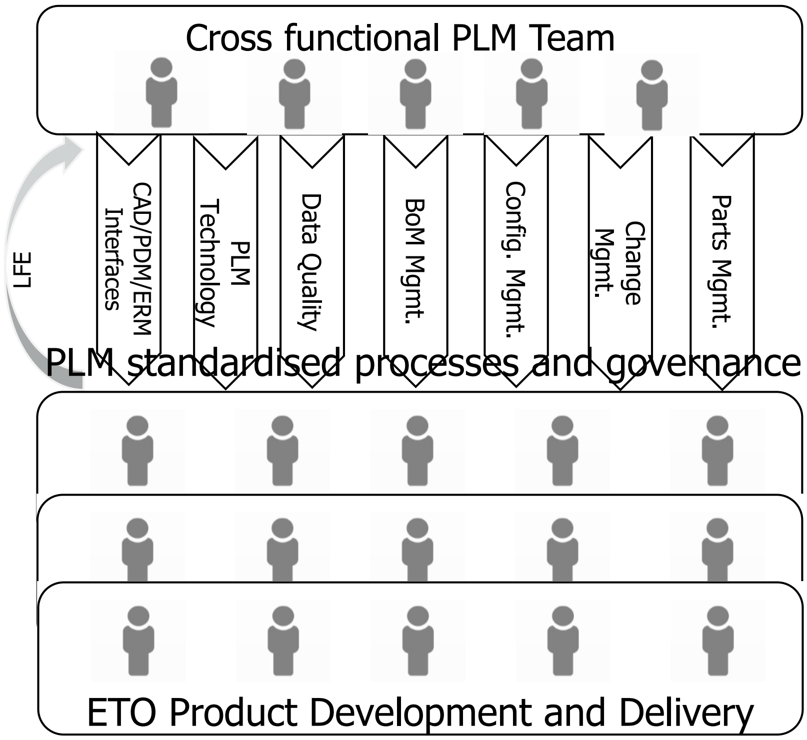


Figure 49 Cross functional team for ownership and effective implementation of PLM processes

They will also have responsibility for learning from experiences and ensure the processes are adhered to. They will lead on the guidelines and governance over process and complexity as described in Section 7.6.2.2. This team must be cross functional to ensure that each of the business functions have their needs represented, this will also assist with the integration of processes across the organisation.

An example of process integration out-with the traditional functions such as engineering and supply chain are those required to support security, export and IPR objectives. The Type 26 ETO product has increased in complexity due to the successful CSC and HCF export wins. This has resulted not only in the extension of the management of information across variants as described in Section 9.1, but also with the processes with which the stakeholders must follow to meet the security, export and IPR obligations. Without the cross functional team representation from security, export and IPR then the processes used for the GCS NPD will be disparate from those required to meet the required legislation.

Type 26 has a number of electronic workflows which represent the PLM processes. These processes were rationalised to reflect the integrated PLM environment and cross functional ownership. The workflows have a balance between complicated and simplicity which represents the varying degrees of complexity in the programme. For instance, the current document review workflow in the PDM system is simple, reflecting a straightforward and well understood process which requires minimal management. These processes will require to be extended for security, export and IPR obligations and to ensure that document management and publication meets the business objectives for the GCS export wins, as each customer will have their own requirements for contractual deliverables. The guidance in the framework must be followed to ensure these previously simple document management processes do not become overly complicated. The change management workflows are more complicated due to the complexity of the programme with regard to uncertainty, emergent change and its relationship to configuration management. This requires a number of configured workflows which represent multiple activities and interactions across information, processes and stakeholders, including engineering, planning, manufacturing, finance, supply chain, programme management and the customer. Due to these complications the workflows are managed centrally with a number of change managers supporting each of the functions to ensure they are processed correctly. The ETO processes such as change and configuration control can become overly complicated to manage the product information such as with the diesel generator scenario described in Section 9.1. Guidelines and governance over process complexity must be introduced to ensure they are simple and usable, as described in Section 7.6.2.2. This is also required to ensure that the GCS processes for the export wins do not become unusable due to the need to manage change across the variants. These processes must be mandated both within the business, across partners and the supply chain, as described in Section 7.6.2.3.

The standardisation of processes in ETO product development is challenging due to the bespoke highly customised nature of the product, as described in Section 2.4.5. The PLM environment can support these nonstandard activities by ensuring that the necessary process support is enabled where appropriate. The case study in Section 5.8 demonstrated the need for the identification of repeatable manufacturing processes and information in the PLM environment. Haug et al. argued that ETO organisations can move towards mass customisation by standardising aspects of their design and manufacturing [86] and Pulkkinen et al. identified that there were significant opportunities for using PLM capability to transform bespoke ETO products into standardised processes more commonly seen in Assemble to Order products [156]. To achieve a level of standardisation the PLM business processes must be rationalised and governed. On Type 26 the PLM environment included rules which ensured that when the product artefacts are designed, consideration is made as to whether these can be standardised. An example is with the parts catalogue where a material is requested by engineering. The electronic workflows will force the engineer to reflect whether a standard material can be used, therefore assisting the supply chain team by reducing the variability of the material specifications and enabling economies of scale with larger orders. The workflow will also force the engineer to add a classification from a pick list of manufacturing processes, assisting the manufacturing engineering team to implement build environments which are based on the number of repeatable processes identified against the product artefacts. This will reduce the number of non-standard manufacturing processes since any identified will be targeted for removal where possible. Whilst the PLM processes, information, training and technology will support improvements in standardisation, there must be a manufacturing strategy which enables the realisation of the improvements through PLM. It also must be supported by the information polices to ensure that the BoM is targeted at the appropriate level, to ensure that the programme schedule is not impacted due to the enormity of the repeatable identification activities on large volumes of data.

9.3 People

The framework provides the people aspects required to enable successful PLM implementation on ETO products. For a successful PLM environment the stakeholders in the programme must be fully supportive of its implementation. This includes the senior management team who are required to support the implementation throughout the lifecycle of the programme as described in Section 7.6.3.1. This will become more important when there are challenges which may cause the senior managers to consider a reduction in the PLM scope. To enable these challenges to be overcome, the management team must be provided with ongoing evidence of its success and the implications of having an ineffective PLM implementation due to reduced scope. Those who use the PLM processes, including the personnel who provide the information and those who consume this information, should be fully committed to the implementation, but the support of senior management is the most important. Hewett provided an example where an engineering team conducted a time and motion study of the overhead of implementing PLM to the day-to-day work of engineers [169]. The company was facing significant quality issues and the senior management team decided to implement PLM even though it would require additional cost to provide resources to support the overhead identified by the engineering team. Bokinge and Malmqvist also stated the importance of ensuring management support and highlighted that a delay in the commitment of managers affected a PLM implementation with initial activities taking longer than necessary [56]. Alemanni et al. developed a method of evaluating PLM implementation through the development and measurement of Key Performance Indicators (KPI) which they validated on a one-of-a-kind organisation producing satellites [170]. They focused on document and configuration management but the approach could be developed to improve the measurement and communication of PLM benefits to the senior management team to ensure continuing support.

The thematic analysis established a number of challenges relating to people that must be overcome. People challenges were raised more frequently throughout the interviews compared to challenges on information, process and technology. This is consistent with the literature where there is significant amount of information relating to people and business change such as with Kotter who established an 8 stage process for implementing business change management [171]:

1. Establishing a sense of urgency
2. Creating the guiding coalition
3. Developing a vision and strategy
4. Communicating the change vision
5. Empowering employees for broad-based action
6. Generating short-term wins
7. Consolidating gains and producing more change
8. Anchoring new approaches in the culture

Kotter’s approach could be applied to business change management in ETO programmes to support the enabler of providing continuing evidence of the benefits of PLM to the senior management team, as described in Section 7.6.3.2. However, due to the unique nature of these products, the PLM implementation framework must provide SQEP to enable the successful deployment of business change as described in Section 7.6.3.4.

Stark stated that more than 20% of employees in a company can be affected by a PLM implementation [172]. Due to the size of ETO products, this will be a considerable number of programme personnel. Evidence from PLM case studies have also concluded that the cost and time constraints related to PLM implementation is not due to technology introduction but with organisational change [158]. ETO products are extremely complex and have a long lifecycle, therefore personnel on these programmes have unique skills which are difficult to replace. When transforming a business with a new PLM implementation, careful attention must be made to those persons who may have been undertaking a similar role on another ETO programme for many years but with a different information management approach and technology. The framework highlights that a comprehensive change initiative must be developed and implemented as described in Section 7.6.3.2. The approach could use approaches such as Kotter’s 8 steps, but the challenges are significant, especially as the benefits to an individual may be minimal as the improvements will be demonstrated later in the lifecycle, which may be many years in the future. Rangan et al. described the weighting given to a conceptual equation used in the car industry to describe how to achieve success in implementing a new PLM system [31]. They stated that they have seen failures in PLM implementations due to the process and technology not being adequately communicated to the programme and provided an equation with weighted factors applied to describe the challenge.

$S=100E+10P+T$

Where: -

S = success

E = empowered trained people

P = having the process defined

T = technology

Therefore, the success of the implementation is weighted heavily on empowered trained people, followed by process definition with technology being the least important factor in the implementation. Rangan et al. went on to describe how PLM implementations must empower and adequately train the user community on the process and business rules which are supported by effective technology. They warn that many PLM implementations have failed due to an over focus on technology and not on the people and process aspects. The thematic analysis in Section 7.6.3.2 found that that a cross functional PLM education programme, which is embedded in the core business, is required to enable the success of the PLM implementation. The SQEP PLM team will enable the development and implementation of that education programme as well as communicating the project's objectives and status to the stakeholders, as shown in Figure 50.

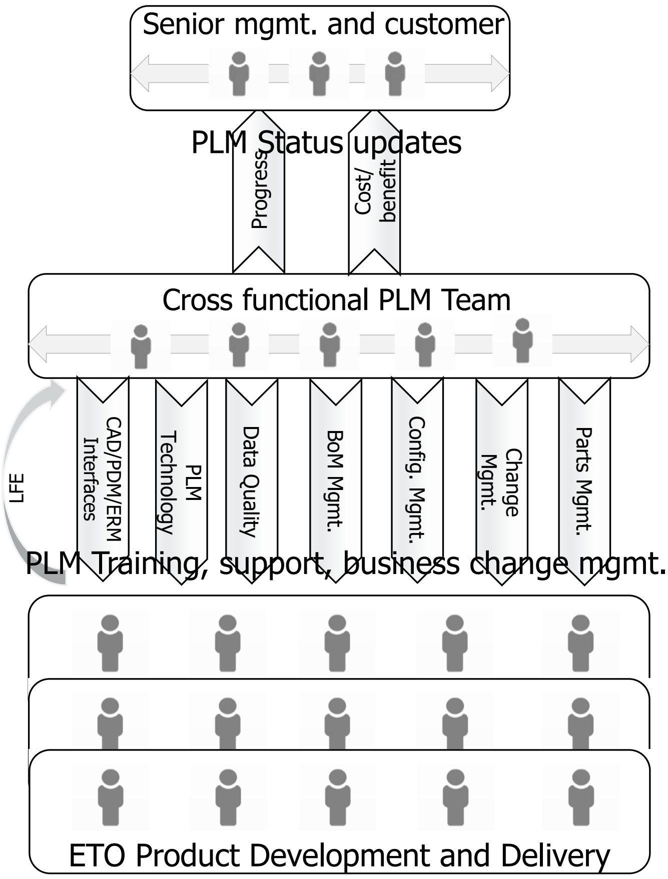


Figure 50 A cross functional PLM team for senior management communication, business change management and education

This approach is supported by Bokinge et al. who followed their review of PLM implementation guidelines [173] with a proposed approach to identify risks associated with PLM implementation [173]. They highlighted research from Hewett [169] who stated that failures in PLM investments are often due to mistakes with the PLM implementation. Bokinge et al. continued by stating that an approach to avoid PLM failures would be to assess the PLM solution during its implementation. They proposed that the PLM architecture of an organisation can be correlated with PLM solution guidelines to provide positive (agreements) and negative (conflicts) to identify risks. In their case study one of the strategies of the organisation was to populate their PLM centre of excellence with representatives from different divisions, which supports the enabler of a SQEP cross functional PLM team. They found a positive correlation between the organisations strategy of a PLM centre of excellence and the implementation guidelines to 'satisfy rather than optimise' and also to 'assist with defining the benefits to all stakeholders'.

Bokinge and Malmqvist stated that users must be educated not only on how to perform tasks, but also why [56]. In the context of ETO products it is important that the stakeholders receive training relating to the implications of their actions and non-actions within the PLM environment and the interconnections across the product artefacts and processes. The balance of training is important and a tailored, differentiated education programme is required to ensure that stakeholders are not overloaded with information but that the structure focuses on their roles in the programme.

Within this educational programme stakeholders should be educated in what to expect from ETO products, such as that emerging factors are the norm, this way they can be trained to manage them. There may be opportunities to learn from other organisations who manage significant emergent challenges, such as from accident and emergency teams who manage their continuing emergencies.

The case study in Section 5 contained a number of new initiatives on Type 26 which are different from previous RN shipbuilding programmes. These have been implemented to support performance improvements across multiple functions in the business, based on lessons learned from these previous programmes. These initiatives required new information management approaches, processes and technology to support the objectives, which necessitated additional focus on the people aspects in the programme. This required a number of employee engagement activities including senior management briefs and user training. The education programme comprised of a number of different approaches depending on the needs of the individual, as shown in Figure 51.

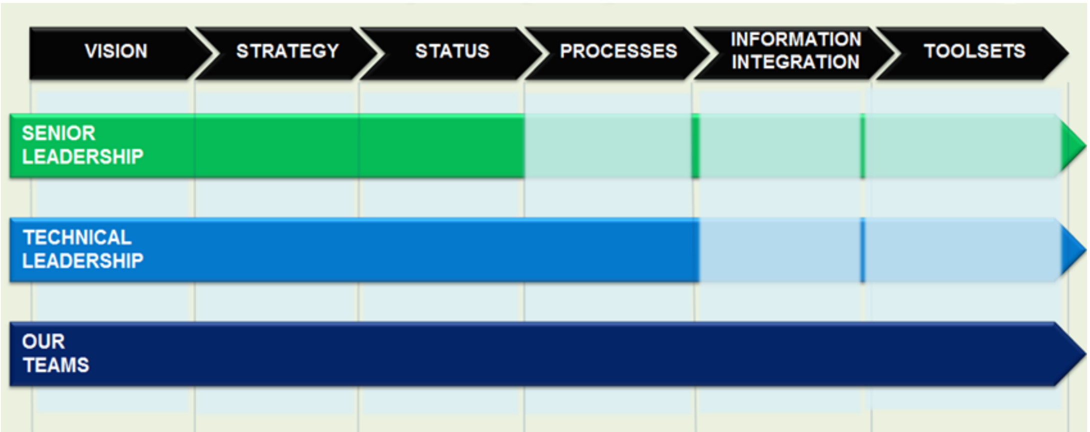


Figure 51 Education delivery for different levels of the organisation.

Each stakeholder's educational requirements differ depending on their role, e.g. senior leadership require detail on the vision, strategy and project status with only a minimum amount of training on the processes, information and toolsets. The technical leadership requires the same detail as senior management but also require training on processes. Everyone who is involved in working in the PLM environment requires training in the aspects relevant to their needs to perform their role. The training delivery is based on each of the relevant business processes and can either be short step-by-step how-to guides, Computer-Based Training courses (CBT) or classroom-led courses for more technical aspects. To help resolve the transfer from a previous programme into the new environment, access to the PLM environment is only provided once the education module relevant to the roles has been completed.

The success of the GCS export programme required additional training as the Australian and Canadian customer, and business units, do not have the experience of the previous RN programmes. Therefore PLM fundamentals which had been learned tacitly on Type 26 from other RN programmes had to be introduced into the curriculum. This included the whole product development lifecycle from concept through to design, build and support. There is an opportunity to improve this education approach by expanding academic partnerships.

9.4 Technology

The framework does not identify technology objectives for the PLM implementation even though there were a number of interviewees with an information management and technology (IM&T) role. The interviewee responses targeted information, process and people as the main objectives of PLM. These findings reflect that technology is an enabler for PLM and not an objective in its own right, but it has significant challenges to overcome. The level of robustness and longevity of the PLM technology to support an ETO programme’s long life was identified as a challenge, as described in Section 7.5.4.1 . These toolsets are required to be maintained over decades to support a large number of different processes and volumes of information with complex interconnections. The thematic analysis demonstrated that technologies in ETO programmes have been heavily customised and this has had a major impact on business performance. It is critical that the technology used in ETO programmes is configurable to meet the requirements of the business as discussed in Section 7.6.4.1. Configurable technology enables the business to upgrade its toolsets quickly and efficiently to the latest versions to ensure that they are supportable and any new vendor supplied capability can be leveraged. Rangan et al. described how early PLM implementations used in-house developed PLM toolsets meaning that ownership resides with the business. They recommended that COTS PLM toolsets which are configurable to align with the business process are used [31]. Bokinge et al. stated that one of the strategies for a PLM architecture in an organisation they used for a case study, was to minimise customisation [173]. The findings from this research demonstrate that moving to COTS PLM toolsets on its own will not stop PLM technology customisation. The examples discussed in Section 7.6.4.1 described how COTS PLM technology was customised to meet the needs of the programme, resulting in significant long-term impact to the business. Any configuration of the PLM technology must be carefully governed and approved only when the requirements are understood, validated and meets the business objectives, this can be managed by the cross functional PLM team.

Toolset development must focus business objectives, priorities and ease of use to ensure technology and process complexity is reduced, as discussed in Section 7.6.4.3. The PLM technology must be able to be configured to deliver these business requirements, such as toolset integration to improve data quality as discussed in the case study in Section 5.4. Not all of these requirements can be delivered through configuring the toolset. The thematic analysis in section 7.6.1.2 found that the integration of CAD and PDM was identified as a significant issue in ETO programmes. An example is with the case study described in Section 5.4 where the requirement was to integrate data, processes and technology. This required CAD and PDM integration between two toolsets which did not have this functionality OOTB. The organisation could have chosen to customise an interface but this would have resulted in significant overhead and risk to the business, as discussed in the technology challenge of creating a system of systems through toolset integration and rationalisation in Section 7.5.4.3. As the CAD and PDM toolsets where not designed to be integrated, the ETO organisation used its influence to convince the CAD and PDM providers to develop OOTB functionality. The persuasive factors on the toolset providers were not only the size of the programme and the revenue it provided, but also that the integration would result in a commercial advantage for the technology companies in the GCS export bids and future ETO programmes. This approach was successful with an OOTB CAD/PDM integration delivered. Due to its long lifecycle the CAD/PDM integration was not required until the detail design phase of the ETO NPD, allowing the technology providers time to develop and implement the integration.

Due to the size and longevity of ETO programmes the businesses will have significant influence over the PLM toolset companies to provide supportable OOTB capability, aligned with a long term development plan, to embed required functionality within their COTS software to meet the programme's needs. Where the interfaces are across toolsets with different providers, consideration should be given to the long-term technology strategy to either replace the toolset/s or a guarantee that commercial agreements will be in place to ensure that the vendors work together to the agreed development plan. This was the approach undertaken by Type 26 as described in Section 5.4. The CAD and PDM applications are provided by different companies who undertook a commercial agreement to integrate their products. Scheubel et al. argued that the implementation of PLM technology must be hand-in-hand with the business change approach [158], which is consistent with the findings from this research, but the relationships should be between all aspects of the business including vision, strategy, information and process as well as people and technology.

The technology enabler to integrate information through toolset rationalisation, as discussed in Section 7.6.4.2, will result in a reduced numbers of PLM toolsets to support more processes than ever before. This will result in a smaller technology footprint in the ETO programme but with the consequence that these systems will have more information, greater user interaction and increased volume of information exchanged between the toolsets with the result of a greater burden on the technology interfaces. To ensure the information integration can be supported the IT architecture must be improved in parallel with the greater burden on the smaller number of PLM toolsets, as discussed in Section 7.6.4.4. Figure 52 illustrates the IT architecture improvements required as the PLM system of systems is rationalised and integrated.

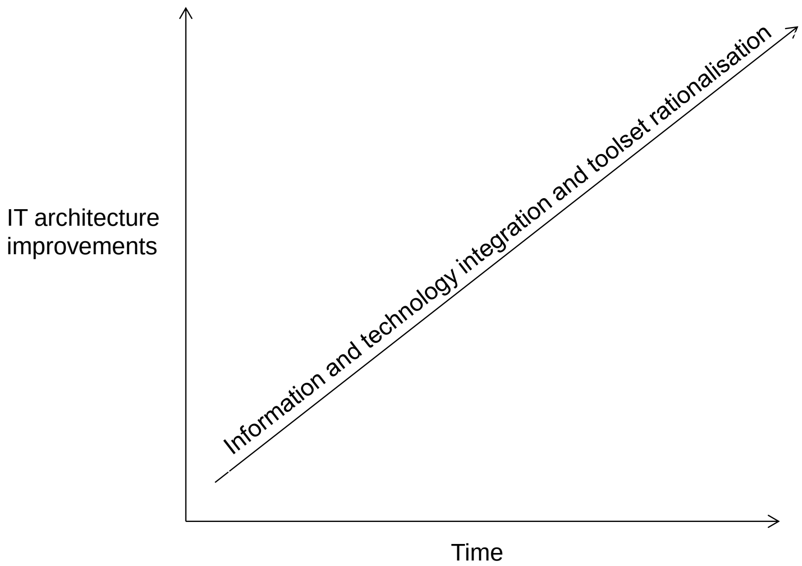


Figure 52 IT architecture improvements as PLM technology is integrated and rationalised.

9.5 Research methodology

The research has relied on experts in the field of ETO products who have an interest in the successful implementation of PLM to generate and evaluate the findings, which was directed by the research methodology. The methodology which explained the methods to conduct the research, support the determination of the results and ensure it can be repeated by others is described in Section 4. Understanding the philosophical perspectives of the researcher, in relation to the research problem, was important as it supported the choice of the tools and techniques used to determine the research results.

The ontological perspective about the nature of reality based on the researcher's beliefs and values was identified as being relativism. The reason for this determination was due to the researcher's belief that there are many truths dependant on the actors in the environment. Truth, meaning and knowledge had to be determined from these many truths. This was captured by identifying patterns in the results. These patterns were evidenced to ensure that they were correct and not contaminated with untruths or poorly evidenced facts. They were clearly explained so that the results could be repeated by others. The choice of thematic analysis and the NVivo qualitative analysis tool software to determine the research results was based on a need to identify these patterns in the research results. The raw data used to determine the patterns is contained in Appendix C, which supports the audit trail for the creation of the meaning. The raw data was combined into common themes to generate the findings.

The epistemological perspective reflects the way to inquire into the theory of knowledge and justification, and its relationship to beliefs and options. The epistemological perspective of subjectivism was identified due to the researcher's belief that within the context of this research there are only subjective truths, and that interaction with experts in the field of PLM will identify meaning and ultimately the research findings. The ontological and epistemological perspectives of relativism and subjectivism directed the methodology perspective as qualitative, as this supported the interaction with the actors in the field of PLM to identify the meaning, truth and knowledge. The basic belief system, or paradigm, based on these perspectives was used to understand the researcher's view of the world. This was identified as interpretivism as the researcher believes that knowledge or meaning can be gained from the expert's interpretation of a situation, i.e. the subjective experience of experts in the field of PLM in ETO products. The research approach based on these perspectives identified participatory action research as it supported the interaction with these experts.

The experts were identified from a number of ETO organisations but the majority were from the maritime sector, due to the motivation for the research was to support business transformation within BAE Systems Naval Ships. Type 26 was chosen as a case study as it provided a unique opportunity to undertake research in an NPD ETO product over more than eight years. Using six sigma DMEDI provided a structure not only to undertake the research but also to assist with planning and to communicate progress. DMEDI identified that capturing the voice of the customer on a PLM implementation was important. It provided the HOQ tool to relate the voice of the customer, in other words the demanded quality improvement, with the functional requirements to meet the identified improvement. The case study provided an opportunity to discuss the real-life PLM implementation with the findings from the research. This provided greater clarity to the enablers provided in the framework.

The semi-structured interview process and the subsequent analysis in NVivo to generate the themes were undertaken over approximately two years. The effort required to generate the themes provided the evidence of truthfulness as each theme can be traced back to the key points in the interview responses. This also assisted with describing each of the themes in Section 7 as NVivo enabled the collation of the key points within each of the themes, as illustrated in Figure 22 in Section 6.5. This also assisted with the discussion between the case study and the enabler themes in the framework by linking the identified quality improvements in Section 5 with the themes described in Section 7

9.6 Summary

This section discussed the framework described in Section 7 in relation to the research problem described in Section 2 and the requirements identified in the Type 26 GCS case study in Section 5. The structure of this section focused on each of the categories of information, process, people and technology. The section described how quality was improved through integration of key PLM technology elements. The case study requirements highlighted the importance of the integration between CAD and PDM and the thematic analysis described how the lack of integration can significantly impacted information quality. This integration will require improved IT architecture to ensure that the rationalisation within the PLM systems of systems will be supported. This is with the greater user interaction in the reduced number of toolsets and also the volumes of information passing across the interfaces. The importance of the relationships between BoM, maturity, change and configuration management was discussed including when information should be published across the interfaces due to the challenges of emergent product development behaviours in ETO products. The stability of information to enable downstream activities to be undertaken was discussed, examples were provided using the case study where engineering information is used by personnel from various business functions undertaking numerous activities to support the programme, with no prototype to remove errors. The lifecycle of a FOC NPD Naval Ship was presented including configuration stage gates and their relationship to more detailed maturity checks across multiple design zones. Scenarios were provided demonstrating how change affected the information across the lifecycle and the resultant impact to the programme schedule. These challenges can be mitigated using the findings from the thematic analysis including information enablers for policies and organisation on integration, quality, maturity, and change and configuration management.

The importance of reducing the complexity of processes was discussed and that a cross functional PLM team will provide process ownership, development, standardisation, LFE and adherence. Governance is also required to ensure that processes do not become overly complex and are fit for purpose. The importance of mandating processes across the programme both internally and externally to the organisation was also discussed. The success of the case study in the export market further supports these enablers as information and process management must be extended to manage export, IP and security considerations across the countries.

The section discussed the importance of ensuring that the people elements of PLM implementation are managed. This included providing continuing evidence to the senior management team that the PLM implementation is providing value. Business change management was highlighted as being important as was ensuring that the personnel are educated appropriately due to the large number affected by a PLM implementation. This can be supported by a cross functional PLM team representing the various business functions. The case study provided examples of requirements which differ from previous shipbuilding programmes and that these required training and engagement, but the level of engagement will depend on the role the person is undertaking.

Technology was highlighted as being an enabler but not an objective in its own right. The importance of longevity of the PLM systems of systems was discussed including the importance of being able to configure the technology to perform the functionality required by the various stakeholders. This configuration would assist with avoiding the customisation of the toolsets which would have a major impact on the supporting and upgrading the technology. Any development of the PLM technology, including configuration, should be based on business priorities and ensure that they support a reduction in process complexity. Changing major PLM toolsets such as CAD and PDM was discussed as being significantly challenging on ETO programmes due to the complicated design and its significant volume, therefore the technology must be able to be support the ETO NPD through-life. The rationalisation of the toolsets was identified as an enabler to information integration. This rationalisation results in a small PLM system of systems but will require improved interfaces and an enhanced IT architecture. These interfaces will be required to support improved information quality, such as CAD and PDM integration. The large volumes of information within a smaller number of PLM toolsets requires improved IT architecture to support an increased number of user interaction in a smaller number of toolsets, and the increased volume of information across the interfaces in these integrated toolsets. Table 14 shows whether the enablers described in the framework have a strong, moderate, and weak or no enablement to overcoming the PLM challenges described in Section 2.

Framework enablers	PLM Challenges					
	Complexity and uncertainty	**Customer interaction and procurement**	**Product customisation**	**BoM, configuration, change and maturity management**	**Project**	**No physical**
Develop policies to capture what information is required and how it will be used within an evolving complex product.	3	3	3	3	2	2
PLM information integration, policy development, standardisation, learning from experience and adherence using suitable expertise within a dedicated cross functional team.	3	2	3	3	2	3
Develop data quality and governance policy and adherence approach.	2	2	2	3	3	2
Develop configuration and change management approach across ETO product classes and variants.	3	3	3	3	3	2
PLM business process ownership, development, standardisation, learning from experience and adherence using suitable expertise within a dedicated functional team.	2	2	2	2	2	3
Guidelines and governance over process complexity to ensure they are simple and useable.	3	2	3	3	3	2
Mandate utilisation of PLM processes internally, to partners and the supply chain.	2	3	3	3	2	3
Provide continuing evidence of benefits to senior management to enable support and maintain PLM sponsorship.	3	3	3	3	3	3
Develop and implement a comprehensive business change initiative on PLM.	3	3	3	3	3	3
Develop and implement a cross functional PLM education programme embedded within the core business training programmes emphasising core values and objectives.	3	3	3	3	3	3
Develop PLM objectives, education approach and support to the business using suitable expertise within a dedicated cross functional team.	3	3	3	3	3	3
Identify and implement configurable PLM toolsets with minimal customisation.	2	2	2	3	2	3
Drive integration and information through toolset rationalisation.	2	2	2	3	2	3
Focus on toolset development on business objectives, priorities and ease of use to reduce complexity of technology and processes.	2	2	2	3	2	3
Implement IT architecture improvements to support new PLM capability and ensure toolset performance.	2	2	2	3	3	3

0	Not an enabler
1	Weak enablement
2	Moderate enablement
3	Strong enablement

Table 14 Framework enablers related to PLM challenges

The research methodology was discussed including the importance of experts to generate and evaluate the findings. These experts were primarily from the maritime sector across international ETO organisations which supported the motivation for business transformation in BAE Systems Naval Ships. The importance of ensuring that the truth, meaning and knowledge can be established was discussed. The use of thematic analysis to provide the audit trail of how the themes were created was used to show how patterns in the results were established and the knowledge created. Using DMEDI as the research design supported the relationship between the knowledge gained from the experts and its relationship to in a real world PLM implementation on the Type 26 GCS.

10 Conclusion

The research presented within this thesis is the first ever framework for implementing PLM within high value ETO programmes. PLM implementation is extremely challenging and expensive with $29.9 billion being invested globally in PLM in 2011 of which $19.1 billion (64%) of that was in the technology applications themselves. The need for adopting advanced programme management techniques, of which PLM forms a key component, is illustrated by 65% of 300 projects with a budget bigger than $1B failing to meet their objectives, whether it is safety, cost, schedule or realising the primary function of the product. When implementing PLM, the organisation should first understand its strategic objectives and core processes and use this to decide on the PLM approach which should influence the PLM technology implementation. This is not trivial as the alignment of business objectives, process and functionality is one of the key challenges to PLM implementation and is an area that the PLM technology providers have difficulty in resolving. This research addresses these and other challenges by developing a PLM implementation framework. This research has influenced the BAE Systems Naval Ships PLM approach for the design, build and in-service support for the FOC new generation Royal Navy vessel, the Type 26 GCS. The PLM approach was also used as a key differentiator in the successful competitive export bids for the Australian Hunter Class Frigate and the Canadian Surface Combatant, both of which are variants of the Type 26 reference design. PLM is critical to the success of the GCS as it is required to ensure that the design information for variants is managed effectively.

10.1 Scope and research problem identification

The research describes the need for the development of a framework with which to implement PLM on ETO products in Sections 1 and 2. The significant contribution to knowledge therefore is: A framework to support the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) products. The thesis describes the unique challenges of ETO products and why a specific approach to PLM is required, compared to other product types.

The research discussed the related literature on PLM focusing on the key differences to PLM implementation on ETO products, in comparison to other product types such as ATO, ATS and MTS, and used this to provide an overview of the PLM related challenges of ETO products. These key challenges were identified as:

- Complexity and uncertainty;
- Customer interaction and procurement;
- Product customisation;
- Bill of Material, configuration, change and maturity management;
- Project management; and,
- No physical prototype.

Research on PLM implementation is relatively young but there is guidance from a number of authors and researchers in the field of PLM. The PLM challenges with ETO compared to other product types provided the context with which to identify what literature is available to determine the gap in knowledge and with which to address the research problem.

10.2 Review of literature relating to PLM implementation on ETO products

The review and critique of the literature on PLM relating to the key challenges with ETO products demonstrated the gap in knowledge with respect to approaches for PLM implementation on ETO products; these are discussed in Section 3. The literature provided information on PLM including implementation guidance but was either generic or not viable. The context of PLM implementation was established as being critical necessitating a framework which will provide guidance on the appropriate product type and or industry. A framework in the context of PLM implementation on ETO products does not exist and is required due to the proven difficulties with cost and schedule overruns on these programmes.

10.3 Research methodology

The research methodology described in Section 4 influenced the research approach, including the three main philosophical perspectives from a researcher's point of view to the research problem: Ontology, Epistemology and Methodology. The importance of understanding these perspectives, and making appropriate choices, was to ensure that the research outcome was based on the appropriate philosophical position. As the knowledge for a PLM framework on ETO products is possessed by experts in the field, relativism was identified as the most appropriate approach as there are many truths which are dependent on the actors in the environment. The epistemological perspective identified was subjectivism as the research perspective is that there are only subjective truths, and it is interaction with the experts in the field of PLM on ETO products that co-create the meaning and ultimately the findings. The methodology perspective identified for this research is qualitative and was determined by the ontological perspective of relativism and the epistemological perspective of subjectivism due to the interaction with experts in the field of PLM in ETO products. The paradigm identified for this research was interpretivism, which assumes that knowledge or meaning can be gained through the members' or actors' interpretation of a situation; the real world of first person, subjective experience of those experts in the field of PLM in ETO products. Participatory action research was used as the research approach as it supports interaction with experts in the field of PLM in ETO products. The research strategy was using business transformation within BAE Systems Naval Ships as the motivation and the Type 26 Global Combat Ship as the case study to support the research approach. The longitudinal time-line was chosen as the time horizon for the research as the case study design, data capture, framework development and evaluation was undertaken over an eight year period through the lifecycle of Type 26. The research design of using six sigma was used as a proven formalised structure that provided a set of tools, using Six Sigma DMEDI, which enabled the development of the PLM implementation framework for ETO products.

Based on this research methodology, the framework was developed using a qualitative methodology from on the analysis of 27 semi-structured interviews, and 1 pilot interview. The participants were senior personnel from 11 ETO organisations in the UK, France, Australia, USA and Canada. The interviewees were selected based on their relationship with PLM in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation.

Thematic analysis of the interviews was used to develop the framework which provided objectives, challenges and enablers for information, process, people and technology to support the implementation of PLM on ETO products. Each theme generated in the framework was supported by both interview responses, and references to literature where available, to ensure that the findings were triangulated across multiple sources. The interviewees were from ETO organisations across the UK, France, Australia, USA and Canada to ensure that the framework has a global relevance.

10.4 Definition of requirements for a PLM strategy for an new generation Royal Navy product

The research design using DMEDI as shown in Figure 11, and described in Section 4.3, uses the Measure phase to define the requirements and its relationship to the research problem. This requires capturing the 'voice of the customer' to define the 'critical customer requirements'. The relationship that these requirements have to the research problem is that it supports the discussion of the framework with actual

PLM ETO customer needs. This enables the PLM implementation framework to be related to the requirements and discussed for improved understanding. The Type 26 GCS was used as the case study to form these requirements and are described in Section 5. The requirements were used to develop the quality characteristics to meet these requirements, i.e. how PLM will meet the requirements.

When comparing the requirements to the PLM objectives in the framework they show that the customer has specific needs within the wider PLM objectives. These are needs which are required to be developed from an existing or new PLM architecture. Therefore these requirements would not form the totality of ETO PLM implementation requirements as described in the framework objectives in Section 7.4. This being the case, the case study requirements will support a discussion on actual customer needs on specific PLM topics in a real-life product. As the requirements and the to-be PLM environment were used to develop the PLM strategy to support Type 26, these can be used to relate the framework findings with examples from the case study to show how the requirements can be met and to improve the understanding of PLM implementation on ETO products.

10.5 Description of data capture and analysis approaches

The research design using DMEDI as discussed in Section 4.3 uses the Explore phase for the creation of high level design concepts. Section 6 described the data capture and analysis approach and how this was used to construct the framework for the implementation of PLM on ETO products. The importance of engaging with experts in the field of PLM was established through the philosophical perspective as described in Section 4.1. The ontological perspective of relativism means that there are many truths dependant on the experts in the PLM environment. This coupled with the epistemological perspective of subjectivism means that these truths are subjective and can only be established through interaction with these experts followed by thorough analysis. Therefore the interaction with these experts followed by analysis was important as allowed the determination of the truths to create the framework for the implementation of PLM on ETO products. The use of semi-structured interviews was used to capture the data to enable the analysis to create the framework. As the interview questions related to PLM implementation objectives, challenges and enablers this supported the development of the high level design concept of the framework.

Once the experts were selected, the semi-structured interviews were undertaken, and the key points transcribed. They were then imported into the NVivo software tool to support analysis. This analysis enabled the subjective data to be transformed into truths. To ensure this approach was effective and that the results are correct, thematic analysis was chosen. This enabled codification and identification of common themes from the interview responses. It also enabled repeatability to support further research and to demonstrate that others would create the same results.

A further benefit of NVivo and thematic analysis is that it supports the referencing of the themes to the raw data in the transcribed interview key points in Appendix B. This enabled an audit trail from the findings back to the raw data, supporting trustfulness. It also supported the development of Section 7 as the codes used to develop the themes, and the raw data from the interview key points, were related in NVivo and easily represented through the software tool. The transcribing and coding in NVivo took significant effort but this was worthwhile due to the benefits for developing the framework, writing the thesis and also to demonstrate that a robust approach had been followed.

10.6 Development of the framework

The development of the framework was described in Section 7 which was primarily derived from the analysis of the interview responses in NVivo but was also supported by literature where appropriate. The codes and themes developed in NVivo enabled the grouping of interview responses allowing the related key points from the interviews to be described. To provide an audit trail to support the truthfulness of the findings, each key point was referenced to the transcribed responses in Appendix B. The results of this preparation supported the development of the findings in Section 7 as each theme and related key points could be easily identified and described. Due to the substantial information provided through the key points from the interviews, and its importance in developing the framework, Section 7 is the most extensive in the thesis.

The themes form the framework, and are grouped based on whether the interview question related to an objective, challenge or enabler. This was to ensure that the context and structure of the framework was easy to understand. A further enhancement to the framework structure was identified through the use of enterprise architecture. EA is a well-established methodology to improve the creation of information to describe the strategy, objectives, processes and technology of a business. It also supports the transition from an 'as-is' to a 'to-be' environment by improving the understanding of the new environment and therefore aiding in the business change activity. To improve the structure and understanding of the framework, EA influenced the grouping of themes to include objectives, challenges and enablers within information, people, process and technology.

When viewing the framework and reading Section 7 there is a number of notable aspects:

- **There are no technology objectives**. On analysis this was a surprising result, but when taken in context that the PLM implementation is to support the NPD of ETO products and not to provide technology for its own sake, then this provides support to this finding.
- **The single process challenge was 'creating processes that meet business objectives and are not overly complicated'**. The conclusion drawn from this finding is that processes are easily created but are difficult to implement without being overly complicated. The finding shows that complicated processes are often translated into equally complicated electronic workflows which can significantly impact business performance as they are difficult to understand and alter mid-flow.
- **The people challenges are the most significant**. The findings show that the greatest challenge with PLM implementation on ETO products relates to people. This unsurprisingly resulted in the enablers section for people requiring various initiatives to overcome these challenges.

10.7 Evaluation

The framework was evaluated initially though presenting the framework to gauge feedback on its structure and content. This feedback was positive with the main point to change the improvements heading to enablers to better describe its aim. To ensure that the structure of the framework aligned with the development of the thesis described in Section 7, the headings were changed from improvements to enablers.

The main evaluation used questionnaires to ask selected participants from ETO products for their opinion on statements related to the framework. These participants were selected from multiple ETO organisations based on their relationship with PLM in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation.

The questionnaire responses supported the value of the framework for the implementation of PLM on ETO products. The Industrial use of the framework themes in an ETO product also demonstrated its value, as findings from the research were used by BAE Systems to input into the Naval Ships PLM strategy. This enabled the PLM strategy to meet the related objectives on the Type 26 programme but also to establish PLM as key differentiator in the successful multi £B export contracts for Australia and Canada.

The flexibility and scalability of the framework was identified as being important through the semi-structured interviews and with the evaluation questionnaires. The interviewees highlighted the importance of being able to pick and choose what element of the framework they wished to target. This would enable them to focus on areas which were a priority in their current lifecycle, or was identified a problem area within the organisation. An example of the frameworks flexibility is with the GCS programmes as specific themes have been identified as business priorities and included in the BAE Systems Naval Ships PLM strategy. This has contributed to the success of the PLM approach on Type 26 but also the export wins on Canada and Australia. The evaluation questionnaires provided evidence as to the value of the framework for the implementation of PLM on ETO products.

10.8 Discussion

The case study demonstrated that the flow of the BoM digital thread from CAD to PDM to ERP is challenging on ETO products. This is due to the large volumes of information which constantly changes due to evolving maturity or product change. The timing of applying configuration control, and to what BoM objects, is important. Too early and on too many object types, then the programme has the administrative burden of managing change tasks to large volumes of information. If configuration control is applied too late, then there is a risk of quality issues and rework throughout the product lifecycle as downstream consumers will be using out of date information, such as after the EBOM is related to the MBOM for digital planning as described in the case study requirements in Section 5.

Understanding what objects will be used, by whom and when will assist with determining the configuration and change approach. This understanding can be achieved using a cross functional SQEP team as they can identify and communicate their needs. This team will also be able to more readily determine what problems may arise, such as with too great a level of detail in the BoM. They can also determine the optimum point for progressive configuration control in the lifecycle. For example, it may be optimum to baseline the system design early in the programme lifecycle, but the detailed design in the CAD model can wait until later, such as when the design has greater maturity and is therefore less likely to have large volumes of changes. There is also an opportunity to delay the start of detailed 3D CAD modelling until later in the ETO lifecycle to mitigate the impact due to changes in the system design. This requires further research due to the potential impact on the programme schedule of a delay; this may be balanced by the reduction on the schedule to change in the CAD model.

The cross functional team can ensure that the processes developed to support PLM are useable and not overly complicated. They can also assist with the business change initiative and the education programme. There is potential for exploiting existing University courses to enhance their relationship to PLM and introduce use cases related to ETO products.

PLM implementation guidelines such as those identified by Bokinge and Malmqvist [56] have related findings to the those identified from this research, but the context of ETO products is important. There are opportunities to enhance the PLM framework for ETO products with those generic findings from other researchers. Aspects such as those related to risk management or people can be generic compared to the information challenges on different product types, this can provide valuable enhancements to the ETO PLM implementation framework.

The selection of technology has particular challenges for ETO products and further research is required to ensure that the criteria for PLM technology selection includes the need for longevity, integration and configuration as opposed to customisation.

10.9 Research limitations and need for further research

This research has been undertaken on multi £B ETO programmes relating to PLM. Due to the scale of these programmes it is not possible to describe all the detail required to successfully implement PLM on ETO products. The framework provides guidance and this can be augmented to assist in the successful implementation of PLM on ETO products. The thesis described the themes and their relationship to the

ETO PLM challenges but there are further opportunities. Due to the scale of ETO products further research would require appropriate planning and resource to support. This could be provided by academia at the appropriate level, such as Doctorate or Masters level projects supported by industrial sponsorship.

The results are bounded by the experts interviewed, but the complexity of PLM on ETO products provides a limit to the individuals who could describe the objectives, challenges and enablers. The research was conducted primarily within a naval ships context but the framework could be used on other industrial mega-projects. The research was completed over a nine year period which aligns with the required timescales of PLM implementation on ETO products. Despite this long timescale for PhD research, the journey is not complete; in order to fully leverage the benefits there is a need to continue. This research has taken a major step towards addressing the problem of PLM implementation on ETO products, but it is the first step. There are further research opportunities to improve the implementation of PLM on ETO products, including:

- **Linking the themes in the objectives, challenges and enablers of the framework but maintaining the flexibility for prioritisation and targeting emergent challenges**. There are relationships across the themes in the framework which could be researched to provide additional guidance across the objectives, challenges and enablers across information, process, people and technology.
- **Developing the framework into an electronic format to allow the selection of a theme and have the detail presented.** There is considerable detail in this thesis which can be entered into a software application for easier interrogation. This could be enhanced to include the relationships across the themes in the framework.
- **Utilisation of the framework in the architectural, engineering and construction (AEC) industry**. The framework can be utilised in other large-scale complex industries such as AEC. The literature identified that PLM is immature in the AEC industry and that PLM learning can be leveraged from other industries.
- **Using technology to automatically identify interconnections between product artefacts, to assist with change management impact assessment.** This may require artificial intelligence but the research would provide value to assist in understanding the interconnections and impact of change or other design decisions.
- **Investigation of the appropriate points in the design lifecycle for configuration control**. The review lifecycle and the timing of baselining the design into configuration control is an opportunity for further research. The balance of moving configuration control to later in the lifecycle against the impact on downstream activities is required to be understood in more detail.
- **Problem management and processes improvements from organisations who deal with emergent and significant challenges.** Other organisations such as the accident and emergency departments or medical retrieval services deal with emergent challenges every day. There is an opportunity for ETO organisations to learn from these services.
- **ETO focused education improvements through partnerships with Universities.** Improving academic relationships can assist with further development of the framework. An example is with the analysis and relationship development of the framework themes. Another is with developing training programmes to assist with education and business change.
- **Industry 4.0 and the implication of the internet of things.** This will have an impact on PLM implementation on ETO products which is required to be understood to ensure impact can be reduced and potential benefits captured and leveraged.
- **Develop KPI’s to measure the performance of the PLM implementation.** This will assist in capturing and communicating the benefits of the PLM implementation to the senior management team and other stakeholders to ensure continuing support.

- **Delay the detailed design in the CAD model to mitigate the impact of change.** The impact of changes in the system design on detailed design is significant. This may be mitigated by delaying the start of detailed design until the system design is stable. Further research is required to understand the balance between delays with commencing detailed design, with the impact on the schedule due to change in the CAD model.
- **Enhance the ETO PLM implementation framework with guidance from other researchers.** The context of PLM implementation has been established as being important, but there are opportunities to enhance the ETO PLM framework with guidance from other researchers.
- **Develop criteria for PLM technology selection on ETO products**. Further research is required to investigate current IT technology selection and augment with those requirements for ETO products, such as longevity, integration and configuration as opposed to customisation.

11 References

1. Nolan, R.L., *Ubiquitous IT: The case of the Boeing 787 and implications for strategic IT research.* The Journal of Strategic Information Systems, 2012.
2. Bodington, R. and P. Sims, *Product data sharing in a virtual enterprise*, in *Web Applications in Aerospace (Ref. No. 1999/079), IEE Seminar*. 1999, IET. p. 5/1-5/4.
3. Clegg, B., et al., *Tool support for integrating extended enterprises*, in *Software, IEE Proceedings-*. 2000, IET. p. 101-108.
4. Post, J.E., L.E. Preston, and S. Sachs, *Managing the extended enterprise.* California Management Review, 2002. **45**(1): p. 6-28.
5. CIMData, *PLM Market Industry Analysis Report*. 2012: Ann Arbour.
6. CIMdata, P., *to PLM: Growth of AN Industry.* A CIMdata Report, 2003. **4**.
7. Emerson, D. *Beyond the Horizon: Canada's Interests and Future in Aerospace – November 2012*. 2012 27th March 2013]; Available from: http://aerospacereview.ca/eic/site/060.nsf/eng/00040.html.
8. Lyon, D.D., *Practical CM: Best Configuration Management Practices*. 2000: Butterworth Architecture.
9. Hicks, C. and T. McGovern, *Product life cycle management in engineer-to-order industries.* International Journal of Technology Management, 2009. **48**(2): p. 153-167.
10. Fichman, R.G. and S. Nambisan, *Deriving Business Value from IT Applications in Product Development: A Complementarities-Based Model.* Information Technology and Product Development, 2009: p. 19-47.
11. Whyte, J., A. Stasis, and C. Lindkvist, *Managing change in the delivery of complex projects: Configuration management, asset information and 'big data'.* International Journal of Project Management, 2016. **34**(2): p. 339-351.
12. Chan, Y.E., et al., *Business strategic orientation, information systems strategic orientation, and strategic alignment.* Information systems research, 1997. **8**(2): p. 125-150.
13. Brooke-Holland, L., *The Royal Navy's surface fleet: in brief*, I.A.a. Defence, Editor. 2013, House of commons library: United Kingdom.
14. Magazine, A.D. *Canada opts for Type 26 frigate*. 2018 [cited 2018 19/12/18]; Available from: http://www.australiandefence.com.au/business/canada-opts-for-type-26-frigate.
15. Press, C.U. *Cambridge Dictionary*. 2018 [cited 2018; Available from: https://dictionary.cambridge.org/dictionary/english/framework.
16. Donoghue, I., L. Hannola, and J. Papinniemi, *Product lifecycle management framework for business transformation.* LogForum, 2018. **14**(3).
17. Sääksvuori, A. and A. Immonen, *Product lifecycle management*. 2008: Springer Verlag.
18. Schuh, G., et al., *Process oriented framework to support PLM implementation.* Computers in Industry, 2008. **59**(2): p. 210-218.
19. Batenburg, R., R. Helms, and J. Versendaal, *PLM roadmap: stepwise PLM implementation based on the concepts of maturity and alignment.* International Journal of Product lifecycle management, 2006. **1**(4): p. 333-351.
20. Stark, J., *Product lifecycle management (pp. 1-16)*. 2011, Springer London.
21. Kärkkäinen, H., et al. *Assessing maturity requirements for implementing and using product lifecycle management*. in *The 9th international conference on electronic business, Macau*. 2009.
22. Iyer, R.G. and A. Adlam Jr, *PLM Overview from a Defense Perspective. Module: Standards-based Product Lifecycle Management for Army Ground Systems at US Army Tank Automotive R&D Engineering Center (TARDEC)*. 2007, TACOM RESEARCH DEVELOPMENT AND ENGINEERING CENTER WARREN MI.
23. Jarrett, T. and C. Taylor, *Bribery allegations and BAE Systems.* Standard Note: SN/BT/5367. London: House of Commons Library, 2010.
24. Tauchen, H.F., *PLM innovation in far away places.* 2005.
25. Bodington, R. and P. Sims, *Product data sharing in a virtual enterprise.* 1999.
26. Stjepandić, J., H. Liese, and A.J. Trappey, *Intellectual property protection*, in *Concurrent Engineering in the 21st Century*. 2015, Springer. p. 521-551.

27. Stark, J., *Product LifeCycle Management-21st Century Paradigm for Product Realisation*. 2015, Springer.
28. Terzi, S., et al., *Product lifecycle management–from its history to its new role.* International Journal of Product Lifecycle Management, 2010. **4**(4): p. 360-389.
29. Brunsmann, J. and W. Wilkes, *Enabling Product Design Reuse by Long-term Preservation of Engineering Knowledge.* International Journal of Digital Curation, 2009. **4**(3).
30. Oh, D.K., et al., *Development of Product Model Management System for Naval Shipbuilding.* Journal of Ship Production, 2008. **24**(2): p. 82-91.
31. Rangan, R.M., et al., *Streamlining Product Lifecycle Processes: A Survey of Product Lifecycle Management Implementations, Directions, and Challenges.* Journal of Computing and Information Science in Engineering, 2005. **5**(3): p. 227-237.
32. Matsokis, A. and D. Kiritsis, *An ontology-based approach for Product Lifecycle Management.* Computers in Industry, 2010. **61**(8): p. 787-797.
33. Tang, D. and X. Qian, *Product lifecycle management for automotive development focusing on supplier integration.* Computers in Industry, 2008. **59**(2): p. 288-295.
34. Baxter, D., et al., *An engineering design knowledge reuse methodology using process modelling.* Research in engineering design, 2007. **18**(1): p. 37-48.
35. Gomez, M., et al., *Through-Life Integration Using PLM*. 2009, Cranfield University Press.
36. Ebert, C. and J.D. Man, *Effectively utilizing project, product and process knowledge.* Information and Software Technology, 2008. **50**(6): p. 579-594.
37. Conway, A., et al., *Specification of an Information Capture System to Support Distributed Engineering Design Teams.* Global Design to Gain a Competitive Edge, 2008: p. 221-230.
38. Lee, J.H., S.H. Kim, and K. Lee, *Integration of evolutional BOMs for design of ship outfitting equipment.* Computer-Aided Design, 2011.
39. Fireman, H., et al., *LPD 17 on the shipbuilding frontier: Integrated product & process development*, in *Proceedings of the Association of Scientists and Engineers 35th Annual Technical Symposium*. 1998.
40. Wilkes, W., et al., *Towards support for long-term digital preservation in product life cycle management.* 2009.
41. Rachuri, S., et al., *Information sharing and exchange in the context of product lifecycle management: Role of standards.* Computer-Aided Design, 2008. **40**(7): p. 789-800.
42. Schubert, L., A. Kipp, and B. Koller, *Supporting collaborative engineering using an intelligent web service middleware.* Advanced Engineering Informatics, 2008. **22**(4): p. 431-437.
43. Kano, M., D. Sriram, and A. Gupta, *International multi-company collaborative engineering: a study of Japanese engineering and construction firms.* 1994.
44. Shooter, S.B., et al., *A model for the flow of design information in product development.* Engineering with computers, 2000. **16**(3-4): p. 178-194.
45. Bakis, N., G. Aouad, and M. Kagioglou, *Towards distributed product data sharing environments—progress so far and future challenges.* Automation in Construction, 2007. **16**(5): p. 586-595.
46. Whitfield, R., et al., *Managing the exchange of engineering product data to support through life ship design.* Computer-Aided Design, 2011. **43**(5): p. 516-532.
47. McMahon, C., et al., *The development of a set of principles for the through-life management of engineering information.* 2009.
48. Oliva, R. and R. Kallenberg, *Managing the transition from products to services.* International Journal of Service Industry Management, 2003. **14**(2): p. 160-172.
49. Ball, A., et al., *A grand challenge: immortal information and through-life knowledge management (KIM).* International Journal of Digital Curation, 2008. **1**(1): p. 53-59.
50. Hicks, B., et al., *A framework for the requirements of capturing, storing and reusing information and knowledge in engineering design.* International journal of information management, 2002. **22**(4): p. 263-280.

51. Sivaloganathan, S. and T.M.M. Shahin, *Design reuse: an overview.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 1999. **213**(7): p. 641-654.
52. Goh, Y.M. and C. McMahon, *Improving reuse of in-service information capture and feedback.* Journal of Manufacturing Technology Management, 2009. **20**(5): p. 626-639.
53. Briggs, T.L., T.C. Rando, and T.A. Daggett, *Reuse of ship product model data for life-cycle support.* Journal of Ship Production, 2006. **22**(4): p. 203-211.
54. Gonzalez, C. and F. Alonso, *Advanced CAD–PLM Iintegration in a Naval Shipbuilding Environment.*
55. Bokinge, M. and J. Malmqvist, *Challenging requirements management issues in PLM implementation–findings from a retrospective case study*. 2011.
56. Bokinge, M. and J. Malmqvist, *PLM implementation guidelines–relevance and application in practice: a discussion of findings from a retrospective case study.* International Journal of Product Lifecycle Management, 2012. **6**(1): p. 79-98.
57. Haddon-Cave, C., *The Nimrod Review: an independent review into the broader issues surrounding the loss of the RAF Nimrod MR2 aircraft XV230 in Afghanistan in 2006, report*. Vol. 1025. 2009: Stationery Office.
58. Duque Ciceri, N., M. Garetti, and S. Terzi. *Product lifecycle management approach for sustainability*. in *Proceedings of the 19th CIRP Design Conference–Competitive Design*. 2009. Cranfield University Press.
59. Barreto, L.V., et al., *Product lifecycle management in support of green manufacturing: addressing the challenges of global climate change.* International Journal of Manufacturing Technology and Management, 2010. **19**(3-4): p. 294-305.
60. Kingsman, B., et al., *Responding to customer enquiries in make-to-order companies problems and solutions.* International Journal of Production Economics, 1996. **46**: p. 219-231.
61. Wikner, J. and M. Rudberg, *On the customer order decoupling point.* Department of Production Economics, Linköping Institute of Technology, Linköping, working paper WP-284, 2001.
62. Bertrand, J. and D. Muntslag, *Production control in engineer-to-order firms.* International Journal of Production Economics, 1993. **30**: p. 3-22.
63. Fine, C., *Clockspeed: winning industry control in the age of temporary advantage. 1998.* Massachusetts: Perseus Books Reading.
64. Mendelson, H. and R.R. Pillai, *Industry clockspeed: Measurement and operational implications.* Manufacturing & service operations management, 1999. **1**(1): p. 1-20.
65. Tolman, F.P., *Product modeling standards for the building and construction industry: past, present and future.* Automation in construction, 1999. **8**(3): p. 227-235.
66. Borrmann, A., et al. *Using product data management systems for civil engineering projects–potentials and obstacles*. in *Proc. of the 2009 ASCE International Workshop on Computing in Civil Engineering. Austin, TX, USA*. 2009.
67. Froese, T.M., *The impact of emerging information technology on project management for construction.* Automation in construction, 2010. **19**(5): p. 531-538.
68. Azhar, S., *Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry.* Leadership and management in engineering, 2011. **11**(3): p. 241-252.
69. Aram, S. and C. Eastman. *Integration of PLM solutions and BIM systems for the AEC industry*. in *Proceedings of 30th International Symposium of Automation and Robotics in Construction and Mining, Montréal*. 2013.
70. Sanderson, J., *Risk, uncertainty and governance in megaprojects: A critical discussion of alternative explanations.* International Journal of Project Management, 2011.
71. Van Marrewijk, A., et al., *Managing public-private megaprojects: Paradoxes, complexity, and project design.* International Journal of Project Management, 2008. **26**(6): p. 591-600.
72. Merrow, E.W., *Industrial megaprojects: Concepts, strategies, and practices for success*. 2011: Wiley.
73. Flyvbjerg, B., *What you should know about megaprojects and why: An overview.* Project Management Journal, 2014. **45**(2): p. 6-19.

74. Sun, J. and P. Zhang, *Owner organization design for mega industrial construction projects.* International Journal of Project Management, 2011. **29**(7): p. 828-833.
75. Sharma, R. and T. Kim, *Development of a Logic-Based Product Life-Cycle Management (LBPLM) System for Shipbuilding IndustryConceptual Development.* Journal of Ship Production and Design, 2010. **26**(4): p. 231-251.
76. Flyvbjerg, B., M.S. Holm, and S. Buhl, *Underestimating costs in public works projects: error or lie?* Journal of the American Planning Association, 2002. **68**(3): p. 279-295.
77. National_Audit_Office, *Ministry of Defence The Major Projects Report 2011*. 2011, National Audit Office: London.
78. Merrow, E.W., L. McDonnell, and R.Y. ArgUden, *Understanding the Outcome of Megaprojects.* Santa Monica, The Rand Corporation. Will Jennings, 1988. **263**.
79. Johnson, D.C., et al., *Managing Change on Complex Programs: VIRGINIA Class Cost Reduction.* Naval Engineers Journal, 2009. **121**(4): p. 79-94.
80. Rahim, A.R.A. and M.S.N. Baksh, *The need for a new product development framework for engineer-to-order products.* European Journal of Innovation Management, 2003. **6**(3): p. 182-196.
81. McKendry, D., R. Whitfield, and A. Duffy. *Business and information management architectures for delivering Product Lifecycle Management (PLM) in Engineer To Order (ETO) products*. in *Internationl Conference in Computer Applications for Shipbuilding*. 2015. Bremen: RINA.
82. Sargut Gökçe, G.M.R. *Learning to Live with Complexity*. 2011 [cited 2012 10th July]; Available from: http://hbr.org/2011/09/learning-to-live-with-complexity.
83. Weaver, W., *Science and complexity.* American scientist, 1948. **36**(4): p. 536-544.
84. Homer-Dixon, T., *The ingenuity gap. Alfred A*. 2000, Knopf, New York.
85. Handfield, R.B., *Effects of concurrent engineering on make-to-order products.* Engineering Management, IEEE Transactions on, 1994. **41**(4): p. 384-393.
86. Haug, A., K. Ladeby, and K. Edwards, *From engineer-to-order to mass customization.* Management Research News, 2009. **32**(7): p. 633-644.
87. Caron, F. and A. Fiore, *'Engineer to order'companies: how to integrate manufacturing and innovative processes.* International Journal of Project Management, 1995. **13**(5): p. 313-319.
88. McGovern, T., C. Hicks, and C.F. Earl, *Modelling supply chain management processes in engineer-to-order companies.* International Journal of Logistics: Research and Applications, 1999. **2**(2): p. 147-159.
89. Heredia Jiménez, J.A., et al. *The development of a novel standardisation-customisation continuum*. in *ICED17, 21st International Conference on Engineering Design*. 2017.
90. Iakymenko, N., et al., *Managing engineering changes in the engineer-to-order environment: challenges and research needs.* IFAC-PapersOnLine, 2018. **51**(11): p. 144-151.
91. Romero Rojo, F.J., et al. *Obsolescence challenges for product-service systems in aerospace and defence industry*. in *Proceedings of the 19th CIRP design conference–competitive design*. 2009. Cranfield University Press.
92. Floricel, S. and R. Miller, *Strategizing for anticipated risks and turbulence in large-scale engineering projects.* International Journal of Project Management, 2001. **19**(8): p. 445-455.
93. Ruecker, S., *A brief taxonomy of prototypes for the digital humanities.* Scholarly and Research Communication, 2015. **6**(2).
94. Vezzetti, E., M.G. Violante, and F. Marcolin, *A benchmarking framework for product lifecycle management (PLM) maturity models.* The International Journal of Advanced Manufacturing Technology, 2014. **71**(5-8): p. 899-918.
95. Kamphuis, A., H. de Ridder, and H. Schevers, *Product Information Management at the Large-Scale Project CALLED Arena" Auf Schalke.* CONCURRENT ENGINEERING IN CONSTRUCTION, 2002.
96. Xue, X., et al., *IT supported collaborative work in A/E/C projects: A ten-year review.* Automation in Construction, 2012. **21**: p. 1-9.
97. von Rosing, M., et al., *Combining BPM and EA in Complex IT Projects:(A Business Architecture Discipline)*. 2011, IEEE. p. 271-278.

98. Corallo, A., et al., *Defining Product Lifecycle Management: A Journey across Features, Definitions, and Concepts.* ISRN Industrial Engineering, 2013. **2013**.
99. Mocenco, D., *Supply Chain Features of the Aerospace Industry Particular Case Airbus And Boeing.* Scientific Bulletin-Economic Sciences, 2015. **14**(2): p. 17-25.
100. Tegtmeier, W., et al. *Information management in civil engineering infrastructural development: with focus on geological and geotechnical information*. in *Proceedings of the ISPRS workshop*. 2009.
101. Andrade, S.L., T.G. Monteiro, and H.M. Gaspar. *Product Life-Cycle Management In Ship Design: From Concept To Decommission In A Virtual Environment*. in *ECMS*. 2015.
102. Jupp, V., *The Sage dictionary of social research methods*. 2006: Sage.
103. Kothari, C.R., *Research methodology: Methods and techniques*. 2004: New Age International.
104. Easterby-Smith, M., R. Thorpe, and P.R. Jackson, *Management research*. 2012: Sage.
105. Wand, Y. and R. Weber, *On the ontological expressiveness of information systems analysis and design grammars.* Information Systems Journal, 1993. **3**(4): p. 217-237.
106. Guba, E.G. and Y.S. Lincoln, *Competing paradigms in qualitative research.* Handbook of qualitative research, 1994. **2**(163-194): p. 105.
107. Audi, R., *Epistemology: A contemporary introduction to the theory of knowledge*. 2010: Routledge.
108. Guba, E.G., *The paradigm dialog*. 1990: Sage publications.
109. Merriam, S.B. and E.J. Tisdell, *Qualitative research: A guide to design and implementation*. 2015: John Wiley & Sons.
110. Swanson, R.A. and E.F. Holton, *Research in organizations: Foundations and methods in inquiry*. 2005: Berrett-Koehler Publishers.
111. Gephart, R. *Paradigms and research methods*. in *Research methods forum*. 1999.
112. Schwandt, T.A., *Constructivist, interpretivist approaches to human inquiry.* Handbook of qualitative research, 1994. **1**: p. 118-137.
113. Kincheloe, J. and P. McLaren, *Rethinking critical theory and qualitativeresearch. InN. K. Denzin& YS Lincoln (Eds.). Handbookof qualitativeresearch (pp. 138-157)*. 1994, ThousandOaks, CA: Sage.
114. Patton, M.Q., *Qualitative Research & Evaluation Methods* 2001: Sage Publications.
115. Lewin, K., *Action research and minority problems.* Journal of social issues, 1946. **2**(4): p. 34-46.
116. Reason, P. and H. Bradbury, *Handbook of action research: Participative inquiry and practice*. 2001: Sage.
117. Greenwood, D.J., W.F. Whyte, and I. Harkavy, *Participatory action research as a process and as a goal.* Human Relations, 1993. **46**(2): p. 175-192.
118. Chatterton, P., D. Fuller, and P. Routledge, *Relating action to activism: Theoretical and methodological reflections.* Participatory action research approaches and methods: Connecting people, participation and place, 2007: p. 216-222.
119. McKendry, D., R. Whitfield, and A. Duffy, *Key Findings to Support the Development of a Framework for the Implementation of Product Lifecycle Management in Engineer to Order Products*, in *International Conference on Manufacturing Research*. 2017: University of Grenwich London.
120. Morris, T. and S. Wood, *Testing the survey method: continuity and change in British industrial relations.* Work, Employment and Society, 1991. **5**(2): p. 259-282.
121. Robson, C. and K. McCartan, *Real world research*. 2016: John Wiley & Sons.
122. Saunders, M.K., P. Lewis, and A. Thornhill, *Research Methods for Business Students*. Fifth ed. 2009, Harlow: Financial Times/ Prentice Hall.
123. Yin, R.K., *Case study research: Design and methods*. 2013: Sage publications.
124. Siggelkow, N., *Persuasion with case studies.* Academy of Management Journal, 2007. **50**(1): p. 20-24.
125. Schweikhart, S.A. and A.E. Dembe, *The applicability of Lean and Six Sigma techniques to clinical and translational research.* Journal of Investigative Medicine, 2009. **57**(7): p. 748-755.
126. Pyzdek, T. and P.A. Keller, *The six sigma handbook*. 2014: McGraw-Hill Education New York.

127. Jeffery, A.B., *Integrating Organization Development and Six Sigma: Six Sigma as a Process Improvement Intervention in Action Research.* Organization Development Journal, 2005. **23**(4).
128. Brue, G. and R.G. Launs, *Design for six sigma*. 2003: McGraw-Hill.
129. Jones, S.H. *To Use DMEDI or to Use DMAIC? That Is the Question*. 21/04/15]; Available from: https://www.isixsigma.com/new-to-six-sigma/design-for-six-sigma-dfss/dmedi-or-dmaic/.
130. Johnson, M. and S. Dubikovsky. *Incorporating Lean Six Sigma into an Aviation Technology Program*. in *Proceedings of SEFI 2008 Annual Conference*. 2008.
131. Skalle, H., et al., *Aligning business process management, service-oriented architecture, and Lean Six Sigma for real business results.* IBM Redbooks, 2009.
132. Hauser, J.R. and D. Clausing, *The house of quality.* 1988.
133. DeMarrais, K., *Qualitative interview studies: Learning through experience.* Foundations for research: Methods of inquiry in education and the social sciences, 2004. **1**(1): p. 51-68.
134. McCracken, G., *The long interview*. Vol. 13. 1988: Sage.
135. Reybold, L.E., J.D. Lammert, and S.M. Stribling, *Participant selection as a conscious research method: Thinking forward and the deliberation of 'emergent'findings.* Qualitative Research, 2013. **13**(6): p. 699-716.
136. Maxwell, J.A., *Qualitative research design: An interactive approach*. Vol. 41. 2012: Sage publications.
137. Braun, V. and V. Clarke, *Using thematic analysis in psychology.* Qualitative research in psychology, 2006. **3**(2): p. 77-101.
138. Guest, G., K.M. MacQueen, and E.E. Namey, *Applied thematic analysis*. 2011: Sage.
139. Bazeley, P. and K. Jackson, *Qualitative data analysis with NVivo*. 2013: Sage Publications Limited.
140. Lincoln, Y.S. and E.G. Guba, *Naturalistic inquiry. Newberry Park*. 1985, CA: Sage.
141. Tashakkori, A., C. Teddlie, and M. Methodology, *Combining Qualitative and Quantitative Approaches. Thousand Oaks.* California: Sage Publications, 1998.
142. Chism, N.V.N., E. Douglas, and W.J. Hilson Jr, *Qualitative research basics: A guide for engineering educators.* Rigorous Research in Engineering Education NSF DUE-0341127, 2008.
143. Borrego, M., E.P. Douglas, and C.T. Amelink, *Quantitative, qualitative, and mixed research methods in engineering education.* Journal of Engineering education, 2009. **98**(1): p. 53-66.
144. Glissmann, S.M. and J. Sanz, *An Approach to Building Effective Enterprise Architectures*. 2011, IEEE. p. 1-10.
145. Griffin, L.K., *Analysis and comparison of DODAF and ZACHMAN framework for use as the architecture for the United States Coast Guard's maritime patrol (WPC).* 2005.
146. Foorthuis, R., et al., *Assessing Business and IT Projects on Compliance with Enterprise Architecture.* Proceedings of GRCIS, 2009.
147. Lillehagen, F. and D. Karlsen, *Enterprise architectures–survey of practices and initiatives*. 2006, Citeseer.
148. Johnson, P., et al., *Using enterprise architecture for cio decision-making: On the importance of theory*. 2004.
149. Ward, J. and R. Elvin, *A new framework for managing IT-enabled business change.* Information systems journal, 1999. **9**(3): p. 197-221.
150. Levine, H.G. and D. Rossmoore, *Diagnosing the human threats to information technology implementation: A missing factor in systems analysis illustrated in a case study.* Journal of Management Information Systems, 1993. **10**(2): p. 55-73.
151. Boddy, D., A. Boostra, and G. Kennedy, *Managing information systems: an organisational perspective*. 2005: Ft Pr.
152. Svatá, V., *Business Process Modelling in Government Institutions.* IDIMT-2009, 2009: p. 95.
153. Bandara, W., et al., *Major issues in business process management: an expert perspective.* 2007.
154. Pereira, C.M. and P. Sousa. *Enterprise architecture: business and IT alignment*. in *Proceedings of the 2005 ACM symposium on Applied computing*. 2005. ACM.

155. Merriam-Webster. *Learner's Dictionary*. 2018 [cited 2018 03/11/18]; Available from: http://www.learnersdictionary.com/definition/theme.
156. Pulkkinen, A., S.-P. Leino, and J. Papinniemi, *Transforming ETO Businesses with Enhanced PLM Capabilities.* Procedia Manufacturing, 2017. **11**: p. 1642-1650.
157. Rohloff, M., *Case study and maturity model for business process management implementation.* Business Process Management, 2009: p. 128-142.
158. Scheubel, C., et al., *Valuing Product Lifecycle Management*, in *Valuing Corporate Innovation: Strategies, Tools, and Best Practice From the Energy and Technology Sector*, G. Friedl and H.J. Kayser, Editors. 2018, Springer International Publishing: Cham. p. 39-70.
159. Qiu, Z., et al., *Role-based 3D visualisation for asynchronous PLM collaboration.* Computers in Industry, 2007. **58**(8): p. 747-755.
160. Perry, D., *2016 Status Report on Major Equipment Procurement.* 2017.
161. Valenti, A., *Type 26 and Fremm-two SEA 5000 contenders in their national context.* Asia-Pacific Defence Reporter (2002), 2017. **43**(2): p. 18.
162. Stark, J., *The Benefits of PLM, Another Why PLM?*, in *Product Lifecycle Management (Volume 3): The Executive Summary*. 2018, Springer International Publishing: Cham. p. 31-36.
163. Clermont, P. and B. Kamsu-Foguem, *Experience feedback in product lifecycle management.* Computers in Industry, 2018. **95**: p. 1-14.
164. Hoffman, C.M. and R. Joan-Arinyo, *CAD and the product master model.* Computer-Aided Design, 1998. **30**(11): p. 905-918.
165. Prawel, D. *Interoperability isn’t (yet), and what’s being done about it*. in *3rd International Conference on Advanced Research in Virtual and Rapid Prototyping*. 2007.
166. Light, B., *The maintenance implications of the customization of ERP software.* Journal of Software: Evolution and Process, 2001. **13**(6): p. 415-429.
167. Bell, E., A. Bryman, and B. Harley, *Business research methods*. 2018: Oxford university press.
168. Loshin, D., *Master data management*. 2010: Morgan Kaufmann.
169. Hewett, A., *Product lifecycle management (PLM): critical issues and challenges in implementation*, in *Information Technology and Product Development*. 2010, Springer. p. 81-105.
170. Alemanni, M., et al., *Key performance indicators for PLM benefits evaluation: The Alcatel Alenia Space case study.* Computers in Industry, 2008. **59**(8): p. 833-841.
171. Kotter, J.P., *Leading change*. 1996: Harvard business press.
172. Stark, J., *Organisational Change Management in the PLM Environment*, in *Product Lifecycle Management (Volume 1)*. 2015, Springer. p. 235-267.
173. Bokinge, M., et al. *A Method to Identify Risks Associated with a PLM Solution*. in *IFIP International Conference on Product Lifecycle Management*. 2012. Springer.

Appendix A Overview of research

 1

Product Lifecycle Management (PLM) Implementation on Engineer to Order (ETO) Products

- ### What is PLM?

"PLM is a product centric business model which is supported by Information Management Technology across the entirety of a product's lifecycle, involving people, information, processes and organisations in order to achieve a product performance objective"

- ### What are ETO Products?

"Engineer to Order (ETO) products can be described as those which include the following characteristics : high capital value, large-scale, complex, long design and build lifecycle, long in-service life, no prototype, highly customised, few or one off"

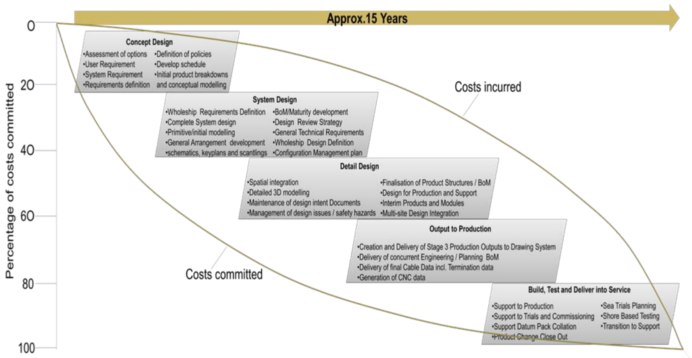
- ### What is the aim of the research?

"Develop a framework for the implementation on PLM on ETO products to meet business objectives"

BAE SYSTEMS
INSPIRED WORK

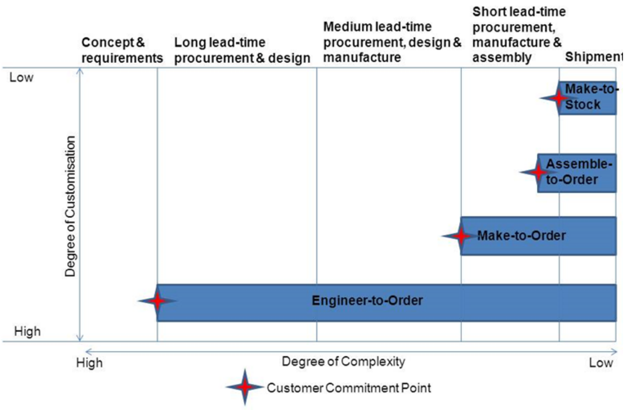
PLM Implementation on Engineer to Order Products Challenges - Complexity and Uncertainty

- Multiple elements with varying complexity (10,000's procured equipment parts from valves to complex radar)
- A high degree of synergy, sum is greater than the parts, designed to be a system of systems
- Parts are designed to be interdependent (e.g. too few ATU's, Radar overheats, navigation system fails)
- A change in a system can produce an effect not proportional to its size, small changes have large effect, increase in wild head, HVAC system fails other systems fail
- Highly customised first time design/build, difficult to predict issues resulting in emergent challenges
- The more complex an environment the more difficult it is to understand all of the interconnections



PLM Implementation on Engineer to Order Products Challenges – Customer interaction and procurement

- Delivery lead time longer than other product types
- The long lead times require a customer commitment earlier than other product types
- In ETO products the customer commits to the order early in the products lifecycle
- Customer has significant input into the specification, design, manufacture and procurement strategies
- Therefore the design is immature when the order is placed
- The design is based on the flow of information from supply chain based on requirements



BAE SYSTEMS
INSPIRED WORK

PLM Implementation on Engineer to Order Products Challenges – Highly customised, few off

- Low volume, highly complex, high cost
- High levels of risk and increased cost due to longer lead times
- Unique set of requirements resulting in bespoke design systems varying in complexity
- Close interaction with suppliers to integrate bespoke designs
- Sporadic data drops from suppliers which require integration with knock on effects to other systems
- Requires careful contract management

PLM Implementation on Engineer to Order Products
Challenges - BoM, Configuration, Change and Maturity Management

- Significant product information management to ensure design meets ongoing customer needs
- ETO products have evolving design which requires management across the lifecycle
- Emerging patterns have to be captured, managed and integrated into the product
- Maturity management of information used to progress the design is critical
- Manufacturing begins before design is fully mature
- Changes need to be captured, their impact to the design, build and cost/schedule understood
- The design configuration must be managed, baselined and integrated with the change process

PLM Implementation on Engineer to Order Products Challenges – Project Management

- Complexity and emerging patterns require effective cost and schedule management
- There a history of considerable cost overruns with ETO projects in civil and defence sectors
- Therefore ETO products have a considerable emphasis on project management
- Cost and schedule estimations are extremely challenging early in the projects lifecycle, when the design is immature but the customer wants a commitment to a plan and cost
- Therefore managing risk is of critical importance as the product moves for concept to a physical representation

PLM Implementation on Engineer to Order Products Challenges – No prototype

- As there are a small number of similar products produced, it is not viable to have a prototype
- Prototyping allows for design and manufacturing problems to be identified and resolved, prior to production of the delivered product
- ETO products have their manufacturing started before the design is fully mature and all items procured
- A need for high quality and right first time is required as a prototype cannot be used to test cost, schedule and quality

Appendix B Interviews

B.1 Chief Engineer - Interview 1

Interviewee

Company

Position Chief Engineer

Date 20/07/2016

Location

Time 11:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Type 26 - customer change, stakeholder change, and stakeholder expectations varied from a few years ago. Good example is a modification of defence standards which resulted in a change for pipe hangers, simple area but significant issue is we've always designed for single shock but the customer changed the standard to include 2 shock incidents. Significant impact as Pipe hangers were designed based another standard. Another example, customer wants us to include modelling for loss of life in our design, new space for BAE Systems. Maturity management is a key factor with supply chain. Can't fully maintain maturity with supplier data, moving to cut steel with not all supplier data. Programmes not waterfall, overlap and in parallel. People challenges, assumes everyone understands top level PLM and are motivated to populate. Where is their reward? Consumers of data, e.g. Load data, as a part owner what is in it for them regarding populating data. Assume everyone is bought in, but I am not always convinced. Also, supplier alignment, they have their own systems; we can't align our supplier to their systems. In large volume production they can share systems. We would disqualify our suppliers if they were dependency on us - risky and not viable
Q2	What are the typical key business objectives which you require a PLM environment to support?	Maturity, raised in every discussion regarding the programme by senior management. Change management and volume of change
Q3	Describe your current PLM architecture	Our understanding has advanced since type 45 significantly Write once use many, single point of truth; source everything from our PLM environment. Informing modelling, stage 1. Massive step change but better. Consistent than correct

Q4	Describe the typical challenges you experienced with utilising PLM?	People. Getting them bought in, expectations of what they need to do, whether supply chain, part owner, system owner etc. Ensuring that 1000 people understand maturity management, taken 2 years and we're still not there. Comms and Training. It is the language of the project, E4 maturity.
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	People - Comms and training Ensure they understand benefits, what it in for people, what's in it for me. Ensuring better integration with supply chain, iBoM data loader, specifications for suppliers regarding maturity, disconnect. Support data, do people understand the benefit which are downstream.
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	People- Going from document to data environment, significant change for people. Working with data and information mind-set for people which are not insignificant. We take it for granted
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	People - business change management
Q8	How could you better enable the implementation of these improvements	EDY (Engineering Developing You - training course) does not equip you for working in the programme wrt to PLM. Totally ill equipping an engineer to work in the programme. Project management, ensure engineers understand maturity and programme management relationship - maturity drive programme. Disconnect between supply chain and engineering. Run from central engineering, focussed on engineers, not Test and commissioning, not supply chain. No hierarchy which drives across all functions. PLM organised for engineering, and perceived that way. Osmosis understanding for other functions. CME getting there, appreciation that we need to be integrated cross functionally. Scaling, can we have a light touch on RCB2 or not at all, do you need it on RCB2 but you need it for Type 26
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Investment, cost/benefit difficult to promote, e.g. data loader - communicating that the cost worthwhile. PLM branched out to other areas, Digital Planning, PDM to ERM (supply chain). PLM branching out to other functions, iBoM strategy doing elements of it. Why should we invest in PLM once build is complete? Commercial elements in the BoM, right to share BoM data for other programmes, i.e. Diesel Generator might have something hidden away which we can't share with export programmes. We understand ITAR now, but there are further subtleties Safety - I can reasonably assert the iBoM, maturity, supplier data and single point of truth. We can offer best endeavours as a reasonable defence if called upon. Safety mitigation in Smarter is my biggest worry
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	People - we assume a lot that there is integration and understanding across the all areas. Type 26 so large everyone understands their part of the ship. Understanding needs to be appropriate, information hiding principle to ensure they are not overloaded
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	People

Q12	How could you overcome difficulties associated with these challenges	See Q8 response
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, we need to keep evolving, take it further, evolving with understanding and learning. E.g. tie maturity into supply chain Should be pictorial; you must be able to understand the picture - backed up with data. Nobody reads detail if they don't need to know, they just need appreciation and buy-in. Suck people in using the high-level framework. Get an appreciation they then look into it if interested. Like PDH
Q14	What other ETO industries would benefits from a framework?	Oil and gas, Nuclear, HS2, space,

B.2 Design Authority CAD/PLM - Interview 2

Interviewee

Company

Position

Date 16/08/2016

Location

Time 14:15

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	All relevant, some take as read - product complexity absolutely true , no brainier Customer high risk -agreed Cause and affect diagram - in IPDE we wanted a right first time, understand what we need later IPDE focussed on maturity, BoM change and Configuration mgmt. - if we done this correctly at the left hand side then the right hand (later) will take of themselves - so looking at data quality, 100% BoM, we manage maturity at decision reviews with a proper understanding of the information we are using, so understand risk So greatest thing is data management and having data management which we can trust and using Teamcenter as the single point of truth Plenty of evidence in the public domain of cost and overruns in Astute - CADDS5 and Optegra - lack of understanding in the business - much better understanding 15yrs on, but PLM is still a big challenge Successor - difficult to assess costs early on, challenges to implement PLM is a big challenge even based on experience difficult to understand PLM and how it works, don't give up Early on when you tell people they are bought in, when you then makes mistakes then you revert back to older ways of working - especially when you underestimate cost and schedule - pressure on payment milestones

Q2	What are the typical key business objectives which you require a PLM environment to support?	Change, Configuration, maturity, BoM mgmt., Fundamentally it was a reduction in rework Integrate planning with engineering - digital planning - use Teamcenter to use planning - Instead of using BoM list and drawings the planners can plan earlier and dictate when they require drawings - Astute -drawings produced, Successor has planning lead drawings IPDE include outputs but not a full business end-end process but focussed on earlier activities - production readiness Involvement from safety, test and commissions and planning involved when they can influence design
Q3	Describe your current PLM environment from your perspective?	Astute - CADDS5 Optegra, items databases Successor - nicer picture but pure systems and less homemade - main difference is using COTS tools with significantly less customisation - still configuration but through the core Teamcenter product, configure workflows as opposed to Astute where there were customisations - Astute now difficult to support 1 big lessons learned we've tried to deploy COTS - Teamcenter 10.1 and Foran v 80 - both current releases - both lynchpins - with interfaces into SAP Rational - testing and toolset requirements
Q4	Describe the typical challenges you experienced with utilising PLM?	phase 1 - it's easier earlier in the project, they have all had their town hall briefs and have bought in, they want to do things earlier, enthusiastic - you can make rapid progress with a small group of people and you can communicate easier Next phase - people become disillusioned - things become harder - more stakeholders - harder to communicate - then people join from other programmes and it's all different - why do we need PLM then hopefully people get to a point that resistance is futile - is for their own good - that's the stage we're at
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	1 - There is always a balance - a couple of things stick out - we overegged the workflows - too complicated and prescriptive - everyone using same process - workflows were too big, if something went wrong it was difficult to fix - so we then reengineered the workflows to make them simpler and undo when required - keep things simple stupid 2 - data quality - Because we are using Foran - when we found when we turned on Teamcenter and Foran integration - there were a lot of rejects when data published from Foran - there are hard and fast rules to move data over the interface, these should be validated at source - we should have put mandatory codes in Foran not let the interface deal with them
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	deficient data quality
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	data quality

Q8	How could you better enable the implementation of these improvements	there is a get well programme but these are after the event - make fields mandatory, education - people need to know why quality is important - previously it was the easiest way of doing drawings - there was little focus on BoM - astute the drawing was the main currency - manual intervention In Successor the focus is on the 100% BoM -now they data is more important - Subs are now data centric - people don't understand they must work differently - previously it would be what looked like in the Model, not must be right - Teamcenter expect not a solid model but broken down to material 2 tools work differently and we keep stumbling on things - keep finding things - we should have done more about the modelling strategy
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Because we have such a long product lifecycle - people can't understand the whole integrated flow - there is less focus on downstream activities that those upfront - so you focus on those you need now, not later - you won't do it till later - we build the system as we go along and discover thongs as we go along Problems with process documentation - we rely on what is in people heads - those who operate the process work rounds then as they understand them - more focus on process development and adherence to support the PLM deployment
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	process documentation
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	process documentation
Q12	How could you overcome difficulties associated with these challenges	We are trying do it - structure the process team - the business guys own process but they don't create them as they need to design subs - so we have created a central team, sop business own process but central team will help business to help themselves - core architecture and principles that you can explain and then create process in the context of the flow
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, it ought to help - when we stated off at our PLM select - we had a selection criteria with working with CIMDATA - they helped with the buy-in process for our board we carried out a robust process - CIMDATA offered help but we went with IBM -We expected IBM to bring prescriptive process to the party but in hindsight but they were over complicated and the IBM consultancy didn't know more than we did - some had done PLM some had others - what really slowed us down was the inexperienced people - we relied on the IBM framework and it didn't work - it works both ways - you need balance - it has to be enough to understand but not too complicated, pitched at the right level - you need good people.
Q14	What other ETO industries would benefits from a framework?	Formula 1, not engineering to order but they were simpler in that they have 1 product a year - innovative components, change - have a prototype but as the design changes it becomes less relevant - - they continually change the design of the car so they are more similar than you think

B.3 Engineering Director - Interview 3

Interviewee

Company

Position Engineering Director

Date 18/08/2016

Location

Time 08:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Start of lifecycle, GPLF, trying to produce accurate estimates of engineering effort and cost - variability of customer requirements Accessing data many years later - transferring between cad systems - taking legacy systems back in our products
Q2	What are the typical key business objectives which you require a PLM environment to support?	Capture organise and share the information - immediate response - prime purpose - get into an org and share
Q3	Describe your current PLM environment from your perspective?	product structure is important - we use Windchill - decomposes the product - different views - functional view, own we end up diving the design task - physical view - different lifecycle view - engineering, as we over into build and support - same end point
Q4	Describe the typical challenges you experienced with utilising PLM?	User adoption - data quality which is linked to adoption - getting people to use it, make sure its current Honing the system to our requirements - gigantic team each a leader in their field We have ended up with a complex environment, we have a complex product - goes too slowly
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Make it more friendly from an engineer's point of view - I get a lot of feedback that a lot of engineers time is doing admin - reorient that it's easy for an engineering to get info in and out - our focus has been on architecting the and reducing the systems such as through integration - we need to focus on usability -something we want to do other than have to do Use earlier in the lifecycle - direction of project moves more repaid too heavy weight - needs to be scalable in processes and control

Q6	Can you prioritise the improvements in terms of business impact	Focus on high value use of PLM
Q7	Can you prioritise the improvements in terms of effort required	Focus on high value use of PLM
Q8	How could you better enable the implementation of these improvements	More strategic on where the improvements are - take stock and home in one area
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Drives customisation - security - peoples phones Mature technology Don't believe we will need to stretch technology - we're tooled up
Q10	Can you prioritise the challenges in terms of business impact	efficiency improvement
Q11	Can you prioritise the challenges in terms of effort required	efficiency improvement
Q12	How could you overcome difficulties associated with these challenges	Actively looking at how the system use - what proportion of what they are doing - survey - user satisfaction - anecdotal it takes too long - investigation - user groups most impact - where can we get the most impact
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes definitely - it would excellent - really supportive
Q14	What other ETO industries would benefits from a framework?	Large hadron collider - aerospace - MAI - engineer to order software products

B.4 Project Manager - PLM Upgrade - Interview 4

Interviewee	
Company	
Position	Project Manager -
Date	02/09/2016
Location	
Time	06:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Yes - generally it comes down to the maturity of the business, we are an evolving market - each project has its own need but we need single MRP and PLM - Low volume - we have a specification from our customer to deliver a BoM to them - so we need to customise our systems and interface into our systems
Q2	What are the typical key business objectives which you require a PLM environment to support?	From my project specifically- key objectives - as configuration mgmt. database -we are dealing with an evolving architecture, they are amalgamation of developed in-house or COTS - we need a business view - so my project is to provide a single approach - first objective is configuration mgmt. and ensuring we can engage with our customer - we don't have direct access to them so we need to deliver configured data We also don't have direct change integration with our product data - we can't feed lessons learned into product - we're planning to introduce change management integrated with our product data
Q3	Describe your current PLM environment from your perspective?	The current environment is an amalgamation of different systems - work gets done but it's not integrated - there a considerable amount of manual effort
Q4	Describe the typical challenges you experienced with utilising PLM?	First/biggest challenge - people don't understand it - they see it as a configuration mgmt. solution - education isn't there as to what a PLM system is and what it can do for them - the cost is large and you need a very good way of marketing of what you need to do Common part library - reduce duplication and redundancy Its difficult to quantify benefits - commonality Business change management - initial then next challenge - incremental

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	We are implementing Windchill to provide an integrated approach - we are removing legacy tools and replacing with Windchill and ERM - the primarily reason is risk reduction, lots of legacy systems, the owners of 'black boxes' leave which introduces risk - Education Business change Quantify benefits - Explain what you are getting from PLM
Q6	Can you prioritise the improvements in terms of business impact	Risk reduction we know there a lot of process we can do better but we won't get there in day one
Q7	Can you prioritise the improvements in terms of effort required	Initially, hardest was requirements due to education - they don't care about the future as they are happy now
Q8	How could you better enable the implementation of these improvements	We are writing software so we need to translate business knowledge to requirements for the software - but it's going well - we are using agile scrum which is mitigating risk - if we had not adopting this methodology then they couldn't see the evolution - traditionally a wasteful approach but if call it a 'waterfall scrum' - we can do iteration activity - its works well as it gives our business early insight as to what the change are and what the system does before we go live - the scrum approach is helping with business change - it helps engage the business early on and gain buy -in before we implement the system - this is critical as it's a live systems with years of data and large data migration
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Defining requirements for what you want the PLM systems to do- you are working with people who have used their systems and process for some time - but I am coming from a programme perspective - the process and requirements has been quite challenging - people are not educated enough - one of the key challenges, but once we get it implemented in Maritime we can see it improving over tome
Q10	Can you prioritise the challenges in terms of business impact	Buy-in
Q11	Can you prioritise the challenges in terms of effort required	buy-in
Q12	How could you overcome difficulties associated with these challenges	agile scrum
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes - I would have loved to have that years ago - buts its scalability is key - the second part is the maturity of your people - a upfront when the project is being conceived a framework would be great - I have been doing this myself and I'd love to see a framework - must be able slice and dice, flexible but mandatory - if rather that than a mandated approach - every project is different - need to include reason so it just isn't ignored I am looking forward to seeing the results
Q14	What other ETO industries would benefits from a framework?	oil and gas, mining - lots of material, anything which has integration of systems and processes - valid across other industries

B.5 Project Delivery Director - Interview 5

Interviewee	
Company	
Position	Project Delivery Director
Date	07/10/2016
Location	
Time	08:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	I agree with them but it's the prototype I struggle with. Typhoon - fits all other criteria, process of getting that prototype was a project in its own right - in the team it wouldn't have felt any different- they had to meet quality and safety - other than that its ok. I've drawn a box round the product - to the customer is a strike capability, ships, submarine, aircraft etc. - this is a system of systems - everyone has a different lens on the boundary of a complex system,
Q2	What are the typical key business objectives which you require a PLM environment to support?	Information is the building block to drive and sell your product - if you can control your information you can better control cost and therefore your price The other thing, controlling all your data through design/build allows you to leverage in-service support
Q3	Describe your current PLM environment from your perspective?	Understanding where we are on the developing maturity of the product - that's design artefacts, supply chain, cost model - all information to understand you status and bid for our next phase of contract The other thing is the business and political landscape - not within our control - customer budget, workforce etc. is not always in our own hands
Q4	Describe the typical challenges you experienced with utilising PLM?	Single business challenge - single point of truth at any one time - common language - turning data into management information is problematic- we are better at capturing data but not turning data into management information to make decision
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	One of the next steps is how we take the data - x number of new occurrences in the BoM so what - what does that mean, do we need to do something different past and future - shining a light on the data for its purpose
Q6	Can you prioritise the improvements in terms of business impact	What does data mean - for making management decisions
Q7	Can you prioritise the improvements in terms of effort required	What does data mean - for making management decisions

Q8	How could you better enable the implementation of these improvements	Within central engineering you have data and processes creation, then we have project management who try to turn it into management information for us to use - are they close enough - do we understand the data which can be used for management information - the key is the dynamic environment, e.g. MCE, we have requirements and that is the lens we see today, then in a few months it changes, how can we be more dynamic, to reflect new management needs
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	People side - people like me and Geoff and others, we don't understand what it takes to put a PLM environment together, and those who do don't understand what our needs are - can we bring these together Do we understand PLM investment and business benefit and those who control finances do they understand what PLM gives you = i.e. 'trust me investment will pay off'
Q10	Can you prioritise the challenges in terms of business impact	Buy-in and understanding for senior management
Q11	Can you prioritise the challenges in terms of effort required	Buy-in and understanding for senior management
Q12	How could you overcome difficulties associated with these challenges	Project controls who try to provide data, forecasts and report data - do we need a forum who brings that together, Central engineering and project controls along with MCE
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	I think so, how do you un-brand PLM, if you mention PLM they will go to sleep, how do you describe to get senior stakeholders buy-in Secondly we are no longer just about a single customer but we have others (export) - are we ready or do we need further investment
Q14	What other ETO industries would benefits from a framework?	MoD, project controls for all MoD projects, can we do this centrally Hinckley Point

B.6 Head of Engineering Strategy and Capability Sustainment - Interview 6

Interviewee	
Company	
Position	Head of Engineering Strategy and Capability Sustainment
Date	21/07/2016
Location	
Time	09:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Type 45, to what extent did we lose control over the data, data becomes chaotic. We try to have a control process which isn't directly linked to the cause of the chaos - cost and schedule being out of synch with capturing the knowledge. Control process not related to our ability to not being chaotic. How do we stop chaos and what do we do when that happens. Type 26 - IPPD, if conducted a significant investigation with Deloitte to try and capture the attributes required managing the affective system. We found we were low, and selected a number of areas to implement. Holistic problem, difficulties with cultural in the business to get them to embrace the size of innovation which was required. As you have covered in your challenges How you accelerate data sets early in the lifecycle, we have not chosen to commit. Managing outputs, data - we have most significantly and improved approach.
Q2	What are the typical key business objectives which you require a PLM environment to support?	We are reactive, the nature of the product means data is king. The way the product has developed and suppliers have provided, the language of engineering has to be data. We are responding to it as we are gathering a set of problems we didn't see coming - which is why we have a PLM environment, to help us react. We haven't got a PLM strategy to meet business objectives, as objectives at the programme level; a PLM needs to be at a business level. Business level objectives are high, programme objectives are product centric. Business objectives are output objectives-win business. PLM - Time to market, how we try to compete so we need the capability to align with way of competing and product in service portfolio.

Q3	Describe your current PLM architecture	Suck knowledge out of a traditional engineering environment, in order to capture, configure and support the operations environment - which is the driving force of the business. Capturing data, parts etc. We've not started to look at completeness and integrity of the data. Focus is getting a compartment mature for operations. PLM can allow product strategy and options of product strategy to be understood and worked, followed, controlled - providing a feedback loop for the designer. Our customer of PLM currently is Operations, the output. We are not establishing a view with the business of what PLM does for engineering.
Q4	Describe the typical challenges you experienced with utilising PLM?	Lack of alignment between project progress and a route to resolving product issues. Bulk progress, i.e. its good if you have enough parts and therefore don't align with priorities of quality, integration such as functional risk reduction. Demands lots of metadata at a part level which then allows evaluation of whether an engineering has done his job, difficulties in providing support to engineers, some who are traditional and other who are trying to integrate. Some engineers are developing systems development but it takes time for implementation into PLM - not getting the right data, people, knowledge involved.
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Cultural elements, skills and awareness of data, what are the things that need to come together.
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	Cultural elements
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	Cultural elements
Q8	How could you better enable the implementation of these improvements	We fail to get accountabilities clear, business objectives fail to trickle down to engineering level. Silos and not responding - until they are joined in a business perspective - until this happens difficult to utilise PLM.
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Nature of relationship with customer means that engineers see their role in an introverted way. They proceed at ensuring they have done their technical task - this is not enough - they have to ensure that they understand what that tasks means to the over project objectives. Timescale first priority - thin layer looking at an integrated product - people understand they're areas - chief engineering was the only product integrator
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	People not understanding
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	People not understanding
Q12	How could you overcome difficulties associated with these challenges	Need to understand current culture, what is the capability from a data awareness and technical level, understanding.

Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Steps we take must help with helping Type 26 in the immediate timescales - framework must help with getting mature data for operations- but this is not the same as a business level framework
Q14	What other ETO industries would benefits from a framework?	Combinations in other areas - unique survival capability of an organisations within BAE - a commercial org would be bankrupt - political involvement - I would like to understand what Electrical boat are doing What are the implications of a PLM business model - what is required - what if the business doesn't have the appetite to change - a fundamental constraint - we only intervene when the business is effected - reactive - you have to try and articulate what a PLM business feel like

B.7 Head of Detail Design - Interview 7

Interviewee

Company	BAE Systems Naval Ships
Position	Head of Detail Design
Date	25/07/2016
Location	Scotstoun Shipyard
Time	16:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Everyone I recognise. No prototype, e.g. Modulisation approach, not being able to build modules to take through all the engineering stages - concept, design, build, manufacture, integration, commissioning. Not able to test as it's done through theoretical means. Others, configuration control, when to implement. You have to avoid unnecessary bureaucracy so you have to get the right timing, but there comes a point in time for cost and schedule control, for configuration control. Product maturity, FOC complex warship often has maturity challenges due to how contracts are placed. Getting details design information
Q2	What are the typical key business objectives which you require a PLM environment to support?	Needs to understand the product lifecycle, collect data from concept to build and commissioning, requires to capture review information, all information and outputs Needs to understand how we structure our data, engineering build data for breaking down into manageable chunks - leads to the creation of our engineering BoM

Q3	Describe your current PLM environment from your perspective?	Changing - a lot of transformation activities such as data alignment between our toolsets - e.g. CAD tools to our BoM into our planning tool, CAD/PDM, digital planning with ERP. It is Improving; we have been burned with lack of data quality across our PDM tools. That is recognised hence why we are a period of transition
Q4	Describe the typical challenges you experienced with utilising PLM?	Getting people to use it properly Getting the right quality measures in place when you have people manipulating it Data more important than ever - biggest challenge getting that quality culture into the people, recognises that quality problems causes problems down the line depending on what engineer has touched.
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Try and cut down the number of variables in the system e.g. use PLM to manage reviews, actions - trying to drive a system to be the only way to capture the data - no local approach's as the themes of quality are missing so we may miss route cause- use a PLM to mandate the way we do business as a whole From a functional view we use PLM differently across all out programme - tailor approach based on own independent requirements of programme, e.g. engineering details, requirements etc. - needs slightly different PLM system - we trend to start from scratch - needs to be owned by the business, not project driven - there should be a PLM function - within systems engineering, but it's not clear Business wide standardised tools would be good. Standard process, systems and tools will drive consistently with the way people behave - eliminates the variation errors - People bring their own ideas - QEC - older versions of Foran and Windchill - they will be instantly frustrated - River class is even further removed - won't get the benefits of translation Difficult when you train in a programme as a opposed to a BAE approach - we would cut down our norms if we could standardise - cut variance makes us more cost effective - more variance more training
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	Standardised approach
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	Standardised approach
Q8	How could you better enable the implementation of these improvements	Standardisation of approach -you should originally set up to support this - 15 year design and build approaches means a programme can be a business within business - you need a way to drive our processes across all out programmes not just a single programme entity
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Getting people to use it correctly
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	Getting people to use it correctly

Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	Getting people to use it correctly
Q12	How could you overcome difficulties associated with these challenges	See Q8 response
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Of course it helps - we have an engineering framework - implementing a PLM system absolutely a framework would help - step 1 in a project implementation, set goals, targets, approach - reference regulations and requirements - all that is what I would call a framework
Q14	What other ETO industries would benefits from a framework?	Big massive engineering civil projects - jetty in a naval dockyard -loads of data, review, massive undertaking

B.8 Principal Consultant - Interview 8

Interviewee

Company

Position Principal Consultant

Date 08/11/2016

Location

Time 15:30

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	It's an interesting way to look at it, the set of challenges that you articulated definitely apply to large bespoke projects - a lot of these issues apply in part to less complex projects - certainty the scale of the projects differentiate them from other system engineering projects I have been trying to understand the differences with Type 26 to other project types, one of those is the length of the lifecycle - we have been working for 8 years on Type 26, and there has been a lot of iteration of the design and the requirements - there has been a long way to understand the design - without a hard schedule the programme can meander, PLM must be able to move with the fluidity of the design that is not the case in other programmes - if you compare with urgent operational requirements (e.g. for Afghanistan), you can have complex projects and small scale but what clarifies the differences is the timescales - what we think we want in day 10 is not what we would want in day 100
Q2	What are the typical key business objectives which you require a PLM environment to support?	I come at it more being able to control and understand the various engineering baselines and be able to refer consistency back, coherence completeness and correctness of the data - What we want is an efficient design with the minimal number of iterations until we constrain the design Good facilities for configuration management but the flexibly to support multiple hypothesis early in the design lifecycle - these projects tend to overrun cost and schedule because we don't do enough design variations/checking early in the design - take longer to get the design right earlier, but that can bite you as it can cause rework as you didn't complete design work early in the design lifecycle There is an opportunity if we took a different commercial opportunity - treat the first vessel differently - consider multiple weights- with multiple design configurations - the opportunity to consider multiple options before commitment would be very advantages

Q3	Describe your current PLM environment from your perspective?	A project of these scale feels like the problem is well understood and a commitment within the company to adequately resource technical SQEP and tool and that PLM is an essential enabler for the project - the value of it is not widely understood and may be seen as an end in itself as opposed to an enabler to the design itself - enabling tools like that can be undervalued - technology in these areas moves ahead quickly- every framework we put in place can be constrained and enabled by whatever toolset we have I can see that you are maintaining awareness of how the toolsets are progressing but ensuring it supports the here and now
Q4	Describe the typical challenges you experienced with utilising PLM?	Value not understood Not seen as enabler I am aware of the value of tools, but to the non-specialist it can be seen as smoke and mirrors - perhaps we don't explain what we are doing and why it's important - why underlying data quality checks are important - some can see it as an overhead - balance the time and expense with the payback - the benefits in manufacturing, better quality and accuracy than you would get in a less constrained environment
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	The challenge you have is you require able and specially trained individuals to operate PLM, sometimes there is a challenge with those individuals communicating with less able personnel - explain aims and objectives - the challenge is always selling the investment in the tool and getting buy-in, this project has successfully demonstrated buy in, senior engineering management are always emphasising the strength of what we have put in place and that it will be realised downstream If management lose confidence in it can be seen as on overhead, Type 26 doesn't suffer from that - its feels like we've got the right balance - evolution not revolution with LFE from the programmes Perhaps the weakness is the ability to brief to the wider teams of the benefits and necessities of what the team are doing - the management are but I am not always convinced that those in the coal face understand - do they understand that the discipline of the tool is not an overburdened, but if you get the big picture you can see its worthwhile
Q6	Can you prioritise the improvements in terms of business impact	Buy-in cost/benefit comms
Q7	Can you prioritise the improvements in terms of effort required	Buy-in cost/benefit comms

Q8	How could you better enable the implementation of these improvements	It's difficult, people only taking it on-board if its relevant - difficult to sell benefits to those at the front end for instance, seen as a burden unless you understand that those at the other end (manufacturing) reap the benefits - what's in it for me - the lifecycle is so long - an individual can track the whole lifecycle on smaller projects - in large project which are 10's of years present a problem to selling slow burning rigours approach's to those who want to design - you put in enabling and discipline - this will be more mainstream on smaller projects once value is shown - tie together the supply chain
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	People have done stuff for years and years, you have to be able to answer the what's in it for me question - you have to satisfy self-interest- at best the advantage to an individual or not a disadvantage to a person is how you sell it I see a difference between Portsmouth and Scotstoun - once of the opportunities is the bring on the younger generation of engineering who are more comfortable with the technology and benefits of the rigour - there is always a cost with rigour but hopefully the cost weights it at the end of the day
Q10	Can you prioritise the challenges in terms of business impact	Buy-in cost/benefit comms
Q11	Can you prioritise the challenges in terms of effort required	Buy-in cost/benefit comms
Q12	How could you overcome difficulties associated with these challenges	BAE systems is an large monolithic beast, some organisations of that scale find it difficult to communicate with the wider team - there is an educational element to this - it's a problem which is less apparent in small companies where there is a better understanding of each other's interactions - in Boeing there as definitely a culture of sharing - perhaps on projects of this size it's difficult to share the knowledge and being part of one team - this project is by far the most siloed environment I have worked with, even within the same building, combat, aux systems etc. are in their own teams - siloed working does not lend itself to a wider awareness of the business - we seem to be staffed with a lot of head down people - perhaps we need more who heads up and share experience - Sometimes central engineering can be dictatorial, but you are more facilitation, but if you take CE away the whole thing just stops - it's difficult in big projects - I can't think of something that has done it better - there is a better dynamic and flexible team in the concept phase, but as you mean up you become less adaptable and there is more inertia - try and look for individuals who are open and keen, - use agile as opposed to experienced people I have not commented on tools as we seem to be well served - to me the whole thing is where the value is
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, I think it would, once of my pet hates is how we shoehorn projects into an organisation as opposed to adapting an organisation to the project - it's a difficult case to make businesswise - we have severe constraints on this project, most big bespoke projects get to a point when you have to move forward
Q14	What other ETO industries would benefits from a framework?	I can see benefits large power generation etc.

B.9 Head of Central Engineering - Interview 9

Interviewee

Company

Position Head of Central Engineering

Date 19/07/2016

Location

Time 14:30

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Challenges are valid and have been encountered on many projects I have worked on, sensors, aircraft, Typ45, QEC. With QEC being a good example especially due to the contracting structure. Decision tree whether a prototype is possible Configuration management and product baselines should be included
Q2	What are the typical key business objectives which you require a PLM environment to support?	Consistent and controlled BoM through the lifecycle, PLM enables this through product structures, docs, meta data
Q3	Describe your current PLM architecture	Integrated Bill of material (iBoM). Windchill backbone. Evolve through the lifecycle of the product to use and enhance a master record approach to the Bill of material. Single BoM as opposed to multiple BoM. Including support solution based on original product data.
Q4	Describe the typical challenges you experienced with utilising PLM?	Problems - data accuracy on QEC project due to lack of integration with other systems. Current system much improved with CAD/PDM/ERP, eliminating manual translation and data integrity. Another problem is change, engineering maturity issues, inadequate information used to progress design resulting in change. How do we implement this change and when. People and ownership challenge in engineering
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Ensure highest level on integration, e.g. CAD aligned with PLM system. Integration with schematics with PDM. Commons meta data captured in other systems, i.e. support system, which is critical as we wish to provide a through-life solution. To resolve the people issues have a centralised team to provide PLM, this would include administrative duties, standardised and practicable, LFE, economies of scale. Process, keep it simple, don't be technology lead. Don't get carried away with vendors solutions, e.g. workflows

Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	1- People issues - Centralisation - people/organisation - you could have a great system but if you don't have the buy-in, capability, lean team, right people 2- Integration - Master record understanding critical 3- Process should be straight forward of 1 and 2 are implemented
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	1- system integration - third party vendors, business rules, testing, interfaces, end to end 2- People issues - Centralisation - explain and buy-in across the organisation - some may say that its empire building and reduces lean thinking. Ultimately centralisation will provide benefit with repeatable approach and ensuring that same problems aren't repeated (which has been the case on previous programmes) 3 - Process- mapping
Q8	How could you better enable the implementation of these improvements	2 - People issues - sell to stakeholders through LFE, implementing previous investment on to new programme. Economies of scale - reduction in staff. Standardised training, induction awareness, professionalises. Initial up front cost and programme resource ownership needs to be overcome through cost/benefits
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Radical change to how we do business wrt to function vs programme. Symbiotic relationship. Typically there are people who work on a programme and those who work in a function - disconnect Data as an asset - importance should be realised
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	Programme v function
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	Programme v function
Q12	How could you overcome difficulties associated with these challenges	N/A - answered in point 8
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	An operating model and framework is the same thing. Evolve the framework when required by the business. Use the same model and tailor.
Q14	What other ETO industries would benefits from a framework?	Oil and gas - long lead, high complexity, high cost, land and sea. Large scale civil infrastructure projects. Bridges, road, HS2. Formula 1?? Chemical/pharmaceutical plants/processes - metadata processes.

B.10 Quality and Project Management Support Engineering - Interview 10

Interviewee

Company

Position Quality and Project Management Support Engineering

Date 14/09/2016

Location

Time 08:00

Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	LHC- No company can provide the product - CERN is the future owner of the facility as well as the engineer- most of the engineering work is done by CERN - most elements are made specifically for CERN - high level of quality required - these products will not be sold to other customers - Most of the people in CERN are working in the engineering side - operation facility are not that big - most are designing new facilities and providing support
Q2	What are the typical key business objectives which you require a PLM environment to support?	Many components - one of the challenges consists of the retrieving component information - where its installed - when it requires maintenance - - replace components that have same form/function - components have to have radiation considerations - support functioning of facility - preventive maintenance
Q3	Describe your current PLM environment from your perspective?	Three pillars - functional layout database, what the facilities are made of, in-house designed tool - 2nd PLM side, every components described, Smarteam to manage and describe items, 3rd - maintenance management system, infor EAM
Q4	Describe the typical challenges you experienced with utilising PLM?	Several challenges - 1 challenge relating to the scope of PLM, most PLM designed for volume manufacturing, with ETO it is not the same approach as with mass manufacturing - PLM tools good for designed equipment (e.g. aircraft) but not systems such HVAC, PLM tools are not designed for facilities such as CERN - Aircraft they don't use PLM for designing their facilities - BIM tools can be support faculties - CERN, design, build and operating a facility, Airbus manufacturing aircraft and require manufacturing facilities, with CERN we create facilities to produce particle in the right quantity - the differences are difficult to manage as PLM approach tries to align with EADS etc. - CERN more similar to construction companies than with companies such as Airbus
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	First from a strategy point of view the difference between Product and facilities information management is understood- it's difficult to align the needs managing the facility (maintaining and upgrading the facility) with managing the product data - improved integration with PLM and maintenance management and facility management

Q6	Can you prioritise the improvements in terms of business impact	Integration
Q7	Can you prioritise the improvements in terms of effort required	Integration
Q8	How could you better enable the implementation of these improvements	My colleagues have a lack of understanding of the architecture of the information - a lack of good information impacts people's ability to understand and work with the system - systems engineering, validation and verification, people don't understand the difference, PLM tools don't explain this, PLM tools don't support this
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	1 - People - management level, principal eng. etc., people want simplistically which isn't always appropriate - 2, People see they own area, e.g. electrical, they think as its works at their level it should work for others - complex enough to meet the needs but not too simplistic 3 -Software vendors don't have sufficient understanding, the processes they propose are not appropriate for complex environments
Q10	Can you prioritise the challenges in terms of business impact	People
Q11	Can you prioritise the challenges in terms of effort required	People
Q12	How could you overcome difficulties associated with these challenges	Training, clear, good organisations, success stories, software vendors have very IT approach, they need to understand real needs, they want to sell their products
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, as far as I know for PLM there is no model, a framework for providing guidance there are not necessarily for the software, but naming, numbering etc. - also link from PLM to quality management - e.g. consultants will argue you should use business process modelling but that doesn't describe collaboration, only emails but not reviews (design reviews), a lot of collaboration is required, the sharing of knowledge is not supported with this approach
Q14	What other ETO industries would benefits from a framework?	CERN - big science, big facilities - other big science across the world would be interested - - others which design complex systems

B.11 Chief Engineer - Interview 11

Interviewee	
Company	
Position	Chief Engineer
Date	28/07/2016
Location	
Time	08:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	People understanding of the toolsets, Dassault, Siemens, and PTC have PLM toolsets. Underutilised or overused if there is capability. Here we have an instance of Teamcenter, heavily customised, and about 20 interfaces. Only really a CM tool, 30 people CM, here only 2 in T45. Not used effectively for PLM, use of the tool very difficult.
Q2	What are the typical key business objectives which you require a PLM environment to support?	Cradle to grave, baseline management, and incl. multiple versions of baselines. Global Combat Ship, 3 different variants on drawn on T26 -Commonality which needs to be managed. Gas turbine room, same for all 3 ships, but weapon sets will be different. So PLM baseline must be able to manage, ship on ship difference based on customer driven changes or obsolescence. Baseline by design, class, ship, manufacturing, capability, - as designed, as-built, as-delivered, and as-maintained.
Q3	Describe your current PLM environment from your perspective?	Shambolic - journey for 3 years to replace Teamcenter with Windchill. The move from old Teamcenter to new Teamcenter difficult, so we decided to go for Windchill. Move to new tool difficult due to customisation, legacy tool sets captured through merger and acquisitions - all different which have to be aligned. Different needs, land systems have different needs from Shipbuilding. We make delivery from our PLM to the customer, e.g. change packages - much more complex than it needs to be. Delivery through different PLM to the customer.
Q4	Describe the typical challenges you experienced with utilising PLM?	See Q3 Also - we are out of vendor support, lots of downtime, impact the business due to more frequent longer downtime User understanding of tool Degree with which we've made it bespoke

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Simplify it - improve integration - purpose to move to Windchill to rationalise satellite systems - people had pet tools which the core tool can do it instead- we can retire 12 out of 20 PLM toolsets- reduces manual interaction, maintenance - forecast was we could reduce 3 FTE by utilising core functionality of the new tool Improve education of the users - don't customise, out of the box, supportable version, vendor brings out new version we can move there quickly - educate in satellite offices to use core toolsets - links in with simply
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	Education - people want to explore what is available - if I want to produce a table - word or excel - wants best for your need - people have preference - some people dread excel and use word even though it's harder - same with PLM, they ask for upgrades because they perceive difficulties or limitation
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	Education - asking people to change the way they've done things for over a decade - steep learning curve - someone shows them how to do it, they may have been doing it wrong and that passes it on
Q8	How could you better enable the implementation of these improvements	Communication., communication, communication - strike a chord with people, what's the value proposition for them - what's it in for them - take them on the journey, explain why - another toolset made life better for everyone except procurements - we brought them on board, they left and new resources were against it - we had to rebuild the bridges
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Getting commitment difficult, Maintaining momentum - other jobs have higher priority so you don't get engagement you require at workshop etc. - if they don't attend them they questions aspects they weren't involved with
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	Commitment from stakeholders
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	Commitment from stakeholders
Q12	How could you overcome difficulties associated with these challenges	Organisational change manager - I was sceptical initially but now I see business benefits - She provides engagement - she tested understanding, resistance levels etc. - identify intervention areas to bring people along on the change journey - done all the way through conducted by the organisational change manager - focussed interaction - first time fluffy HR but if now see benefits - now default way of how we engage
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, definitely - hardest thing for people going from as-is to to-be, people don't know how to get there - prompts to help you get there - helps the thought process
Q14	What other ETO industries would benefits from a framework?	Civil engineering - every projects a one off- high capital - LNG train in north territory - technically the same but every plant is different, geographically different - Framework for those types of projects an enabler

B.12 Head and Operation and Future Build - Interview 12

Interviewee	
Company	
Position	Head and Operation and Future Build
Date	23/09/2016
Location	
Time	09:00

Question No	**Question**	**Response Key points**
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	In type 26 we want to introduce standardisation, interim products, modules - prototype, you can't prototype the whole ship but you can prototype aspects of the ship- systems of systems means prototype can't be done but you can target aspect such as first fixing which allows a different approach
Q2	What are the typical key business objectives which you require a PLM environment to support?	4 p's- people, process, product and plant - I need a balance across all of those things, focus on the product we use and the processes we use, right info at right time, - simple examples are what products are lifed items which require replacing after 5 years so we will delay fitting till later
Q3	Describe your current PLM environment from your perspective?	wide ranging - key things are simple examples on OPV or Khareef - Tribon legacy systems, we are Foran in Type 26 - our burning machines and tools in production environment, important that Windchill to Foran to production environment, in OPV the legacy systems didn't support the burning for the production machines -
Q4	Describe the typical challenges you experienced with utilising PLM?	Information and technology integration - any information flows to the ship is critical Coding of things within the ship such as Part codes, then it makes life difficult on the ship - HPSW in the past we would know, now it doesn't - information descriptions Interim products - We are building a tailored bespoke ship, we need to come up with new approaches - in Sweden they have a 2hr requirements to float once hit by a missile, for the RN it is much stricter - so it’s a very bespoke approach - We have a standard list now to help

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Standardised parts, coding, reducing variation - has helped on Type 26 - I need the information flow in a language I can understand - codes and standards in all future ships - such as GPLF which has a legacy design to reduce costs, we need that to flow the same standardised approach
Q6	Can you prioritise the improvements in terms of business impact	Standardised approach
Q7	Can you prioritise the improvements in terms of effort required	Standardised approach
Q8	How could you better enable the implementation of these improvements	Type 26 Step change from the past, first time we have introduced a manufacturing engineering approach, we are telling people what we need and want - it was difficult getting people to do what we need as they were used to do something difference- institutionalise the concept, what each stakeholders requires
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	First challenge - policy deployment, vision such as design for manufacture, people should understand and follow Next is changing the culture to nothing in silos - shadow of influence diagram
Q10	Can you prioritise the challenges in terms of business impact	Changing the culture, organisational thunderbolts
Q11	Can you prioritise the challenges in terms of effort required	Changing the culture, organisational thunderbolts
Q12	How could you overcome difficulties associated with these challenges	Cause and effect, train and coach people of the consequence of their actions, so if someone in a CAD model are they thinking about how someone can install the equipment, E.G. enough gaps in-between
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	It would help - think of a mind map with product in the middle with key functions and stakeholders around it, with relationships around it, it would be massive to undertake due to complexity - but a framework would help with a collaborative coherent product
Q14	What other ETO industries would benefits from a framework?	One of the things changing is the manufacturing system - people becoming involved in a process which has hit a snag - modelling on Boeing, they introduced a system where they stopped a line as it drives though a product lifecycle approach to improve quality

B.13 Chief Engineer - Interview 13

Interviewee

Company

Position Chief Engineer

Date 31/10/2016

Location

Time 16:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	In summary they are really good ones in terms on ETO and the different products out there. What we don't do is manage that upfront and manage them differently, some are more complex and as a business we don't fully recognise that and manage that up front. In RCB2 there was a lot of pull through from previous programmes, but some which were ETO
Q2	What are the typical key business objectives which you require a PLM environment to support?	Manage the definition of the product, there are always different toolsets and they are specialised for different reasons, and you need to understand that, you can't have one big tool so you need to understand interfaces. Configuration and change mgmt. Link to how users intend to use it - that's something we don't fully utilise - you have some in engineering who understand PLM and others in other functions such as supply chain and ops who don't understand it, e.g. what we need to buy
Q3	Describe your current PLM environment from your perspective?	Challenging, and ever changing - we really struggled to define it at the outset and manage it as that. We don't manage and align those expectations. There is a level of frustrations of IT support and integration - to the point you turn it off. Very data rich and people lose sight of what is important - when is data useful information and then is it just data - nice to have it (just data) not configured and not maintained, so it is used for something it wasn't intended for- big overhead with managing data, and you need identify what is important - wood from the trees We don't always equip our people to be integrated with PLM, people often see PLM as a toolset, you need policy, process and people
Q4	Describe the typical challenges you experienced with utilising PLM?	Ever changing, our projects are long, our environment will change, we'll go in with grand ideas, then changes ae done to use which none has costed for or resourced up, such as the Aveva ERM implementation.

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Spend more time educating people on what is expected, where it is and how to access it - our environment is different from T26 and T45, but people need to use it correctly - a lot of time and effort must be put into the IT toolsets and interfaces - they get frustrated if it doesn't work - its further up the Maslow hierarchy of needs, if it goes down people are up in arms after 5 mins We also need to make the process really slick, so it's easy to use - RCB2 change process is a bit slim but if you go the other way when you put everyone in one such as T26, complexity in change impacts flexibility and speed of response
Q6	Can you prioritise the improvements in terms of business impact	Change process really sick - that's achievable Systems integration issues - really achievable Functions embedded within teams to work together- integration - quick access to people who can do interrogation
Q7	Can you prioritise the improvements in terms of effort required	Easiest - change process slick - in our gift Second easiest - put people in heavy users team - go-to person for that function (bill of materials contact for supply chain and planning) Third - System integration
Q8	How could you better enable the implementation of these improvements	Change process works until change is issued, it doesn't get managed in an end to end process - not enough prioritisation of key things - a lot of people think engineering own it, when it is programme management who own it because of the multiple functions involved, eng, quality, ops etc. - part of me think it doesn't matter who owns it, but someone has to step up
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Biggest is how is it going to costed- then it's what is the benefit, this is really difficult - everyone's knows it's the right thing to do but it's difficult to get the business to agree - change is a risk mitigation and it's difficult to get investment - how do you quantify
Q10	Can you prioritise the challenges in terms of business impact	cost/benefit
Q11	Can you prioritise the challenges in terms of effort required	cost/benefit
Q12	How could you overcome difficulties associated with these challenges	It's difficult to scope what the impact is - it gets back to the perceived lack of benefit - if you can write a business case then its fine, but if something isn't working properly you should just fix it We use risk to manage emergent challenges - there needs to be a better balance on cost of risk - such as labour costs which need to be in our plan If there is a change to the product then to ripple through the PLM environment - you need to plan, which is difficult or you would get it right in the first place
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Whether I would agree with the terminology of framework I don't know, but there needs to be a method of communicating the key things - in that we should include those things we do well - those we need do should be scaled, high impact and planning is important

Q14	What other ETO industries would benefits from a framework?	I think the car industries is the wrong place to look, they do prototype and mass production - I look at what we do, sea worthiness and statutory procedures - regulatory regimes - there are parallels with aircraft as they have to manage their product through their lifecycle - nuclear are one offs, I am not sure we could learn from them - something which small batch sizes

B.14 Engineering Manager - Technical Authority Detail Design and all Draughting - Interview 14

Interviewee	
Company	
Position	Engineering Manager - Technical Authority Detail Design and all Draughting resource
Date	18/07/2016
Location	
Time	16:30

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	All relevant An example is no prototype, key challenge as a business, something we have struggled with over my career. Attempted many ways to mitigate risk, continue to explore opportunities around that - virtual prototyping
Q2	What are the typical key business objectives which you require a PLM environment to support?	Product evolution - configuration control of the design as it evolves The need of collaboration for the wide range of stakeholders wrt to the design they are providing A data repository for the information we have to maintaining over the range of the project
Q3	Describe your current PLM environment from your perspective?	My responsibility is the 2nd and 3rd phase of the design - the initial phases deliver to my area - concept and functional design deliver to my area - I am a customer of this - the configuration of this is critical Change and evolution of this is critical We are taking PLM to levels which we have not taken to in other areas - using a single source engagement which we can publish to other areas, supply chain, planning, back into stage 1 areas - the fact we are publishing the physical design (3D model) we can publish this data and allow stakeholders to review Previously we've not had the capability to publish the design - through PLM we can do this but now - we can share our design - virtually importance considering the time that the design evolves over - configuration
Q4	Describe the typical challenges you experienced with utilising PLM?	Data alignment - system breakdown of the design (full BoM detail), tools and applications - CAD (Foran) and ERM, PDM

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Alignment of the systems - we are still on that journey - ensure we have the alignment of the key data that the business requires We can't allow onerous processes - some of the workflows we have to go to are onerous on the engineers - keep simple and endeavour and aspire to continue to simplify
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	1 - alignment - I know the impact of the misalignment of the data - the cost associated on previous programmes is a significant costs data alignment between CAD system and the PDM system (K checks and odap/pdap) - when we push data to the manufacturing environment we have to take reactive - we should have a more proactive approach
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	1 - alignment of the data - 2 data sets that are misalignment - pain we have to go through to understand what the correct data we should be using is significant - my experience is the greater challenge as a business
Q8	How could you better enable the implementation of these improvements	We want we don't do is enough of define the issues/requirement considering the solution to that and understanding the processes associated to that solution - then putting that into an environment which satisfies the requirement - more often we have to implement when we are managing a project Resourcing the improvements is not something we can do within programme - we too often rely on resource who have a day job plus the implementation of the improvement The resources are the ones with the knowledge and experience of the processes and toolsets - we don't have them in surplus - recognition with the projects schedules - overlaying implementation on top of challenging programme schedules will present challenges which are not always achievable - we might need more time Can we get other resource - yes - but do they understand in details the processes and the difficulties - not a knowledge which is held eternally due to uniqueness and complexity of our product
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	As above - making resource available to support the implementation Time, commitment - IT collaboration across the function Behavioural aspects - commitment from the key stakeholders in order to make the implementation successful - various support elements are committed and provided and that we are ensuring that these individuals have the right behaviours – it's easy to take a negative view
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	Resources
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	Resources
Q12	How could you overcome difficulties associated with these challenges	Demonstrate impact to business and sell it in such a way that although it has an impact on resources we will feel the same pain and incur the same costs - demonstrate cost/benefits to allow people to recognise that the benefit will come
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes of course, it's a given - its shows people the why, what and how
Q14	What other ETO industries would benefits from a framework?	I'll have a think

B.15 IM&T Director - Interview 15

Interviewee

Company

Position IM&T Director

Date 12/10/2016

Location

Time 15:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	I agree, the biggest challenge is that the people work according to a process, and if it's well defined PLM works
Q2	What are the typical key business objectives which you require a PLM environment to support?	A clear PLM design objective and requirement then it will works properly - I don't know how we can link the business objective to PLM - our objective is that PLM is central to the business, not just engineering but all functions so that everyone speaks the same language
Q3	Describe your current PLM environment from your perspective?	It is not just Windchill and CAD, it is the entire process from concept to delivery of the entire CADMID cycle, including in-service
Q4	Describe the typical challenges you experienced with utilising PLM?	To convince people - a series of tools to define the lifecycle of the product. From my perspective we do PDM and a little bit more, we don't link into in-service, those components are missing - I think that's the real challenge - include all the functions and have everyone working towards the same process. PLM is a process, it doesn't matter what toolset you use
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	As far as I am concerned, when you look at Naval Ships, we should bring in operations, we have as-designed and as-planned but not as-built, its weak compared to design and planning, when we have as-built it can lead on to in-service. We should look at enterprise, end to end, CADMID which links everyone together, better customer satisfaction
Q6	Can you prioritise the improvements in terms of business impact	End-end integration

Q7	Can you prioritise the improvements in terms of effort required	End-end integration
Q8	How could you better enable the implementation of these improvements	We have to look at operations and level of technology that they use, they are the weakest link in our chain, we are trying to introduce technology such as PDM to allow them to access the data and build up an as-built BoM, which will promote quality, all relevant data inputted and available, we are looking at new mobile technology to operations, and bring to in-service.
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Link every transformation, its winning hearts of minds of the people, they just build the ship, they don't care about the information used to design the ship, the information is high-value and they need to change the way they work, that's why any transformation project takes 3-5 years
Q10	Can you prioritise the challenges in terms of business impact	Hearts and minds
Q11	Can you prioritise the challenges in terms of effort required	Hearts and minds
Q12	How could you overcome difficulties associated with these challenges	The approach would be 2 way, top down and bottom up, firstly the management should be convinced that this is the right way to work and then bottom up - when it comes to implementing these things on the shop floor, my experience is that actually people have less resistance to change and can create pressure from down upwards when you have their buy-in, convince the majority
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Well it would be very helpful to us as it will show not just what the IM&T director thinks but also others
Q14	What other ETO industries would benefits from a framework?	I'm sure there is

B.16 Head of Programme - Interview 16

Interviewee	
Company	
Position	Head of Programme
Date	11/10/2016
Location	
Time	17:00

Question No	**Question**	**Response Key points**
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	The challenges are accurate - I have worked in military aircraft - we spent a fortune on a team aligning the datasets, CAD/PDM misalignment - a lot of controlling dataset is valid - my experience in carrier, our ability to deal with complexity is a big issue It feels a lot better on Type 26 In military aircraft maturity mgmt. was more mature than QEC but Type 26 is closer The people aspect - there are technical aspects, but the people side is a huge part of it, behaviours, interactions, somebody's judgement makes a big part of it - subjective
Q2	What are the typical key business objectives which you require a PLM environment to support?	It's looking at establishing a maturity level to define a standard, completeness - based on the entering into the build phase
Q3	Describe your current PLM environment from your perspective?	Design baseline, but developmental timeline, how engineering programme is delivered on time and cost
Q4	Describe the typical challenges you experienced with utilising PLM?	The unknown, we are doing things for the first time, it is difficult to plan out what we're doing - trying to establish a programme baseline for non-recurring engineering tasks - I was talking to the Eng. director and we're asking 'do we have people to create/ deliver a plan' - we seem to plan at a higher level - do stuff to support a review programme - a bit woolly as opposed to build when we know how many pipes there are, more prescriptive Another one is the link between design evolution and when it becomes change You size the team then look at the complexity We are doing something different as a business and with the customer - compared to the aircraft carrier we have a better risk provision/management for time and cost

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	The people, when I joined the programme I got a good understanding of what we needed to do in terms of maturity, but we have diluted it, if we didn't need those things why did we ask for them, will we end up short but will try and convince ourselves its ok - resulting in change in the build programme - it's not the baseline we set out to achieve The other one is maybe we shouldn't be too prescriptive - things change, we need to be flexible with complexity- I looked at Railtrack and they had a way of dealing with it - get message to senior management - at what point can we be flexible - we are not perfect technically, but we are much better - it's the intelligence presented to us, what do we do about The ability to understand where we are - CAD/PDM alignment etc.
Q6	Can you prioritise the improvements in terms of business impact	Prescriptive /flexibility
Q7	Can you prioritise the improvements in terms of effort required	Prescriptive /flexibility
Q8	How could you better enable the implementation of these improvements	60% of cost is in the supply chain, a huge amount of data comes from supplier - in OPV we didn't have the supply chain team in place and we never recovered - Understanding that our design in integrated with supply chain, integration with supply chain and Eng., there are still divisions - it's the right model but we need to look at improving how we work together - ensure we can manage and understand change
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	we have 100's of changes which are agreed but are late - the change managers have not been prioritising from an internal customer perspective - they are not recognising other's needs - understanding change and what it means to others in Eng. and build
Q10	Can you prioritise the challenges in terms of business impact	Understanding each other's needs
Q11	Can you prioritise the challenges in terms of effort required	Understanding each other's needs
Q12	How could you overcome difficulties associated with these challenges	From my aircraft experience we had a saying - Right people right role - people are technical but we need to move our resources, people with right skillsets doing right role - we have gaps in our capability, planning in engineering phase of the programme and delivery of the engineering phase of the programme - do we have engineering leaders who are driving cost and time - I was really impressed by the chief engineer, 'you said you would deliver this by then then you didn't' let's not sign-up to something we can't do So we need right people in right places but there are gaps - I know there are some in planning Pull people from different industries

Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Some of it has to be prescriptive, this is what you would do and measure - but we need to be less prescriptive to move in a direction and the programmes flow in different directions - getting people to work together shouldn't be prescriptive - we're not robots
Q14	What other ETO industries would benefits from a framework?	Railtrack, oil and gas

B.17 Supply Chain Director - Interview 17

Interviewee	
Company	
Position	Supply Chain Director
Date	21/07/2016
Location	
Time	17:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Ability to 'value engineer', build cost in while designing the product - trade off of capability v affordability Manufacturing engineering - design something which is easy to manufacture, maintain and upgrade extremely challenging Obsolescence management of the product, incl. software, and emergent technology and enhancement which emerge through a long lifecycle Continuity of resources - different people and skills working effectively together
Q2	What are the typical key business objectives which you require a PLM environment to support?	Very complex project management Ability to mobilise disparate and physically dispersed teams Ability to leverage and integrate with supply base - suppliers have multiple customers - we become too dictatorial with how data needs to be presented - we have different types of input and how we manage that is key - also being able to manage feedback for the disperse supply base
Q3	Describe your current PLM environment	Data management and control - that data can be commercial and contractual - right design information, right governance of suppliers Good information and data from a bill of material, give me lead time to leverage the market for the best deal
Q4	Describe the typical challenges you experienced with utilising PLM?	Typically we focus on high value items, don't give sufficient emphasis on smaller items - these impact you greatly Configuration and BoM control working effectively with people and process End of life working effectively - post-delivery control, warranty and support for product questions - knowledge managed - ongoing challenges to answer questions 10 years after delivery of product

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Business change management - people Product change - accurate view of material and what supply chain needs to support it Knowledge management - more integrated decisions creates biggest burden on single point of knowledge failure - people retire - more complicated the product those interdependencies become more difficult to manage
Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	1 - Short term impact - product change, majority of people manage change 2- medium term impact - business change, mergers etc. 3 - knowledge, longer term, how do we leverage knowledge capability in different ways, careful that don't hamper innovation. More controls in PLM more constraints to innovation, need to encourage new ideas. Less project managers to manage integration, more engineers All 3 have impact in different ways
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	Too hung up on schedule adherence, difficult to implement improvements when adhering to a schedule We are driven by the customer for value for money - when you are building a complex house and you have a milestone for a TV, you will focus on building the front room - instead of putting a roof on first
Q8	How could you better enable the implementation of these improvements	In any PLM environment - IT infrastructure must be robust and flexible, must allow change management to be done effectively The way we administer ourselves, there are ways we can leverage ourselves better. Don't put constraints into Technical Equipment Specifications - let suppliers innovate based on our requirements. Let suppliers come up with the solution, we come up with fixing solution and tell a supplier then supplier comes back later with a better idea - too late Digital visualisation and digital twin
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Focus on schedule adherence - not enough focus on strategic outcome Investment on tools techniques and systems As leadership changes business direction changes, objectives change Managing customer expectations - both internal and external - engineers want best products, finance cheapest therefore tension. Telling customer the art of the possible difficult Ensure what we do doesn't stifle innovation
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	*(not covered due to time constraints)*
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	*(not covered due to time constraints)*
Q12	How could you overcome difficulties associated with these challenges	Covered in Q8

Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes - one of the key challenges we are too good at is we don't learn from experience - analogy is a limited amount of people learn from reading, few learn from observation - everybody else learns from own personal experience but having a framework will assist with systemically measuring what went well. Framework as to be translatable for different environments and needs
Q14	What other ETO industries would benefits from a framework?	Civil construction - birge kheeler (tallest building in world) Not air sector as they have test production run Space - international space station - single most expense thing in history (what else is in this bracket) New nuclear power stations

B.18 Combat System Technical Authority - Interview 18

Interviewee	
Company	
Position	Combat System Technical Authority
Date	13/10/2016
Location	
Time	15:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Completely, particularly in our area, we design and continually develop while the manufacturing is ongoing, equipment would be 6 years old by the time we deliver the design if you choose COTS, hence why we evolve the design, develop and design while the ship is being designed/manufactured, different for engines but definitely for the fancy stuff the user is interacting with just look at mobile phones now and 6 years ago
Q2	What are the typical key business objectives which you require a PLM environment to support?	Querying the design is the big thing I demand, which means other have to input the data (which we use) Also linking the schematics to see the interconnections In the combat work we have a functional/user model of the system to ensure it all hangs together Requirements decomposition/management Does the design hang together
Q3	Describe your current PLM environment from your perspective?	Its Windchill and iBoM but also DOORS for requirements and System Architect for the functional model of the system, and performance modelling tools, SMARTER for safety etc.
Q4	Describe the typical challenges you experienced with utilising PLM?	Coherence between toolsets, particularly SMARTER for safety, DOORS and Windchill is good but we don't have good integration with SMARTER I can query the functional and physical design quite well but I need to see a bigger picture Speed of being able to get new reports
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	It's all about report generation from my perspective from my teams point of view I have to relate affected artefacts to a change, this can take days - we are always missing things, if the toolset had the capability to help a person understand what else could be affected that would be very helpful

Q6	Can you prioritise the improvements in terms of business impact	Getting changes right - you can always get reports
Q7	Can you prioritise the improvements in terms of effort required	Getting changes right - you can always get reports
Q8	How could you better enable the implementation of these improvements	Start with checklists - a perfect example of a complex change, combat raise changes to electrical data, electrical then say there isn't enough power which means a bigger change, GA update required, then HVAC say its broken HVAC assumptions in an area - we didn't have the prompts in the system to get the impact right - some kind of automation if you have a change have you thought about the impact to other parts
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	The toolset would need a really complex understanding of how the parts work together - and for it to say that thresholds have been affected - even if it raised that would need manual investigation
Q10	Can you prioritise the challenges in terms of business impact	Toolset understanding
Q11	Can you prioritise the challenges in terms of effort required	Toolset understanding
Q12	How could you overcome difficulties associated with these challenges	A better understanding of what the thresholds are, what looks like a local change to somebody could have big impact - there needs to be a guide to say what the effect could be - especially if it has a limit, such as with weight margins policy - an engineer would need help to understand - if you put equipment in an area which has an impact - even if we capture the change impact they take a long time and are not always right A combination of education and presented with information - what looks like a small change to you may not be - first scope the change right then get it through the system quicker - the more we can standardise the change impact the quicker we can get it through
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Yes, just improve understanding and expand their minds - combat love electronics but see physical space as boring, the guys get stuck into what they enjoy from computer and electronics but they know nothing about production and mechanical Eng. and vice versa Combat don't get as many surprises as we are more joined up with supply chain Every so often put people into other domains
Q14	What other ETO industries would benefits from a framework?	Big rail projects, we've seen people come and go from cross rail and Chunnel extension - big and complex and tick the boxes

B.19 Head of Enterprise Systems IM&T - ERM/PLM/Planning and Finance systems - Interview 19

Interviewee	
Company	
Position	Head of Enterprise Systems IM&T -ERM/PLM/Planning and Finance systems
Date	22/11/2016
Location	
Time	16:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Yes I definitely agree with what you've said - what's comes to mind, as well as the project being long term and expensive, they are few organised businesses who can do this work and it depends on the kind of work, in our situation shipbuilding we have national sites for shipbuilding and people/skillsets, there is clearly an age issues on business - people who know how to build ships but don't know PLM - One of the surprises I have now that we are on our 3rd ships is the change to the system they want - people see the benefits of PLM, but want to use the tool differently - we now have tools overlapping such as PDM and ERM using planning at different times in the schedule
Q2	What are the typical key business objectives which you require a PLM environment to support?	It can't be seen as a toolset you dip into, such as document management, it must use the full set of capability - you should have a mechanism for the BoM, the engineering data, the extra things such as Manufacturing - ERM supports other things such as commissioning management - it's got to be flexible to invent new business objectives that come along, flexibility - must manage workflow - Must be able to adapt to new ways of working which people haven't thought of yet - must be adaptable, so we don't need to go back to the supplier, must have latest software capability which my team must have, my team need more training than when we started,
Q3	Describe your current PLM environment from your perspective?	I see it as one of several engineering systems, you need to link to CAD, visualisation, augment/virtual reality, internet of things will be part of the future

Q4	Describe the typical challenges you experienced with utilising PLM?	The same challenges as in the past, the potential uses that any one project can take advantage of, taking an opportunity, people don't see future problems, only present solutions, e.g. using exiting drawings management tools and not thinking about future improvements to the delivery of information, For CAD/PDM we are linking two tools which are not designed to work together, they have come up with a solution which sits on top, whatever design principles a CAD tool has may not fit in with PDM - However you integrate the tools you have to compromise The other challenge used to have more freedom before the interfaces, they are saying this is the way we have always worked - the interfaces may not support the way of working The tools are also tied together, you cannot upgrade one without the other (CAD/PDM) The teams are quite siloed, the CAD teams work in one way but the PDM teams work in a different way - The teams don't quite see the benefit of it sometimes - they require more training When we put the architect together we said we would use standards for the data model, such as STEP, what we didn't recognise that there is different logical models, but the developers rejected it as it meant nothing to them You must put an architecture in place which requires selling to the business, -The architecture must be kept up to date, as people don't see the benefits until it's not there - having a simple architecture diagram is really complicated - the seniors need to understand what the architecture is and how it benefits
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	There is a constant architecture change - corporate want a different PDM tool they haven't the architecture - the journey with our current PDM toolset has helped, you know what you need
Q6	Can you prioritise the improvements in terms of business impact	Architecture improvements
Q7	Can you prioritise the improvements in terms of effort required	Architecture improvements
Q8	How could you better enable the implementation of these improvements	There are new techniques in IT, the cloud, virtualisation technologies - we will virtualise our toolsets - we need to update our toolsets quicker than we've ever done in order to respond to business needs - e.g. upgrade our PDM system takes 8-9 months, we now need to do it in 3 months - these architectural improvements will help, any toolset that doesn't help us we won't use, e.g. quick back-up, do one roll-out
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	We still do it in the waterfall method, we need to break up the testing so its testing and rollout as we go along, sometimes you can do it sometimes we can't - the cycle time of change within the toolset takes too long - architecture is software

Q10	Can you prioritise the challenges in terms of business impact	Break up testing and implementation for faster turnaround (SCRUM)
Q11	Can you prioritise the challenges in terms of effort required	Break up testing and implementation for faster turnaround *(SCRUM)*
Q12	How could you overcome difficulties associated with these challenges	You have to bring confidence with the team - the problem is that the users what to test everything - Waterfall takes too long
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	I think in the end the silos have to go away - I know I will not get proper requirements, we need to get those who write requirements within the team, work together and deliver it incrementally - deliver it into bits There is a culture of we've done our bit and we're waiting - we need to improve how we work together - we can't blame to use for not delivering a requirement as they know what they want but not how to get there Its about being better organised - get an expert team who roles our new capability and engages with the business - break down barriers Some people say in CAD/PDM we've haven't been trained and we don't know the process - we need to sit down and work with the teams, such as the changes to the F-builds which we didn't know - There is a definitely a big gap/barrier between IT an the business
Q14	What other ETO industries would benefits from a framework?	Utilities

B.20 Nuclear - Interview 20

Interviewee

Company

Position	Programme Director for Security Resilience Head of Engineering Design Assurance Programme Design Manager
Date	25th Oct 2016
Location	
Time	10:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Lead programme of security and resilience dept. of Sellafield, a series of projects and programmes to enhance security assets on site, as well as emergency and resilience improvements - new buildings, new deterrents, emergency resilience equipment, cyber resilience All sounds very familiar A lot of the work we do is bespoke, many of our products deal with things that have been down before- retrieving and treating nuclear waste - nothing off the shelf, design time quite long, a lot of time before you see anything from your work - we have a lifecycle with concept though details through build Phased approach in shipbuilding, in Sellafield there is a hard line on maturity before manufacturing - security and resilience - balancing time pressure and risk, wanting something to do a job and releasing to build - we've spent a significant amount of money which isn't bearing fruit - it’s a balance You need to be able to adapt - technology adapting is a critical element which needs incorporating
Q2	What are the typical key business objectives which you require a PLM environment to support?	Safe, secure, stewardship of the site, safety is the top one for obvious reasons Reputation damage We are also spending tax payers money, spend it wisely, commercial contracts are viewed carefully The full project may be not of the shelf but there are elements within it which are - drive to include COTS Right first time - once its fitted you can't just take it out

Q3	Describe your current PLM environment from your perspective?	DOORS for requirements management We have a large standards, managed in a typical way, consistency, Drawing registry system, document recording, every project has a defined reference number - they are scanned and put into a document system called icepack which gets a formal reference Record master system where the master systems go
Q4	Describe the typical challenges you experienced with utilising PLM?	The detail design in the shipyard is predominately done by BAE, in Sellafield it is sub contracted out - we use Atkins and other sub-contractors We have a value transition to market approach - for a brand new build the technology has to be mature before we go to market for tender for design build and install Challenges can be IT consistency across supply chains IT systems
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	We have a requirement to provide an intelligent customer for everything we do - everything which happens on Sellafield's has to accepted by Sellafield LTD, that process of providing intelligent customer can cause problems but can be successful - so it can be behavioural, and that it's between Sellafield and do the supply chain who provide the information The supplier chain if its new to Sellafield we can underestimate the intelligent customer If you take the example on QEC, BAE was the co-ordinator and Thales doing the design - setting that practice to enabling the design for progressive maturity and acceptance - this is something we have success within that collaborative approach
Q6	Can you prioritise the improvements in terms of business impact	Both are important, behaviours are so important - you can have the same contract position but if the behaviours aren't right then the projects can go off in different direction - Sellafield and supply chain A balance to be had with blue chip companies who one things well it's a challenge to bring that in on Sellafield, as there are different spec and standards - we have dept. of energy and you have the MoD pushing for value for money and competitiveness which drives uncertainty into the programme -
Q7	Can you prioritise the improvements in terms of effort required	*As per Q6*
Q8	How could you better enable the implementation of these improvements	We would prefer long time collaboration with supply to build relationship - not just retender every time - going out to competition isn't always the best approach, if you have a long term framework with a number of suppliers where you can turn around mini competition quickly and you know what your getting - in shipbuilding its peaks and troughs, maintaining capability of supply chain and designers, but the supply chain have to deal with uncertainty - we would rather a healthily supply chain which isn't reliant on Sellafield but other areas which sustains apprenticeships, invest in skills, retain skills etc. People just move where the work is
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	One of the challenges would be from the supply chain angle, the certainty of business - we have a yearly supply chain contracts - customer decisions to delay or cancel work means that that supply chain are reluctant to invest that this work is coming along - it's a challenge to get future certainty of work Geography is an issue, sustaining a workforce in Cumbria, making these companies invest in personnel

Q10	Can you prioritise the challenges in terms of business impact	Supply chain Investment/future certainty of work
Q11	Can you prioritise the challenges in terms of effort required	Supply chain Investment/future certainty of work
Q12	How could you overcome difficulties associated with these challenges	We have a design alliance which renewable very 5 years, we have to demonstrate value for money - but you weren't getting much savings in the first 2/3 years, that investment bears fruits after, they are not short term arrangements You need to SQEP the assets, that they get involved, they're skills increase, if they don't get certainty
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	On one particular project we're dealing with we are tackling issues with the relationship of project management - setting up training a university (multiple universities involved - Manchester University, local colleges) for Sellafield, the project management academy - it's not it's PM, earned value etc. - its planning, risk management - it's a wider area which interfaces with other others including engineering
Q14	What other ETO industries would benefits from a framework?	Petrol chemical, pharma, a lot of companies which work with us are those, because they similar safety scenarios, clean rooms etc. - complex one of project, not car industries

B.21 Head of Surface Ship Division - Interview 21

Interviewee

Company

Position Head of Surface Ship Division

Date 30/08/2016

Location

Time 14:30

Question No	**Question**	**Response Key points**
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Many challenges - formality of managing a product and a portfolio of projects - the whole lifecycle - development of product into support – maritime defence - a large scale and small scale
Q2	What are the typical key business objectives which you require a PLM environment to support?	Our lifecycle process is built around the project lifecycle - fully capture what we need to interface to - risk associated - dependencies - understood and management - if the prime upgrades what are the effects - how do we get off contract - contractually
Q3	Describe your current PLM environment from your perspective?	We've got a project lifecycle at a high level - we have a systems engineering process - that is where we manage the integration and the gates are understood - product, process
Q4	Describe the typical challenges you experienced with utilising PLM?	Varies between project to project - from a supplier perspectives it is well defined
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Our lifecycle process covers - ensure everything is captured upfront - our lifecycle management - contractual is understood - contract
Q6	Can you prioritise the improvements in terms of business impact	Lifecycle mgmt.
Q7	Can you prioritise the improvements in terms of effort required	Lifecycle mgmt.

Q8	How could you better enable the implementation of these improvements	Your trying to pre-empt and feedback all the time - the more knowledge of the systems you have to interface with the better - you try and avoid bespoke but you have to expect it Ensure you include the primes engineering community and not just project managers - include experts
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Promote your product - early engagement
Q10	Can you prioritise the challenges in terms of business impact	Understanding of supplier perspective in maturity - communicate our maturity management and product approach to supply chain
Q11	Can you prioritise the challenges in terms of effort required	Understanding of supplier perspective in maturity - communicate our maturity management and product approach to supply chain
Q12	How could you overcome difficulties associated with these challenges	Our lifecycle management - we have systems engineers review to ensure that we understood the changes and how to engineer, develop etc. - early technical
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Factor all the information and impact from information - a process which allows comments and feedback - improve the communication- details of communication
Q14	What other ETO industries would benefits from a framework?	(*Not asked due to time constraints)*

B.22 Head of Systems Engineering - Interview 22

Interviewee

Company

Position Head of Systems Engineering

Date 19/09/2016

Location

Time 14:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Agree with key challenges, but depends on context. We don't make enough use of skills and capabilities of mass manufacturing such as cars, welding technologies etc. I agree with requirements and customer driven approach, the way the customer approaches contracting, individual contacting 'salami contracts' design, manufacturing - sub optimal solutions - focusses on year costs and a more optimal through-life cost Customer abilities to model their costs, their ability to model cost is limited and impacts our ability to model cost against capability and architecture, to give a much better forecast of costs
Q2	What are the typical key business objectives which you require a PLM environment to support?	PLM has to support profit value for the business, leaner, more for less, appropriate metrics. What are the right people when we want enterprise resource management? How do we optimise those for delivery - how do we deliver that capability. How do we provide an integrate process set. How can we integrate with our business units such with maritime service for support - PLM through life into maritime service - a vehicle for integration
Q3	Describe your current PLM environment from your perspective?	The application of Process to manage our data, IPPD gave use configuration, change, BoM integration The flow through into production.
Q4	Describe the typical challenges you experienced with utilising PLM?	From a systems engineering point of view we have poor integration - requirements mgmt. are stove-piped for example. How can we tailor our processes so we can provide better value for money - Scalable, not Type 26 process for an OPV - the same for roles - the overhead Type 26 can bear is not what an OPV can Capability of people and capability delivered by groups - as we look at high technology the skills of a fitter etc. In terms of validation/verification etc. is a key component in providing certification of the delivered products - how do we enable that Requirements management - people, processes toolset improvements

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Process and people - the toolsets are low down in the scheme of things, ensuring we have an integrated process sets to ensure it meets ours and customer needs Up skilling people - some people get it and understand what PLM is, there is an implicit understanding - how do you get an explicit understanding Then there people are those who don't get the main thrust of the concept - how do you educate and bring them along - change in behavioural aspect
Q6	Can you prioritise the improvements in terms of business impact	Process and people
Q7	Can you prioritise the improvements in terms of effort required	Process and people
Q8	How could you better enable the implementation of these improvements	Identifying demographics of what the market is - some marketing - understand dimensions people have - those which are explicit/implicit, resistance to change etc. Try and make training, awareness tailored, a bespoke offering to take them to the appropriate level and identifying those which you would then take to move to a higher knowledge - where are the leaders - then you look at leadership roles Understanding the position and then target approach - money for maximum bang for buck
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	People acceptance of change is the biggest thing- many decades of resistance which we're trying to change - rail industry have a similar level of pain but are getting to the other side - classical industries can be compared with regard to culture, rail and shipbuilding, highly skilled but transactional
Q10	Can you prioritise the challenges in terms of business impact	Business change management
Q11	Can you prioritise the challenges in terms of effort required	Business change management
Q12	How could you overcome difficulties associated with these challenges	Promoting message within Central Engineering, they understood, many tens of people who are change engines - within the marine team they have improved significantly - we need to demonstrate and show what it has delivered - this is what we have done - articulate benefit to the business and the individual
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	It would help in as much it would give you a roadmap to indicate the direction of travel - Sometimes architectural models are criticised for just being formulaic a tick box, too rigid - you need to think of what you are doing rather than reflecting on what you are doing - guide you but not tell you, seed ideas, give you things to think about but not have a one size fits all - in our product we have complexity, is a Type 26 and OPV have different complexities
Q14	What other ETO industries would benefits from a framework?	Rail industry - critical engineering projects managing many years - what's in those projects what can we learn, what can they learn from us. The weapons industry is responding to a customer need but they have many 1000's of units, can they use this framework.

B.23 Business Systems Manager - Interview 23

Interviewee

Company

Position Business Systems Manager

Date 25/08/2016

Location

Time 09:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	I recognise a lot of these challenges particular in Maritime In maritime we have 2 Landing Helicopter Docks, a very bespoke customised design to meet Australian perspective Some of those challenges such as BoM maturity is not well understood across many of our products
Q2	What are the typical key business objectives which you require a PLM environment to support?	Change management, engineering change, regardless big or small that's where we see cost overruns - implementing PLM No one has defined key objectives, when we have a product centric project we need a more configuration management approach - key project management approach for managing change A lot of people manage configuration as design challenge, not as a full lifecycle approach- when in in-service - PLM across the full lifecycle, that is how we are maturing in the company
Q3	Describe your current PLM environment from your perspective?	Our process is very focussed on configuration management in design phases Outside the core aspects we using it for supply chain - asset management On the technology space we're moving from very bespoke systems to a COTS Windchill - taking time, another 5 years - because we are consolidating on the toolset we are suffering from not being able to evolve our technology - because we are co-ordinating we are not putting enough time into capability improvement, it's very small - when we come to down our SEA 5000 approach we can take what has been done in the UK - impacting our ability to innovate to condition - just what has come from the new Windchill functionality, not what has come from our process or people Some people use change and it's central, other it is just document management - people is the big challenge If we asked people what they understood as PLM - for different people is means different thing - getting a definition which is not just Wikipedia is difficult, as we have different projects which are acquisition- but we are seeing difference such as AWD which is moving into the support space

Q4	Describe the typical challenges you experienced with utilising PLM?	People, peoples uptake - one of the biggest challenges we face is that everyone wants their own customised systems - this is massive overhead - With something like Type 45 you can have 1, but for over 40 projects its difficult, we have tried to come up with standardisation, but every project wants their own way The perceived high cost of implementing PLM, they say it's a hammer to crack a nut, then they come back after using second tier system such as SharePoint, but they come back and invest in Windchill licences Getting away from legacy tools, data migration is what blows out the cost as everyone wants to keep the history
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	I have a very clear business owner - maybe this is unique because we have a many projects - our head of maritime had one visions which was fine - across our other business we don't have that single owner - if we went with iBoM ON Type 26 we've have UK telling us what to do or IM&T telling us what to do - Engineering don't have a good overview of how PLM is important to the business We are very project centric org rather than a product centric - project managers lead - so the importance of PLM is lost base of cost and schedule
Q6	Can you prioritise the improvements in terms of business impact	One clear PLM owner would help more which would help focus PLM and focus our approach - but as there is no clear owner across the business - needs to be the right owner so single approach and disparate customised systems
Q7	Can you prioritise the improvements in terms of effort required	Changing from project to product centric due to the way our customer works it's about delivering the project as opposed to the long term efficiency of the project
Q8	How could you better enable the implementation of these improvements	Put a lot more effort into wining the hearts and minds of the senior people - the understanding of the importance has been very difficult - they see it as IT, someone lese project, if it goes wrong it can impact projects- more effort into winning hearts and minds of senior people
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Everyone agreeing what the overall process and process are and what the overall architecture is - some areas of the business wants large and some small - scalable, due to the varying size of the projects that scalable is a challenge they see it as IT, someone lese project, if it goes wring it can impact projects - they don't want to be seen - the history of PLM over the years is that acquired customers have done it their way - they see it as IM&T telling them want to do - in the past we were never truly one company - business change element Stability
Q10	Can you prioritise the challenges in terms of business impact	Everyone agreeing - Data migration is the biggest thing - we double cost and schedule estimates as a rule of thumb Scalable - smaller working for smaller projects, other Windchill on tablets for working on the products
Q11	Can you prioritise the challenges in terms of effort required	Easy thing is to be as consistent as possible to build integrity into the systems - we didn't tried to migrate, build stable system that never goes down - easy and most important is to build stability and be consistent with development and training - we have full time trainer

Q12	How could you overcome difficulties associated with these challenges	If I could do it differently I would put a lot more effort into the organisational change piece - we don't go out and approach people and say this is the BAE Australia approach - We don't have the bandwidth - we have to make our comms and training generic as possible - more comms, posters, bulletins etc. - we had to reduce the head count so business change was impacted, seen as low value, then people see it as low value
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	I think it definitely help - like anything if you have a clear vision you can continue with comms when you are building your systems - you got the strategy signed off then its lost as other seniors don't get it - we have met the key objectives but with a clearer framework, sponsorship and vision it would help a lot - if we want to take this forward we need a consistent visions
Q14	What other ETO industries would benefits from a framework?	Really understanding what people want from the Enterprises architecture - they see it as tools not processes - we have a big investment with Oracle for ERP but we need to link in with other functions - supply chain etc. - PLM should join up processes - ITAR is a good example of we can utilise PLM - we are looking at export control - with a combination of Windchill and oracle (for asset management) it will manage 80% of the problem

B.24 Wholeship design owner - Interview 24

Interviewee

Company

Position	Wholeship design owner
Date	23/08/2016
Location	
Time	15:30

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	One of transfer of risk, how much risk can we transfer to industry - it can break big companies if we get it wrong - can we realistically transfer - that is why we have a MOD team - ensure that the design is being managed and are manageable Government will own consequence of product - we can put life's at risk Taxpayer value Commonality across defence We know how these ships will be operated in a combat environment - industry can't understand this - so we bring this into the design and requirements We need to align with Government Furnished Information across whole ships
Q2	What are the typical key business objectives which you require a PLM environment to support?	I need the information to confirm we are developing a solution that meets our requirements and will be achieved Risks are understood Track the information - not data but information, what does that mean - maturity, quality, risks, performance measure
Q3	Describe your current PLM environment from your perspective?	Reports for understanding issues, listening in on meeting - critical zone reports are quite good, needs further work with what it means to the schedule - I go into the MCE and Cognos Still need the discussion with people - need to understand how make it useful so we can act upon - we're good at generating data but needs to be meaningful The systems dashboard has lots of data but what does it mean - people need to describe what it means - human bit needs to be on it to ensure we can interrogate the data to make it meaningful - data to information key which requires human element
Q4	Describe the typical challenges you experienced with utilising PLM?	Boiling down all that data is our there to understand what the engineering status is so I can articulate to my customer - need to boil down to something which shows us risk, safety and schedule status

Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Data digestible which you can make decisions against - Subs in-service nearly got there - a dashboard which shows you the status of the information progress - engineering risk we have, risk, schedule, key issues etc. Integration and understanding of the consequences of other people's information access - we are good at putting data in the iBoM but if we don't put in the right data for others - better understanding of what other requires - e.g. electrical needs, combat didn't understand, weights - do we recognise what we are really missing
Q6	Can you prioritise the improvements in terms of business impact	Consequences - if people understand consequences they would understand the need for better data
Q7	Can you prioritise the improvements in terms of effort required	Good quality data is not difficult - harder to work with people understanding each other data - working on stovepipes - it gets harder the bigger the team, when you have a team of 1000 people split over a number of sites it becomes really hard
Q8	How could you better enable the implementation of these improvements	EGG meetings work well - MAITS re position as it brings different functions together Geographically stove piped even within Scotstoun - build more integrated teams - common issues - disperse teams, e.g. safety - AA leads sit together not with their teams - means they talk to each other
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	We are doing it, are we doing it enough - naval architects - should they not be with stage 2 - at a point in the programme we should adapt accordingly - stage 2 focussed so stage 1 should be focussed on stage 2 delivery Challenge is not enough people - can't allocate individuals to each zone Lose peer support - LFE becomes more difficult to speed around Some don't like working outside their area - location is challenge There is a danger we try and drive an integrated approach through process and toolset - which is fine as long as you define your process and toolsets follows - that's fine but we need to focus on people - people have different needs - need to get right balance - understanding where people fit into
Q10	Can you prioritise the challenges in terms of business impact	Understanding where people fit in
Q11	Can you prioritise the challenges in terms of effort required	Understanding where people fit in
Q12	How could you overcome difficulties associated with these challenges	Try and inspire a level of ownership - I can go into maturity meeting and sometimes I feel people don't care enough - not good responses in meetings - inspire ownership individually and as a team - same problem in mod side
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	MoD has acquisition guidance doc which is our starting point -should be good advice, as opposed you must do that - a framework is required but I think we should have aims and directions - more of a guide, this is how other products have done it - not steps as it may hamper innovation - more guidance less prescription - tailor it, more of steer - easily digestible - they must be able to understand it they won't follow it, same if it's too difficult - must be able to help them - more difficult people won't use them so we'll lose out
Q14	What other ETO industries would benefits from a framework?	Most will benefit as all have to put a team together, secure money - quirks between mod and non-mod but they are parallels - governance, business case, people management etc. - different technology, integration etc. but they are similar - e.g. underground rail system

B.25 Head of Platform Engineering - Interview 25

Interviewee

Company

Position Head of Platform Engineering

Date 11/08/2016

Location

Time 16:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	Wouldn't remove any My role is understanding the performance of programmes from a design perspective Type 45 - I was in project management, huge focus on risk - BoM mgmt. BoM Maturity - the procured BoM didn't align with the design BoM, the delivered BoM didn't align with the build - BoM alignment - parent item ordered and design, but broken down and challenges with alignment change management, lots of change once production is underway - costly
Q2	What are the typical key business objectives which you require a PLM environment to support?	Minimise rework - minimal the cost of quality - cost of failure/rework Design definition should support easy acceptance by the customer Product definition handed over the customer would help to maintain through its life Should help us be internationally competitive - a tool for efficiency and not an added cost for no return
Q3	Describe your current PLM environment from your perspective?	When I hear PLM - I hear concept design through to disposal, but from our perspective it's through to handover Organisation - we have a hard boundary between people - system design and detail Data handover between disciplines - not well integrate - CAD team demand information from system design whereas they should be involved themselves
Q4	Describe the typical challenges you experienced with utilising PLM?	Detail design team have their competence dumbed down - they should be able to design model and pass to outputs - separate Organisation barriers Overcomplicate design maturity - we overcomplicate system maturity and spatial maturity - maturity management defiantly area which adds value, we add progressive refined of a system which don't mean it's not mature
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	Simply the systems design maturity - at requirement level the customer sign up to it On the Irish OPV I introduced a maturity criteria with change - simplification

Q6	Can you prioritise the improvements in terms of business impact (use impact/effort matrix)	Simplification Get to the important principles before you get to part level
Q7	Can you prioritise the improvements in terms of effort required (use impact/effort matrix)	Simplification
Q8	How could you better enable the implementation of these improvements	Simplification
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	It has been recognised by naval ships - we are looking at organisational design - a capable hub for the business - it is taking us to a capability hub across all out areas - cross functional teams at appropriate points, e.g. systems designers management aspects would reside in the project - also project mgmt., customer mgmt., detail design (due to schedule mgmt. with volume) more resource available Improve utilisation of key resources - focus on core business value adding activities
Q10	Can you prioritise the challenges in terms of business impact (use impact/effort matrix)	Organisational construct
Q11	Can you prioritise the challenges in terms of effort required (use impact/effort matrix)	Organisational construct
Q12	How could you overcome difficulties associated with these challenges	Don't know - pilot on the HVAC area
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Absolutely - a framework/method/process - how does that team interact and be consistent - schedule demands - the answer is unknown
Q14	What other ETO industries would benefits from a framework?	Hospital - new Queen Elizabeth, massive undertaking - systems of systems - operability issues - complex organisation, NHS Nuclear power station I want outside expertise - I am recruiting test and commissioning and I want some who has commission a hospital or chemical plan

B.26 Lead Combat Systems Integrator - Interview 26

Interviewee

Company

Position Lead Combat Systems Integrator

29the March 17

Date

Location

Time 15:00

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	You captured it well, you've put it in a cohesive manner, from my background and experience it is relevant and expected, I would note because of your background or research you touched on key points which would have occurred to me naturally
Q2	What are the typical key business objectives which you require a PLM environment to support?	Profitability, lifecycle management, in my mind 2 things – risk reduction for exposure to warranty costs or rework, it is also a key resource for customer satisfaction – the delivered product meets customer requirements
Q3	Describe your current PLM environment from your perspective?	We were trying to get the latest technology in, but had immature technical ref material, configurations such as software were immature – challenges rolled down to other systems due to interconnections. PLM challenge of on non-Lockheed sourced supplier data The size of the programme a challenge – variants/design streams which needed to run from same PLM platform e.g. export orders for Japanese, Spanish and US navy expanded to different ships. SAP products were used
Q4	Describe the typical challenges you experienced with utilising PLM?	We would make a design change and often found it difficult to export properly into government systems or our partner Bath Iron Works systems. Government and bath had propriety in-house developed systems.

		Different supply chain procurement activities across partners which affected production such as bolts not fitting nuts as a crude example. Technical document when they expanded the programme they had different standards for testing, constantly rewriting test specs due to different partners having different specs they used for their sites. Information for training out of synch with the new products
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	I love your iBoM, also your data loader for vendor information which populates supplier information; it would have been an enormous improvement for us. The customer was paying multiple times for multiple information changes due it being in different systems. Single sourcing is the key, all of the technical, design, logistical and schedule all single sourced. Single point of truth We then used the cloud which has helped
Q6	Can you prioritise the improvements in terms of business impact	Single, integrated source
Q7	Can you prioritise the improvements in terms of effort required	Single, integrated source
Q8	How could you better enable the implementation of these improvements	Start with it from the beginning, I would write the contracts so that all players use that system/approach. That the integrated data environment is stipulated for all players, equally obligated to use that system, no way for them to go away and created their own
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Contract misalignment. With a big company I had resources to draw on; with smaller vendors/suppliers they didn't have the resources to support what we wanted to do.
Q10	Can you prioritise the challenges in terms of business impact	Resource for smaller vendors/suppliers to take integrated approach
Q11	Can you prioritise the challenges in terms of effort required	Resource for smaller vendors/suppliers to take integrated approach
Q12	How could you overcome difficulties associated with these challenges	We leveraged ours resources to help the smaller companies understand, comply and integrate
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Of course it would, anything such as a pick-list or template would help. We could give them to the contracts to say what we want, to the suppliers to say what they need to do, and schedule what they need to do. Helps people to understand. Keeps the end in sight from the beginning, helping getting to the end point
Q14	What other ETO industries would benefits from a framework?	Civil engineering activities, Power plants, once off type things such as missile defence system in Romania

B.27 Senior Systems Engineer - Interview 27

Interviewee

Company

Position Senior Systems Engineer

Date 31/03/17

Location

Time 1000

Question No	Question	Response Key points
Intro	Brief overview of research using appropriate diagrams	
Q1	Interviewer describes the key challenges identified in the research and asks interviewee of examples where he/she has encountered them, would you add or remove any?	I would agree with them, we've encountered all of them. Biggest being the level of customisation from programme to programme. Not high volume compared to other industries
Q2	What are the typical key business objectives which you require a PLM environment to support?	I think PLM to cradle to grave, concept to disposal. We're very much focussed on the development lifecycle to meet the customer needs and contractual requirements
Q3	Describe your current PLM environment from your perspective?	We view the PLM environment as tool centric, for me the PLM environment we think of is Windchill, I know it's more than that but it's the capabilities that Windchill provides us, development of the product, document control, management of supplier information, ensuring the configuration management of our product is secure, traditional Change Management
Q4	Describe the typical challenges you experienced with utilising PLM?	One you haven't mentioned is culture, trying to convince the company to use PLM. We are new to PLM, it's difficult to change the business model We have a certain company business model which was developed before the days of PLM and tools like Windchill. It's a challenge to standardise our business processes and use Windchill. Everyone has different opinions with multiples projects which go through different lifecycles. What those processes are and what data requires to be managed is difficult. Its difficult due to those like us who are new to PLM
Q5	What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	For me personally it's more attention to the design of PLM itself as opposed to jumping in too quickly, which we've done in the past. Figure out what you want to do and the processes before you jump into it too quickly.

		All the things you want to do upfront but the senior just want a demo, they want it done and they don't understand the complexity of the problems which need to be figured out upfront
Q6	Can you prioritise the improvements in terms of business impact	Process, data and people approach in place upfront
Q7	Can you prioritise the improvements in terms of effort required	Process, data and people approach in place upfront
Q8	How could you better enable the implementation of these improvements	Education, it's what my intent is on the Canadian Surface Combatant *(CSC).* Education to ensure those who have a stake in it understand the importance of doing it right up front. Training which can help the process and Windchill expertise, those who understand data management principles, education and skillsets
Q9	What typical challenges can you foresee with transitioning from an as-is to a PLM environment which incorporates your improvements (to-be)	Same old problem, getting the funding in place to get from A to B.
Q10	Can you prioritise the challenges in terms of business impact	Funding
Q11	Can you prioritise the challenges in terms of effort required	Funding
Q12	How could you overcome difficulties associated with these challenges	Understanding how much BAE approach can be incorporated, learn from the industry that does it better, you guys in BAE are ahead of us. We often don't leverage the knowledge of the Tool vendor, PTC have developed Windchill to do something and we don't reach back to the vendor, we try to do things with the tool which it wasn't designed to do. I am a big advocate of working with the vender, this gets back to funding again
Q13	Would a framework assist with the transition from as-is to the to-be, if so how?	Absolutely, what I think you are suggesting is that the output of all your research will be briefed back to us for us to reap the benefits on CSC. Our senior folks would love to get that briefing and it would help with the education I am trying to battle
Q14	What other ETO industries would benefits from a framework?	We do work for the air force and I know as an example the F35 programme is heavily engaged in Windchill. Anywhere we're been contracted to deliver a product

Appendix C Interview Analysis – NVivo export

Themes and codes	No of Sources	No of References
A - Additional key challenges	0	0
BoM, Configuration, Change and Maturity Management	0	0
BoM and Maturity management	4	4
Config mgmt. and baselines	2	2
Immaturity from supply chain to support programme dates e.g. cut steel	1	1
Complexity and Uncertainty	0	0
Complexity - Misc.	1	1
Product complexity	1	1
System of system not just with the product but for its use	1	1
Customer interaction and procurement	0	0
Changing customer expectations	2	2
Customer - misc.	3	7
General supporting comments	14	14
Highly customised, few off	0	0
Alignment of our supplier information to supplier systems - key difference in large volume suppliers who can be dependent on one supplier, we disqualify if so	2	2
Bespoke and long design lifecycle	3	3
Few and one off	1	1
Few organisations who can undertake ETO projects	1	1
Maturity of the business	2	2
Obsolescence due to long lifecycle	1	1
Only company which can provide the product	1	2
PLM in ETO immature compared to other industries	1	3

Themes and codes	No of Sources	No of References
Product specific customised elements	1	2
No prototype	0	0
Design and manufacturing overlap	1	1
Design for manufacture	1	1
High quality of product required	1	1
No prototype - misc.	2	2
Project Management	0	0
Control over the data due to size and length of programme	1	1
Cost estimations	3	3
Cost overruns	2	2
B - Key business objectives for PLM	0	0
Information	0	0
Manage security, export and IPR obligations	2	2
Management & presentation of evolving product maturity	7	8
Management of product configuration & emergent change	0	0
Change, BoM, config and maturity - control, consistency and history	11	13
Through life design definition (baseline) management	2	2
Through life multiple ship design definition (baseline) management	1	1
Single point of truth to capture evolving product data once, use many times to reduce duplication and increase quality	7	9
Single point of truth	3	3
Through life capture, integration and management of all evolving product information from all stakeholders	2	3
Change, BoM, config and maturity - control, consistency and history	11	13
Consistent and controlled BoM	1	1
Design integration	1	1
Managing supplier data	1	1

Themes and codes	No of Sources	No of References
Through life - whole life into support	4	4
Up-to date, traceable, relevant and configured information that can be accessed	14	14
Design integration	1	1
People	0	0
Demonstrating to the customer that the product meets requirements	4	4
customer requirements -Linking delivered product to requirements	3	3
Taxpayer - demonstrating value for money	1	1
Enable improved decision making	3	3
Enabling collaboration across multiple-sites	1	1
Management of the culture of PLM across all stakeholders	1	1
Support organisational knowledge management and learning	1	1
Process	0	0
Cost, profit, risk reduction and value for money	1	1
Cost control through information management	1	1
Profitability	1	1
Risk reduction	3	3
Enable product development & build collaboration across all stakeholders	3	4
Integrate engineering with digital planning	2	3
Safety, test and commissioning influencing design	2	2
Enable quality through right first time and reduction in rework	5	6
Reputation protection and enhancement	1	1
Enabling standardised design and build	2	2
Standards	1	1
Support the design and build for product safety and environmental considerations	1	1
Safety, test and commissioning influencing design	2	2
C - Current PLM environment (from your perspective)	0	0

Themes and codes	No of Sources	No of References
Information	0	0
Change, config, BoM, Drawing and document management	3	3
Data rich	1	1
Manage, decompose, structure, protect and describe components	3	3
Managing different views for different stakeholders	3	5
Master record Management	1	1
Maturity - understand status and plan for next phase	1	1
Reports - understanding status of programme	1	2
Single evolving BoM	2	4
Standards Management	1	1
People	0	0
Business and political landscape - not within our control	1	1
Process	0	0
Design baseline to deliver to schedule and cost	1	1
Facility management	1	1
Improved understanding of PLM from earlier projects	1	2
In transition to improve quality and integration	1	1
Maintenance Management	1	1
Requirements management	1	1
Supplier management	1	1
Through-life, Whole life	3	3
Transition from engineering to operations environment	1	2
Technology	0	0
Multiple engineering applications	1	1
PDM backbone	2	2
Toolsets	1	1

Themes and codes	No of Sources	No of References
Unintegrated systems	3	3
D - Key challenges of utilising PLM	0	0
Information	0	0
Integrating complex product information through-life across multiple toolsets	1	1
Integrating information through-life across multiple toolsets	1	1
single point of truth challenge	1	1
through life technology and data integration	7	7
Mgmt. of product information maturity & it's relationship to change & configuration management	3	3
Engineering maturity issues resulting in change	1	1
Supply chain information	1	1
What is Design evolution and when does it become change	1	1
Not relevant to research	0	0
Focus on high value items, not smaller, many off	1	1
Information management - training information out of synch with new on ship systems	1	1
Through life challenges, e.g. issues 10 years from delivery such as warranty	1	1
Not relevant to research	0	0
Business intelligence	1	1
People	0	0
Education, adoption and understanding value of PLM, and its relationship to quality	8	11
People - new ways of working	2	2
People - ownership	1	1
People - stakeholder engagement	1	1
People - understanding why its required	5	5
What's in it for me! - What are the benefits to engineers entering and maintaining the PLM data	1	1

Themes and codes	No of Sources	No of References
Lack of PLM expertise	0	0
Central team to help with ownership, implementation, requirements capture, process creation and management	1	1
Obligations and through-life implications of peoples actions or non-actions	1	1
Understanding maturity management and their obligations	1	1
Understanding processes, toolsets and through-life product information integration	1	1
People- understanding change and config	1	1
Working collaboratively across all functional areas	1	1
People - unintegrated teams	1	2
Processes	1	1
Creating processes which meet business objectives but are not overly complex	1	1
Multiple programme level approach to product lifecycle management	1	1
Commercial and Export obligations	1	1
Schedule development and management with bespoke product	1	1
Difficult to implement improvements on live programme	1	2
Standardising processes due to bespoke nature of product	2	2
Technology	0	0
Creating a system of systems through toolset integration and rationalisation	11	16
Evolving technology from previous long-lifecycle products	0	0
Integrating and changing technology from legacy programmes, project data into new environment	2	2
legacy systems integration impacting ability to innovate	1	2
Symbiotic technology management, and integration on long-lifecycle products	6	7
Long programme - dealing with changing environments	1	1
Symbiotic and integrated toolsets challenges - Integrating toolsets means they have to be upgraded together	1	2

Themes and codes	No of Sources	No of References
Technology robustness & longevity to support long-life product design & build (L)	3	4
Toolset performance with massive datasets	1	1
Toolset complexity and simplicity balance to meet business objective	2	2
Configuration management technology - variants	1	1
E - What improvements would you make to PLM to meet your objectives	0	0
Information	0	0
Central Team with SQEP for PLM information integration, policy development, standardisation, LFE & adherence across business	0	0
Common metadata with support	1	1
Information integration within engineering systems	2	5
Integration through life	2	2
Integration with maintenance and facilities	1	1
Plan up front - information approach, processes and people	1	1
Standardised approach for data across programmes	1	1
Develop Configuration & Change Management approach across single ETO product classes & variants	1	1
Understanding of data to support change management	1	1
Variant management - both within single and multiple ships	1	1
Develop Data quality and governance policy, team and adherence approach	4	4
Develop policy to capture what information is required by the business and how it will be used	2	2
communicating information so its relevant and meaningful as to programme status	1	2
Understanding of information integration impact - for making engineering decisions	1	1
Use of data for understanding programme maturity, risk, cost and schedule status to make management and engineering decisions	2	2
People	0	0
Comprehensive business change initiative on PLM	0	0

Themes and codes	No of Sources	No of References
People - business change	3	3
People - Understand benefits	5	7
Cross functional PLM education programme embedded within the core business training programmes emphasising core values and objectives	2	2
Enable improved decision making	1	1
Ensure you drive through what you planned with PLM -Don't stop when it becomes difficult	1	1
People - skills, comms and training	6	9
Provide evidence of benefits to senior management to enable support and maintain sponsorship	2	3
Quantify benefits	1	1
Senior business owners, sponsor	1	1
Process	0	0
Central Team with SQEP for PLM business process ownership, development, standardisation, LFE & adherence across business	0	0
Standardise processes across all programmes	3	4
Use early in the lifecycle and scale	1	1
Guidelines and governance over process complexity to ensure they are simple and usable	6	9
Technology	0	0
Drive integration of information through toolset rationalisation	6	7
Technology and interfaces	1	1
Focus on toolset development on business objectives, priorities and ease of use to reduce complexity of processes	2	3
user friendly	1	1
Identify and implement configurable PLM toolset with minimal customisation	1	1
Don't customise	2	2
Drives customisation	1	1
Flexible configurable technology	1	1

Themes and codes	No of Sources	No of References
IT architecture improvements to support new ways of working and ensure toolset performance	2	2
F - Better enable implementation of PLM improvements	0	0
Information	0	0
Develop Configuration and Change Management approach across single product classes and variants	2	2
Improved information from systems as to impact of engineering changes	1	1
Develop policy to capture what information is required by the business and how it will be used	0	0
Closer integration with Central Eng. team and Project management to help turn data into project information	1	1
People	0	0
Central team with SQEP to develop PLM objectives, education and support to business	3	4
Business level central team to drive business objectives to team	2	2
Centralised team to help cost and benefit- Implement investment from previous programme	3	4
Comprehensive business change initiative on PLM	0	0
Dedicated business change manager	1	1
Training - communicate what’s in it for them	1	1
Training - business change management - why they need to change something they've been doing for years	1	1
Training - success stores from other organisations	1	1
Cross functional PLM education programme embedded within the core business training programmes emphasising core values and objectives	0	0
Training - Better understanding of how information is structured	2	2
Training - better use of training	1	1
Training - Dedicated training on PLM and why it’s critical	1	1
Training - educating the consequences of the information	1	1
Training - link PLM training to other functions whole life PM, Supply Chain, T&C, Planning, Ops	4	5

Themes and codes	No of Sources	No of References
Training - why architecture was designed this way	1	1
Not relevant to research	0	0
Validation and verification - use of system engineering principles	1	1
Process	0	0
Central Team with SQEP for PLM business process ownership, development, standardisation, LFE & adherence across business	0	0
Central team to help with ownership, implementation, requirements capture, process creation and management	3	3
Process and technology ready and mature for programme - not implement on live programme	1	1
Software vendors - improved approach, not just sell licenses	1	1
Mandate utilisation of PLM processes internally and to partners and supply chain	1	1
Contractual, both internal and external, agreement that integrated approach will be taken	1	1
Drive supply chain experience into business - don't dictate to them	1	1
Supply chain - improved integration	2	2
Supply chain certainty of work	1	1
Technology	0	0
Focus on toolset development on business objectives, priorities and ease of use to reduce complexity of processes	0	0
Analyse system use and act	1	2
Keep tools and process simple	2	2
Scaling depending on programme size	1	1
Survey user satisfaction and act	1	1
Identify and implement configurable PLM toolset with minimal customisation	2	2
Balance between technology functionality available & what is required to support the business	3	3
IT, robust and flexible, Agile scrum	2	2

Themes and codes	No of Sources	No of References
IT architecture improvements to support new ways of working and ensure toolset performance	3	7
Testing	1	1
G - Challenges with implementing PLM improvements	0	0
Information	0	0
Mgmt. of product information maturity & it's relationship to change & configuration management	1	1
Not relevant to research	0	0
Supply chain integration cost benefit	1	1
People	0	0
Cost and benefit buy-in to allow investment an ongoing management support	6	7
Cost - resources for smaller groups, partners or suppliers to use integration approach	1	1
Moving from programme to business centric organisation	1	2
Education, adoption and understanding value, and its relationship to quality	1	1
Cultural change	4	5
People - agreed approach for different stakeholders who have different needs	1	1
People - getting right balance to ensure they are not overloaded	1	1
People - Keeping momentum going when there are other challenges	4	5
people - not too information and toolset focussed, rather they get the right support	1	1
People - they want it simple, easy to understand, difficult with complex requirements	2	2
People - understanding technology	2	2
Lack of PLM expertise	0	0
People - lack of right PLM expertise	3	3
Obligations and through-life implications of their actions or non-actions	0	0
People - Do they understand what's required	3	3

Themes and codes	No of Sources	No of References
Understanding processes, toolsets and through-life product information integration	1	1
People - they understand their areas, not others	2	2
Process	0	0
Creating processes which meet business objectives but are not overly complex	0	0
Ensure all organisations adhere to PLM approach	1	1
Development and adherence to PLM processes	1	1
Technology	0	0
Creating a system of systems through toolset integration and rationalisation	1	1
Technology robustness & longevity to support long-life product design & build	0	0
Mature technology	2	2
Software vendors - don' understand complex ETO environments	1	1
Rapid development to meet urgent emergent needs	1	1
Managing changes to PLM environment due to changing business needs	1	1
H- Overcome difficulties with PLM implementation challenges	0	0
Information	0	0
People	0	0
Central team with SQEP to develop PLM objectives, education and support to business	1	1
Central team to help with facilitation	1	1
People confidence with systems and approach	2	2
Comprehensive business change initiative on PLM	0	0
Business change management	2	2
Drive PLM improvements into Operations environment	1	1
People - ownership of information	1	1
People - sell benefits	3	3

Themes and codes	No of Sources	No of References
Cross functional PLM education programme embedded within the core business training programmes emphasising core values and objectives	1	1
Cost and resource, top down, to support to help everyone use an integrated approach	1	1
People - culture of sharing	1	1
People - right skillsets	1	2
People - train how their actions impact other functions	2	2
Provide evidence of benefits to senior management to enable support and maintain sponsorship	3	3
Senior Management ownership	1	1
Sustainable benchmarking across related industries and vendors for business improvement and confidence	2	2
Process	0	0
Technology	0	0
Identify and implement configurable PLM toolset with minimal customisation	1	1
I - How would a PLM implementation framework help	0	0
General positive comments	4	4
Information	0	0
People	0	0
Help to communicate to senior management what PLM means and its benefits, to release funding	2	2
Help with communicating roadmap - how to go from as-is to a to-be - sets goals and targets	6	6
Help with communicating why we are using PLM	1	1
Help with learning	7	7
Help with showing relationships between functions and stakeholders	1	1
Pictorial - not data heavy or will not be used	1	1
Schedule integration - educate relationships	1	1
Process	0	0

Themes and codes	No of Sources	No of References
Align with Engineering Framework	1	1
Assist with early project planning	1	1
Flexible and scalable, a guide as opposed to mandatory	4	4
Help to link across functions	2	2
Help with multiple programmes including export	2	2
improve supply chain integration	1	1
Improved link to maturity management	1	1
Improved link to quality management	0	0
Improved realisation of business objectives	1	1
Operating model and framework the same - evolve to suit	1	1
Replace current models which don't meet ETO needs, e.g. IBM generic PLM model	1	1
Scalable	2	2
Technology	0	0
Help to implement new technology with an integrated stakeholder community	1	1
J - Other industries which could use framework	0	0
Big Ports developments	1	1
Big science - e.g. CERN	2	2
Bridges	1	1
Chemical and pharma	2	2
Civil Engineering	1	1
ETO software	1	1
Formula 1	2	2
Hospitals	1	1
MoD projects	3	3
Nuclear	5	5

Themes and codes	No of Sources	No of References
Oil and gas	4	4
One off aerospace - prototype	2	2
Power stations	3	3
Rail	7	7
Space	2	2

Appendix D The draft framework

	Objectives	Challenges	Enablers
Information	Through life capture, integration & management of all evolving product information from all stakeholders Single point of truth to capture evolving product information once & use many times to reduce duplication & increase quality Manage product configuration & emergent change Manage security, export & intellectual property Management of evolving product maturity Up-to date, traceable, relevant & configured information that can be accessed	Identifying, managing & presenting emergent complex information for management decision making Integrating complex product information through-life across multiple toolsets The management of product information maturity & its relationship to change, configuration, schedule & cost	Develop policies to capture what information is required & how it will be used within an evolving complex product PLM information integration, policy development, standardisation, learning from experience & adherence using suitable expertise within a dedicated cross functional team Develop data quality & governance policy, team & adherence approach Develop Configuration & Change Management approach across an ETO product & its variants
Process	Support the design & build for product safety & environmental considerations Enable quality through right first time & reduce rework Enable product development & build collaboration across all stakeholders Manage schedule, cost, profit, risk reduction & value for money Enable standardised design & build	Creating processes to deliver business objectives and are not overly complicated	PLM business process ownership, development, standardisation, learning from experience & adherence using suitable expertise within a dedicated cross functional team Guidelines & governance over process complexity to ensure they are simple & usable Mandate utilisation of PLM processes internally, to partners & the supply chain
People	Enabling collaboration across multiple-sites Demonstrating to the customer that the product meets requirements Support organisational knowledge management & learning Enable improved decision making	Personnel's understanding of their obligations & through-life implications of actions or non-actions Education, adoption & understanding the value of PLM & its relationship to quality Understanding processes &toolsets & its relationship to through-life product information integration Working collaboratively across all business functions Lack of expertise to enable and support PLM	Provide continuing evidence of benefits to senior management to enable support & maintain PLM sponsorship Comprehensive business change initiative on PLM Cross functional PLM education approach embedded within the core business training programmes, emphasising core values & objectives Develop PLM objectives, education approach & support to the business using suitable expertise within a dedicated cross functional team
Technology		Technology robustness & longevity to support long-life product design & build Technology complexity & simplicity balance to meet business objective Creating a system of systems through toolset integration and rationalisation	Identify & implement configurable PLM toolsets with minimal customisation Drive integration of information through toolset rationalisation Focus toolset development on business objectives, priorities & ease of use to reduce complexity of processes Implement IT architecture improvements to support new PLM capability & ensure toolset performance

Appendix E Poster used for evaluation

A Framework to Support the Implementation of Product Lifecycle Management in Engineer to Order Products

Danny McKendry[1], Dr Ian Whitfield[2], Prof Alex Duffy [3]
1 –Design, Manufacture & Engineering Management (DMEM), University of Strathclyde
2 –Design, Manufacture & Engineering Management (DMEM), University of Strathclyde
3 –Design, Manufacture & Engineering Management (DMEM), University of Strathclyde

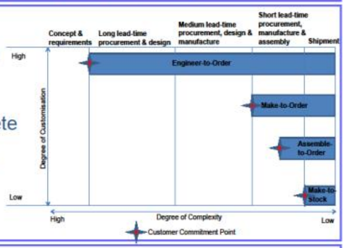
University of Strathclyde Engineering

Overview

- Engineer to Order (ETO) products include characteristics such as high capital value, large-scale, long-life, no prototype, highly customised & few or one off, e.g. Naval Shipbuilding, Large Hadron Collider, Nuclear Power Stations
- ETO products require a means to manage the millions of information objects used throughout the lifecycle of the programme
- Product Lifecycle Management (PLM) utilises people, process & technology to ensure this information is robust & controlled
- In order to achieve effective PLM the relevant information has to be identified at key points throughout the products life-cycle
- It then has to be captured in a way which is useful, configured, controlled & reusable to support the business objectives

Challenges with Engineer-to-Order (ETO) products

- Customer interaction & procurement – a system of systems designed using supplier data
- Highly customised & few off – design evolves throughout the product lifecycle
- BoM, change & maturity management – manufacturing starts before the design is complete
- Project management – cost & schedule control critical due to a global history of overruns
- No prototype – design & manufacturing cannot be tested for quality, cost & schedule
- Complexity & uncertainty – emerging challenges throughout the design & build

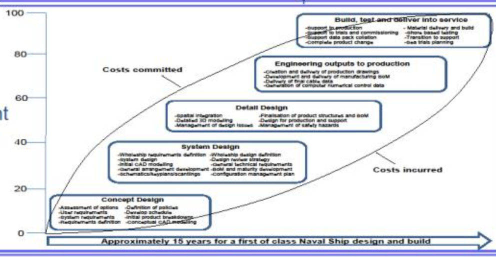


The Problem

- ETO products have a greater reliance on PLM due to their unique challenges.
- The costs committed early in the products lifecycle will incur significant overruns if PLM not successfully implemented

Research Aim

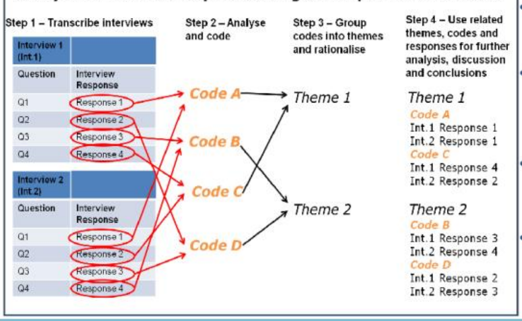
- A framework to support the implementation of Product Lifecycle Management in Engineer to Order Products



Progress Highlights (after 8 years part time)

- Draft thesis completed early April 2018–submission for examination early Q2 2019 (which includes University feedback)
- 2 papers published & presented at international conferences
- 28 interviews undertaken with senior personnel from multiple ETO organisations in the UK & internationally
- Interview responses analysed using thematic analysis & key themes identified
- The framework for the implementation of PLM on Engineer to Order products developed based on interview key themes
- The framework has been validated through questionnaires from senior personnel from multiple ETO organisations

Analysis of interview responses using NVivo qualitative software



- Each theme has a comprehensive description in the thesis which has direct links to the source anonymised interview responses
- The themes have been grouped into 4 sections - information, process, people & technology across objectives, challenges & enablers to create the framework
- The framework is designed to provide guidance & be flexible depending on the objectives of the organisation
- The guidance for each of the key themes described in the thesis is being integrated for easy interrogation.

DMEM Design, Manufacture and Engineering Management

BAE SYSTEMS Delivering Total Engineering

Appendix F Evaluation Questionnaires

F.1 Head of Detail Planning

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.
All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.
The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.
Thank you for your participation.

Danny McKendry CEng MIET
Type 26 Wholeship PLM and iBoM Engineering Manager
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daniel.mckendry@baesystems.com
BAE Systems Surface Ships Limited
South St, Scotstoun, Glasgow, G14 0XN

Name (optional) ……………………Position (optional) Head of Detail Planning

Company (optional) Date : 05/10/18 Location Time 12pm

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					Y
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					Y
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					Y
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				Y	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				Y	
2.3	The content of the framework can be easily followed.					Y
2.4	The framework appears to be flexible in its use.				Y	

2.5	I/we would use this framework to implement PLM on ETO products.				Y	

General comments:	
General comments on the framework or research.	There is often an over reliance on toolset when discussing product data management, but in my experience it is the human factor, and how we communicate, that undermines successful implementation. It is refreshing therefore to see that the framework considers technology as the last of its four critical factors.
General comments on the validation approach.	I am happy with the breadth of case studies used, and the methodology employed, and grateful to be able to add my thoughts in support of the research.

F.2 Engineering Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional) ……………… ………………………… Position (optional)Engineering Manager(Maritime)…………………………………………………………….

Company (optional) ……………………………………..Date 20 Jun 2018……………… Location… ………………….. Time……………………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				X	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					X

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				X	
	2. **<u>Framework structure and versatility</u>**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					X
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				X	
2.3	The content of the framework can be easily followed.				X	
2.4	The framework appears to be flexible in its use.				X	
2.5	I/we would use this framework to implement PLM on ETO products.				X	
	General comments on the framework or research.	There are some areas that will need tailoring for the intended audiences, but generally the framework articulates many of the issues we are facing in our business growth today.				
	General comments on the validation approach.					

F.3 Engineering Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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South St, Scotstoun, Glasgow, G14 0XN

Name (optional) ……………… Position (optional) Engineering Manager

Company (optional) Date 4/10/18 Location Time: 1530

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					5
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				4	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					5
	2. **<u>Framework structure and versatility</u>**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					5
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					5
2.3	The content of the framework can be easily followed.				4	
2.4	The framework appears to be flexible in its use.					5
2.5	I/we would use this framework to implement PLM on ETO products.				4	
	General comments on the framework or research.	The framework appears to be the result of a wide and varied research approach encompassing different industries and ETO products. There are key themes, particularly the challenges that I can identify with during our PLM implementation. This framework would be an invaluable asset to any business embarking on the implementation of PLM.				
	General comments on the validation approach.	A thorough and extensive approach has been undertaken.				

F.4 Detail Planning Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional) …………………. Position (optional)…Detail Planning Manager……….

Company (optional) ………….Date 05/10/18 Location… Time 11:00hrs………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				yes	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				yes	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				yes	
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				Yes	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				Yes	
2.3	The content of the framework can be easily followed.				Yes	
2.4	The framework appears to be flexible in its use.				Yes	
2.5	I/we would use this framework to implement PLM on ETO products.				Yes	
	General comments on the framework or research.	I can see a lot of research has gone into this. The information presented was very informative and as a business we need to embrace.				
	General comments on the validation approach.					

F.5 BOM Integration Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional)………………. Position (optional)………BOM Integration Manager

Company (optional)………Date…04/10/18 Location……………………. Time……………………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					x
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				x	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				x	
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				x	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.			x		
2.3	The content of the framework can be easily followed.				x	
2.4	The framework appears to be flexible in its use.				x	
2.5	I/we would use this framework to implement PLM on ETO products.					x
	General comments on the framework or research.	I think the research highlights very well the challenges faced on large engineering/manufacture programmes. My only comment on question 2.2 is that there is an important element related to timescales. Implementing a framework such as this takes a large amount of time, especially for a large organisation. This often conflicts with advances in technology as well of programme schedules themselves. Any solution must be implementable in line with the business' operating timescales and the rate of technological innovation.					
	General comments on the validation approach.	I believe the approach to be sound (noting the comment above). Perhaps an alternative approach looking more at the quantitative (cost/schedule) factors could be applied to gain a different perspective.					

F.6 Engineering Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional)… …………………… Position (optional)……Engineering Manager

Company (optional)… Date…05-10-2018 Location…. Time……11:10……

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				*	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				*	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.			*		
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				*	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				*	
2.3	The content of the framework can be easily followed.			*		
2.4	The framework appears to be flexible in its use.				*	
2.5	I/we would use this framework to implement PLM on ETO products.				*	
	General comments on the framework or research.	When undertaking a big task such as implementing a PLM approach to managing information having a guiding framework is always useful. This framework appears to address all the key elements to be considered in a systematic way. The elements within the framework could be tailored to suit a real world set of circumstances.				
	General comments on the validation approach.	N/A				

F.7 IM&T Enterprise Architecture and Design Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional) ……………… Position (optional) Enterprise Architecture and Design Manager

Company (optional) Date 05/10/18 Location Time 08:00

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				X	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				X	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					X
	2. Framework structure and versatility	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					X
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				X	
2.3	The content of the framework can be easily followed.				X	
2.4	The framework appears to be flexible in its use.				X	
2.5	I/we would use this framework to implement PLM on ETO products.				X	
	General comments on the framework or research.	- Thorough research paper with validatory evidence from other sectors that confirm the importance and relevance of PLM on large engineering projects - Framework has applicability for ETO projects but also has learnings that can be applied to more general PLM implementations - Framework also has relevance for implementing other technology solutions on ETO projects particularly in the information and people streams of the research					
	General comments on the validation approach.						

F.8 PLM Consultant

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET

Type 26 Wholeship PLM and iBoM Engineering Manager

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BAE Systems Surface Ships Limited

South St, Scotstoun, Glasgow, G14 0XN

Name (optional)……) ……………………………………. Position (optional)…………………………………………………………….)PLM Consultant

Company (optional)…………………………………….) Date …………….. 08/06/2018 Location……………………. Time……………………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					X
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				X	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				X	
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					5
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					5
2.3	The content of the framework can be easily followed.				4	
2.4	The framework appears to be flexible in its use.				4	
2.5	I/we would use this framework to implement PLM on ETO products.				4	
	General comments on the framework or research.	Would need to access in more detail the research behind the framework to comment fully, but on the face of it the framework appears sound.				
	General comments on the validation approach.					

F.9 Master PLM Architect

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET

Type 26 Wholeship PLM and iBoM Engineering Manager

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South St, Scotstoun, Glasgow, G14 0XN

Name (optional)………………… ………………………. Position (optional)……………………Master Architect……………………………………….

Company (optional) ……………………..Date…08/06/18………….. Location…………..UK……….. Time……………………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					5
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				4	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.			3		
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					5
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					5
2.3	The content of the framework can be easily followed.				4	
2.4	The framework appears to be flexible in its use.				4	
2.5	I/we would use this framework to implement PLM on ETO products.				4	
	General comments on the framework or research.	Difficult to assess framework in detail without the accompanying documentation, especially its implementation effectiveness.				
	General comments on the validation approach.	The approach is valid but much is also applicable to other non-ETO products				

F.10 Platform Design Authority

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional)… ……………………………………… Position (optional) Platform Design Authority ……………………………………………………………

Company (optional) ……………………………………Date 22/06/18……………… Location, VIC…………………….. Time…………………… 14.20

Please respond to the following statements by using the 5-point rating scale

	1. **<u>Framework quality</u>**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				X	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				X	

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				X	
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					X
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					X
2.3	The content of the framework can be easily followed.					X
2.4	The framework appears to be flexible in its use.					X
2.5	I/we would use this framework to implement PLM on ETO products.				X	

General comments on the framework or research.	The research appears to have been conducted in a very robust manner, across a decent sized sample of varied domain / product types. The analysis conducted on the research also appears to have been robust and well considered. Hence the resultant proposed framework appears to have credibility and validity.
General comments on the validation approach.	As with the research and analysis, the approach to validation appears to have been robust, giving a degree of confidence in the recommendations.

F.11 Waterfront Operations Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focusses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET

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BAE Systems Surface Ships Limited

South St, Scotstoun, Glasgow, G14 0XN

Name: (optional)…………..…………………………………………. Position: (optional)……………………….. ………. Waterfront Operations Manager.

Company: (optional)…………………………………… Date……………… 09AUG18 Location:…………………….. Remote. Time: N/A……………………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					X
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					X

1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				X	
	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					X This is a noteworthy strength
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					x
2.3	The content of the framework can be easily followed.				X	
2.4	The framework appears to be flexible in its use.				X	
2.5	I/we would use this framework to implement PLM on ETO products.					x
	General comments on the framework or research.	It is evident that the author based his research on actual field interview and assessment vice leaning on academic or theoretic sources. This framework is clearly the result of a well-conceived and comprehensive fact-based approach. I applaud the author for providing a unique insight and synthesis of this complex material. The author has provided a simple and intuitive graphic representation. In considering the construct of a PLM the organization presented provides a simple and easily interpreted arrangement. The author's leverage of feedback from subject matter experts is evident and I cannot add to the content included. One minor suggestion would be to define acronyms where used.				
	General comments on the validation approach.	I appreciated the structure and ease with which feedback was solicited. As a busy manager, I was grateful that I could complete this assessment in under 30 minutes. I have been in the business producing ETO product for nearly 25 years and have not seen such a reasoned, thorough and rational presentation. I believe this meets all stated criteria for utility and uniqueness. I can easily envision using this framework as a basis for establishing a PLM program and providing direction to my team. I think a narrative or workbook product to supplement the framework depiction would be most useful. As depicted, the framework provides a thorough analytic approach to establish an effective PLM specifically for ETO projects. I believe the framework could benefit from an additional slide defining each item on the axis.				

F.12 Head of Engineering

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET

Type 26 Wholeship PLM and iBoM Engineering Manager

T 03300460835 | M 07801717714

daniel.mckendry@baesystems.com

BAE Systems Surface Ships Limited

South St, Scotstoun, Glasgow, G14 0XN

Name (optional)…… ….   Position (optional)……Head of Engineering…………….

Company (optional)… ……..Date…04/10/18… Location… …….. Time…15:15………

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				x	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				x	
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					x

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				x	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					x
2.3	The content of the framework can be easily followed.				x	
2.4	The framework appears to be flexible in its use.				x	
2.5	I/we would use this framework to implement PLM on ETO products.					x
	General comments on the framework or research.	The framework as specified is being tailored for use on a number of new/prospective programmes in our organisation. The information, people, process and technology approach has allowed us to focus on the 'real areas of challenge' in terms of PLM implementation, specifically cultural change and enabled process. Overall the framework provides a scalable and tailorable approach that we see as a valid method to implement PLM in a complex environment.				
	General comments on the validation approach.					

F.13 Head of Enterprise Architecture

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

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All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional　　　　　　'osition (optional)..

Company (optional　　　　　　Date.................. Location......................... Time.........................

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					✓
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					✓
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					✓

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					✓
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.					✓
2.5	I/we would use this framework to implement PLM on ETO products.					✓

University of Strathclyde Glasgow

General comments on the framework or research.	Great presentation Key points covered Good to see objectives centred around people / process / information. PLM, configuration control & mgt provides way to comp. advantage.
General comments on the validation approach.	

F.14 Head of IM&T

University of Strathclyde Glasgow

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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BAE Systems Surface Ships Limited
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Name (optional ..Position (optional) HEAD of IM&T

Company (optio ....Date 24/7/19 Location.......................... Time.........................

Please respond to the following statements by using the 5-point rating scale

University of Strathclyde Glasgow

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					✓
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					✓
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					✓

University of Strathclyde Glasgow

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					✓
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.					✓
2.5	I/we would use this framework to implement PLM on ETO products.					✓

University of Strathclyde Glasgow

General comments on the framework or research.	We are currently setting up PLM for the first time in a new company. The framework document hit every point that the current set up workshops are discussing and trying to get resolved. This framework doc hit every aspect of the issues in the PLM install programme ~~today~~ today!
General comments on the validation approach.	

F.15 Underwater systems specialist

University of Strathclyde Glasgow

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional) ..Position (optional) UNDERWATER SYSTEMS SPECIALIST

Company (optio ...Date 24/7/19 Location S...... Time 1505

Please respond to the following statements by using the 5-point rating scale

University of Strathclyde Glasgow

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				✓	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				✓	
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					✓

University of Strathclyde Glasgow

	2. **Framework structure and versatility**	Strongly disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly agree 5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				✓	add culture and it would be strongly agree.
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.					✓
2.5	I/we would use this framework to implement PLM on ETO products.				✓	

General comments on the framework or research.	more emphasis on culture and the (why/ benefits) • cost (through life support) • cost (obscelesense management) • cost (rework) • schedule (rework) • safety (avoid failure due to config) • cost (avoid safety incidents above)
General comments on the validation approach.	

F.16 Programme Director

University of Strathclyde Glasgow

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

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All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET

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BAE Systems Surface Ships Limited

South St, Scotstoun, Glasgow, G14 0XN

Name (optional). Position (optional)....PROGRAM DIRECTOR.................

Company (option .Date July 24/19 Location.......................... Time.........................

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					✓
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				✓	
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					✓

	2. **Framework structure and versatility**	Strongly disagree 1	Disagree 2	Neutral 3	Agree 4	Strongly agree 5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.					✓
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.				✓	
2.5	I/we would use this framework to implement PLM on ETO products.				✓	

University of Strathclyde Glasgow

General comments on the framework or research.	Would be useful to our organization as we begin the implementation process. I appreciate the priority given to the cultural change required for a successful implementation & operation. Would be interested in exposure to next level of detail.
General comments on the validation approach.	

F.17 Deputy Head of Programme Management

University of Strathclyde Glasgow

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

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Name (optional) Position (optional)....CSC Deputy PM..........

Company (optio ..Date 25/4/2019 Location ....

Please respond to the following statements by using the 5-point rating scale

University of Strathclyde Glasgow

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					✓
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.			✓		
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				✓	

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				✓	
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.					✓
2.5	I/we would use this framework to implement PLM on ETO products.				✓	

University of Strathclyde Glasgow

General comments on the framework or research.	Well thought out. Securing support of the business is and will always be a key challenge and very important enabler.
General comments on the validation approach.	All good.

F.18 Systems Engineering Manager

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET
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daniel.mckendry@baesystems.com
BAE Systems Surface Ships Limited
South St, Scotstoun, Glasgow, G14 0XN

Name (optional) Position (optional) Sys Eng Mgr

Company (optiona Date 2019-07-24 Locatio Time 14:00 BST

Please respond to the following statements by using the 5-point rating scale

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.				✓	
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.					✓
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.					✓

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.				✓	
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.			✓		
2.3	The content of the framework can be easily followed.			✓		
2.4	The framework appears to be flexible in its use.			✓		
2.5	I/we would use this framework to implement PLM on ETO products.					✓

University of Strathclyde Glasgow

General comments on the framework or research.	Danny consulted sufficient Industry PLM Companies/ People to come to his thesis conclusions.
General comments on the validation approach.	I would like to learn more on Danny's PLM for ETO products. All in all, very helpful PLM framework

F.19 Engineering Director

University of Strathclyde Glasgow

Product Lifecycle Management (PLM) Implementation framework in Engineer to Order (ETO) products to meet business objectives – Questionnaire

This questionnaire focuses on the framework developed to support the implementation of PLM on ETO products to meet business objectives. Through your experience and knowledge, we intend to identify the validity of the framework.

All responses will be treated in strict confidence and anonymised. Personal information is sought in case there is a need to clarify any information given.

The questionnaire is four pages (including this page). It will take no more than ten minutes to complete. If you have any questions regarding the questionnaire, please do not hesitate to contact me.

Thank you for your participation.

Danny McKendry CEng MIET
Type 26 Wholeship PLM and iBoM Engineering Manager
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South St, Scotstoun, Glasgow, G14 0XN

Name (optional)..   'osition (optional)..ENGINEERING DIRECTOR ....

Company (option   Date.10 Jun 17. Locatior   Time..14:00........

Please respond to the following statements by using the 5-point rating scale

The place of useful learning

	1. **Framework quality**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
1.1	The framework contains the necessary elements for the implementation and successful use of PLM on ETO products.					✓
1.2	The framework assists in overcoming the challenges with implementation and successful use of PLM in ETO products.				✓	
1.3	The framework is effective for the implementation and successful use of PLM in ETO products.				✓	

University of Strathclyde Glasgow

	2. **Framework structure and versatility**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
		1	2	3	4	5
2.1	Using information process, people and technology across objectives, challenges and enablers is a useful way of structuring the framework.					✓
2.2	Information people, process and technology across objectives, challenges and enablers covers all the categories for the implementation successful use of PLM in ETO products.				✓	
2.3	The content of the framework can be easily followed.					✓
2.4	The framework appears to be flexible in its use.				✓	
2.5	I/we would use this framework to implement PLM on ETO products.				✓	

General comments on the framework or research.	Useful to think about the priority and order of implementing I, P, P, T in order to assist the user.
General comments on the validation approach.	Visual poster good. N Vivo themes on responses look sound but dependent on codification validity.

Appendix G Published conference papers from research - International Conference on Computer Applications in Shipbuilding 2015, Bremen, Germany

BUSINESS AND INFORMATION MANAGEMENT ARCHITECTURES FOR DELIVERING PRODUCT LIFECYCLE MANAGEMENT (PLM) IN ENGINEER TO ORDER (ETO) PRODUCTS

DA McKendry, BAE Systems Naval Ships, UK

RI Whitfield and AHB Duffy University of Strathclyde, UK

SUMMARY

BAE Systems Naval Ships is undertaking a comprehensive overhaul of all aspects of its approach to the engineering, design and manufacture of complex warships. Through a partnership with the University of Strathclyde, research is underway on the implementation of Product Lifecycle Management (PLM) to meet organisational objectives. An overview of PLM is provided highlighting the challenges specific to the characteristics of Engineer to Order (ETO) products. These challenges relate to understanding PLM organisational objectives and aligning these with the relevant technology. Central to BAE Systems Naval Ships PLM approach is the Integrated Bill of Materials (iBoM) which is a critical enabler for the organisations transformation objectives. The implementation of the iBoM will be used to develop a framework for implementing PLM to ensure that the technology supports the business objectives of ETO product development, i.e. the integration of business and technology architectures.

1. INTRODUCTION

BAE Systems Naval Ships is the UK’s leading provider of surface ships and through-life support, a world-class industrial partner for the UK Ministry of Defence and a leader in the global market for warships and innovative naval surface ship support.

At BAE Systems Naval Ships, a comprehensive overhaul of all aspects of its approach to the engineering, design and manufacture of complex warships is underway. Significant investment in technology, infrastructure, people and processes is enabling a step change in efficiency, quality and safety, helping to ensure Naval Ships remains competitive and delivers the best value for money to its customers.

BAE Systems has established a long-term partnership with the University of Strathclyde, one of the UK's top centres for engineering research and education. The move aims to encourage close co-operation in the development of advanced maritime research and technology. This paper describes research collaboration between BAE Systems and the University of Strathclyde on the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) Products. The paper demonstrates that a tailored approach to PLM implementation is needed for ETO products to ensure that PLM aligns with the organisation's strategic objectives, related processes, requirements and technology. The paper will provide an overview of PLM followed by a description of specific PLM challenges on ETO products compared to other product types. There will then be a description of the concept of an Integrated Bill of Materials (iBoM) which is a key PLM enabler for achieving BAE Systems Naval Ships transformation objectives. The next step for the research will be to analyse the implementation of the iBoM on a BAE Systems Naval Ships programme with the findings used to develop a framework for implementing PLM as an enabler to technology supporting business objectives on ETO products, i.e. the integration of business and technology architectures

2. PLM OVERVIEW

To realise business objectives in complex new product development requires sophisticated IT systems such as Product Lifecycle Management (PLM), Computer Aided Manufacturing, (CAM) and Computer Aided Design (CAD) [1]. Whilst these technologies bring significant benefits they also introduce new challenges to the organisation, such as balancing design creativity with the robust rules implemented in the system, and the difficulties with managing the configuration of the information across multiple geographical locations. The technologies have enabled organisations that produce large-scale, complex (Engineer to Order) products to become integrators of systems developed in an extended enterprise by the various stakeholders across multiple geographical locations [1,2]. These technologies are a key enabler to BAE Systems Naval Ships ensuring cost and quality improvements for their products considering the challenges of designing complex Naval Ships across an extended enterprise.

Sääksvuori and Immonen describe the benefits of PLM as providing easy access to up-to date, relevant and configured information [3]. This enables tasks such as design or planning to be improved and timescales reduced as the approved information can be presented, used and reused in a more efficient way. PLM supports the extended enterprise by ensuring not only that information is available to all those who require it, but at the same time controlling access to only those who have authority to view or update this information. This is especially true in BAE Systems Naval Ships where the design and build takes place across multiple locations with multiple stakeholders. Information access must be carefully analysed, configured, implemented and managed, to ensure quality and that the organisation is compliant with its security and regulatory obligations.

Information management in the context of PLM is not only to aid the delivery of a configuration chosen by a customer, but to ensure the design, build and support of the product is robust. PLM ensures that during the product's lifecycle, the information is properly structured and that any design changes are highlighted and effectively communicated, aiding improved decision making, decreased approval time, decreased rework and improved quality as relevant information is presented to those who need it when it is required [3]. Robust configuration management processes and technology across the entire project and supply chain are needed, which is a requirement from the high volume of evolving information which affects the design of Naval Ships, resulting in a critical need to capture, understand, communicate and action new information concurrently with the design, manufacture and support phases. A full audit history of the timing and responsibility of change is critical for decision traceability. This not only contributes to the organisation's knowledge but is also necessary for managing the maturity of the design and to support business measurement for targeting areas for improvement.

These descriptions and benefits can be summed up as PLM being a product centric business model which is supported by Information Management Technology (IMT) across the entirety of a product's lifecycle, involving people, processes and organisations in order to achieve a product performance or service goal [4]. Brunsmann and Wilkes describe the main goal of PLM as supporting the integration of people, information, process and systems, to provide an information backbone to the business [5]. What is certain is that "IT Applications that support PLM have assumed critical importance as companies focus on enhancing the efficiency and effectiveness of their innovation across the enterprise" [6]. These benefits are especially important for major defence products given the limited budgets but increasing demand for advanced capability [7].

It's important to distinguish between the concept of PLM and the supporting technology. PLM is often mistakenly confused with the PLM technology, when in fact the technology is there to support the people, process and product objectives of the organisation. The supporting technology, or PLM System, is typically referred to as a Commercial off the Shelf (COTS) product which aims to provide a single vendor integrated solution to meet all the PLM needs of an organisation, often by acquiring and integrating smaller commercial solutions into their overall suite of systems. A single solution which meets all the needs of an organisation throughout the lifecycle of the product is not yet available; a more accurate representation of a PLM system is a series of interconnected applications, or systems of systems, which perform various functions throughout the lifecycle of the product across the extended enterprise [4]. These interconnected systems have their own integration challenges resulting in numerous examples in industry where the COTS products are heavily customised by the organisation to meet their capability needs within a single solution. They can be integrated for data exchange and reporting purposes through a backbone such as a data warehouse where the information is structured and represented based on the source PLM systems [8]. An important requirement of a PLM system is to capture information and to provide traceability throughout the lifecycle of the product [9] including providing version and audit management of the product information [10]. This information should be 'smart' to ensure that it can be used effectively and to support the transformation into knowledge [9]. Capturing this information across the lifecycle of the product in the PLM system will support design reuse through managing the configuration of the design and its intent [5]. This reuse is supported through the relationships with supporting documentation and workflows, ensuring that when engineers change roles, retire or leave the organisation, the legacy of their work can be exploited in the future [5].

Changes to the traditional nature of Naval Shipbuilding have resulted in the transformation from a design/manufacture perspective to include the product's behaviour in-service and after sales support, which is driven by the customer's need to increase quality and reduce costs. This product-service paradigm means that information management technology must be robust enough to last the entire lifecycle of the product from concept through to disposal [11]. Ensuring that this information can be robustly stored, controlled and reused has been an area of research for industry and academia over the last decade [12-14] and has been identified as being a way to increase revenue and customer satisfaction, for both the product provider and customer [15].

PLM Systems are now seen as a mandatory element in reducing risk in large-scale, complex, long-life products by supporting virtual simulation and prediction [16]. This is especially true with defence products which have to undertake rigorous inspection and auditing in not only the virtual and physical elements but also with the supporting decision making information [7].

In their 2012 PLM market analysis report, CIMData stated that PLM implementation was extremely challenging and expensive with $29.9 billion being invested in PLM in 2011 of which $19.1 billion (64%) of that was in the applications themselves. Despite these investments, few companies have realised the projected benefits [6]. There are numerous reasons for the varying degrees of success including the organisation focusing on individual aspects of PLM and failing to take a holistic approach. This may be due to the organisation failing to really understand what PLM means [17]. There are gaps in literature and research relating to PLM [17] highlighting a lack of detailed research into actual PLM implementations [18]. There is also the challenge of understanding which functionality should be adapted to support the business processes, and which processes should be adapted to support the functionality [3]. This is a key point as often organisations will turn to system vendors or internal analysts/programmers to solve their PLM problems, which leads to heavy customisation of the PLM systems, and in turn results in the organisation assuming more ownership of these systems, impacting on-going support and future upgrades [19].

When implementing PLM, the organisation should first understand its strategic objectives and core processes and use this to decide on the PLM approach, which in turn should influence the PLM system implementation. This is certainly not trivial as the alignment of business objectives, process and functionality is one of the key challenges to PLM implementation [20] and is an area that the PLM systems vendors have difficulty in resolving [17]. This may be due to a lack of understanding on the part of the PLM system vendors with regard to their customer's needs, which may in turn be due to a customer's inability to understand their own relationship between strategic objectives, process and technology requirements. Therefore it is clear that further research is required in the implementation of the technology to align with the organisation's processes and the strategic vision, with problems arising tracking performance and quality across the extended enterprise [1]. Without this research, the organisation will suffer the fate impacting other major enterprise IT investments, that of a disconnect between the investment in IT itself and lack of return in business value due to problems with aligning IT with other aspects of the organisation [6].

3. CHALLENGES WITH ENGINEER TO ORDER NEW PRODUCT DEVELOPMENT

Engineer to Order products, such as Naval Shipbuilding are extremely challenging due to their unique characteristics and challenges, these are described below:-

Complexity and uncertainty

The level of complexity is one of the greatest challenges to manage within the development of ETO products as they have a large number of different types of elements interacting across its lifecycle in difficult to predict ways. Complex systems can be described as being unpredictable as a result of change within their operating environment, which differs from complicated systems where there are many interactions between the elements of the system but they can be predicated and understood. A naval ship can be described as being complicated in its operational behaviour as a product but is highly complex in its design, manufacture and support due to its unpredictability throughout its lifecycle, meaning that its complexity varies through life.

Customer interaction and procurement

The delivery lead-time for ETO products is considerably longer than other product types as the design and subsequent procurement is developed to satisfy the customer requirements [21]. These delivery lead-times relate to the commitment from a customer on the order. Customers generally commit earlier within ETO projects, this is often called the customer order de-coupling point [22] or order penetration point [23]. The customer in ETO products commits to the order early in the design lifecycle and therefore has a significant input into the design, manufacture and procurement strategies, such as insisting on a supplier tendering process for each programme.

Product Customisation

Hicks and McGovern state that ETO products have a high level of customisation due to their low volume and high-complexity [2]. This results in higher levels of risk relating to longer lead times and increased costs. They also state that the structure of ETO products consists of a mixture of supplier systems that are both designed bespoke or heavily customised to perform a specific function, and are subject to a unique and specific set of requirements such as a weapons systems on a naval ship. These are alongside aspects of the design which are commercially available off-the-shelf, which are subject to a more general set of requirements such as valves. This mixture results in various degrees of complexity in the design and manufacturing process, where the design is managed through careful interaction with the suppliers, which is achieved using contract management principles and sporadic data flow through the lifecycle of the product.

Bill of Materials (BoM), change and maturity management

Customer commitment early in the design lifecycle requires significant product information management to ensure the evolution of the design is managed to conform to their specific requirements. The Bill of materials (BoM) is well defined within MTS and ATO products once manufacturing begins, which means that there are few emergent patterns to contend with during the manufacturing planning and execution phases [24]. Naval ship products have an evolving BoM where the product information gradually matures and requires careful management due to the emerging variables and its dynamic nature [24], these variables include changes due to the evolving supplier information which impacts the design, such as the size of a gas turbine increasing which in turn affects the space allocated in the compartment. In naval ship new product development, the manufacturing phase begins before the BoM is fully mature, in order to reduce the overall design and manufacturing lifecycle. Therefore changes to the BoM can have an extensive impact to the schedule and cost of the product if not managed effectively [24]. The impact of these changes increases as the design and manufacturing lifecycle evolves due to the locked-in costs. The more mature the lifecycle phases the more rework is required which will have a potentially considerable impact on the product’s development cost and schedule. Hicks and McGovern describe standard product development as a structured evolution from concept, design and manufacturing [2]. However in ETO products this is a highly iterative process which results in change in areas such as the design, manufacturing, contracts with supplier and customer, and with the cost model. Due to the close interaction with the various stakeholders, these changes must be analysed, understood and managed carefully, with impact-assessment being one of the key techniques used to support this management. Hicks and McGovern go onto say that whilst there is considerable research into change management there is little with direct relevance to ETO products [2].

Project management

Amongst the challenges of ETO delivery are the complexity of the product due to emerging patterns which impact the initial cost estimations and requirements resulting in cost increases and schedule overruns

[25]. These complexities require consideration within project management for the design, manufacture and in-service support of these products [25]. This recognition of the need for robust project management reflects a history of considerable schedule and cost overruns on ETO products. This results in a need for more advanced project management principles beyond those normally applied to less complex products relating to risk, schedule, resource and governance management [26]. These are used to support specialised production processes that have widely varying operational types spread across an activity driven schedule, which are based on the lifecycle of the product [27]. The challenges relate to the difficulty in taking a bottom-up approach to estimating and establishing plans for these products. These are the norm in other engineering and construction projects [28], which is due to the characteristics of ETO product delivery such as the emerging patterns and lack of prototypes that require a means of contingency and risk management which are difficult to predict and manage. The lifecycle of these products mean that the requirements are at a very high-level before a gradual transformation into a physical product over a long period of time; this transition introduces changes to the product which affect the cost and schedule estimates [28]. The extent of the project management challenges has been highlighted by Merrow: 65% of 300 projects with a budget bigger than $1B failed to meet their objectives, whether it's safety, cost, schedule or realising the primary function of the product [29].

No prototype

With ETO products there is a critical need to ensure that it is 'right-first-time' due to the lack of a prototype which in turn is due to the small number of similar products produced [7]. Typically prototyping allows error removal and efficiency improvements through their various iterations, this includes aspects relating to the design, manufacture and in-service support. While considerable design and planning is undertaken prior to a prototype being developed, before actual mass production is started the prototypes have proven the design and manufacturing process and demonstrated the concept. In comparison, a first of class (FOC) naval ship begins manufacturing prior to the design being completed. It would therefore be accurate to state that an FOC naval ship is both a prototype as well as a delivered product. PLM plays a significant role in virtual prototyping in conjunction with the 3D CAD models, allowing for visualisations of the product to be produced, but there are no physical prototypes produced prior to the FOC. Automotive and Aerospace in comparison have prototypes created prior to the production-line generating actual products.

4. PLM AS AN ENABLER TO TRANSFORMATION

As described above PLM is a critical enabler to the successful new product development process for Engineer to Order products due to their unique characteristics and challenges. BAE Systems Naval Ships has implemented an approach to manage these challenges for Naval Shipbuilding. The core of the PLM approach is the concept of an Integrated Bill of Materials (iBoM). The vision for the iBoM is: 'an integrated Bill of material which evolves throughout the products lifecycle to enable the business objectives of all of the stakeholders'.

This means that Naval Ships will create BoMs for each stage of the lifecycle that are aligned, integrated, are timely, and do not need translating at the point of use. This will enable significant benefits to all activities which rely on quality product information. There are a number of key business objectives of which the iBoM is a key enabler, these include:

Maturity management to support product evolution and cost/schedule adherence

The iBoM is the backbone to the maturity measurement and management approach for Naval Ships. In order to enable active management of the parts, and their associated data within the iBoM, a policy has been developed to capture and measure maturity, such as with Geometry, Electrical Data, Wild Heat; Weight, Provenance etc. These not only enable individual use of the BoM data to feed key engineering activities such as the design review programme, but they will also serve as a foundation to enable maturity measurement at spatial (e.g. compartment) and system level.

Cross functional BoM hierarchies

As shown in Figure 1 the iBoM consists of a number of hierarchies that break the product definition down in ways appropriate to different business needs. These hierarchies are interdependent forming an integrated Bill of Material. This is achieved by using a common set of configured items to identify part usage across multiple hierarchies. These configured items uniquely identify every usage of each part within the Parts Catalogue and link to applicable hierarchies to create a cross functional product definition. They include: Design, Planning, Operations and Support

Association of related BoM elements

Where there are instances of the design which relate to one another but require to be configured in their own right, they will be related and managed through the iBoM. Examples include seats or mounts for equipment, contents of a server or those which constitute a module.

PDM as the Master

First time quality will be improved by reducing waste and change within Engineering, Operations and Supply Chain caused by inadequate alignment to engineering product data between CAD, PDM and ERP. This is shown in figure 1.

The benefits of this approach are:

- Significant reduction in waste and rework from misalignment of the product data, the consequential cost of change and ensures Engineers spend more time focussed on value-add activities to improve the quality of the product.
- Toolset rationalisation to reduce data duplication, misalignment of data and technology costs
- A key enabler to the reduction in the cost of product change management
- PDM as the means to drive the population of ERP
- Enables a full BoM in the PDM system to support other initiatives, e.g. Digital Planning, Completions Management, PDM to ERP etc.

Digital Planning

An integrated Bill of Material which identifies the product breakdown to an installable level, and accurately describes their maturity, enables planning activities to be undertaken 18-24 months earlier than is traditionally the case. As shown in figure 1, this coupled with a 3D visualisation of the model, means that work sequencing can be planned earlier and data pushed to ERP when the maturity is deemed to be at the required level.

Design for support

Traditionally there have been issues with capturing and managing in-service support product data that have caused the transition of BoM management between the design and build phases into in-service support to be problematic. These include:

- Not effectively capturing the required Support data against the BoM, resulting in misalignment and quality issues
- A lack of transition planning, including responsibilities and process, between the Design & Manufacture and the In-Service Support teams;
- A lack of coherence between Naval and design numbering structures,
- Maintainable level parent and child relationships not being captured in the BoM prior to the handover point;
- Different IT systems used for the management of the BoM.

As shown in figure 1 the iBoM will address these concerns by:

- Maintainable parent and child breakdown and associated data from the supply chain which will be captured and integrated with the design configuration
- Use of in-service support numbering convention for BoM occurrences.
- Use the same capability for iBoM management within the in-service environment
- No duplication of data between design and support systems therefore no misalignment and quality issues

Supply chain data capture and delivery

A requirement for PLM is to reduce manual data entry and improve data quality, particularly with the supplier information. The iBoM will incorporate a mechanism to support the receipt and verification of supplier equipment information, as shown in figure 1. This enables the capturing of supplier equipment attributes and breakdown, which in turn can be easily reviewed and when approved automatically implemented into the PDM system, thus significantly reducing review, data entry and quality issues. The key benefits of this approach are:

- Increase in data quality from the supplier
- Reduction in same data being requested (and paid for) more than once
- Engineering no longer have to manually update supplier information into the PDM System
- Reduces queries with suppliers
- Full Parent/child breakdown of Part captured and automatically loaded into the iBoM for support and damage/loss activities
- Reduces timescales for review and verification of supplier data
- Comprehensive attribution of Parts for Engineering, Support, Planning and Supply Chain

Repeatable manufacturing identification

One of the key PLM enablers for business transformation is using the iBoM is to support the identification and management of repeatable manufacturing processes to reduce the number of bespoke activities during build, as shown in figure 1. The benefits of this approach are:

Build

- Reduced Norms through defined\simpler designs & developing specialised processes
- Eliminate process redundancy/unnecessary investment
- Standard operating procedures & improved safety

Engineering

- Reduced design effort - pick from a controlled, refined product catalogue or design within known boundaries
- Spatial requirements defined , reduced rework

Supply chain

- Reduced material variation and greater order volumes thus reducing cost
- Reduced inventory foot print, and easier part management
- Defined design characteristics for re-sourcing like products

In-service support

- Reduced inventory cost\footprint for in-service support and enabling commonality across the fleet vessels
- Standard operating methods for removal and refit

Planning

- Predefined routings to support Digital Planning & reduce planning at quarterly look-aheads
- Enables planning focus on the bespoke activities
- Earlier & more accurate capacity planning

PLM is central to meeting the transformation objectives of BAE Systems Naval Ships, with the iBoM implementation a critical enabler. An approach to the successful implementation of PLM for ETO products can be generated by examining the implementation of the iBoM.

5. ALIGNING BUSINESS OBJECTIVES WITH TECHNOLOGY

Enterprise Architecture (EA) provides a potential approach to PLM implementation within ETO product development as it is designed to facilitate the alignment of business objectives and organisational models/processes (business architecture) with technological capability (technology architecture). Amongst the benefits of using EA is the capture of an as-is problematic state and a targeted to-be environment which aids greatly in managing the transition and capturing the organisational complexity.

EA supports the creation of information describing the business strategy, model, process and technology in an organisation. This allows a business to manage a major undertaking, such as remodelling a complicated design and manufacturing process, by splitting it up into smaller chunks [30]. These smaller elements are documented and their relationships captured, which enables an improved view and understanding of the relevant aspects of the business, thus supporting an improved decision making environment [31].

One of the key challenges with EA is the link between the business and the technology architectures. Research has been undertaken to provide guidance on integrating business and technology architectures and also to validate the importance of aligning business strategy with technology investment [6, 32], but not in the context of implementing PLM for ETO Products.

The business architecture focusses on people and process to meet the needs of the product or management of the product delivery, and to produce resultant requirements to move to an improved position. The technology architecture links the technology required to enable the requirements identified through the business architecture. In order to realise the business value required by the technology, the investment must ensure alignment between the organisational context and the IT itself, so that they complement each other [6]. Further research is required to identify the level of connection both environments should share in the context of PLM implementation in ETO products. This gap is identified as a significant problem in both industry and supporting literature, with little research on solving the problem.

The implementation of the iBoM will be piloted on a BAE Systems Naval Ships programme with the benefits measured and compared across multiple ships. The results will be analysed and the findings used to improve the realisation of the BAE Systems Naval Ships transformational objectives. In collaboration with the University of Strathclyde a framework for the successful implementation of PLM as an enabler for the integration of business and technology architectures for Engineer to Order products will be developed.

6. CONCLUSION

ETO products have considerable challenges to overcome when implementing PLM to meet organisational objectives. These are described as:-

- complexity and uncertainty
- customer interaction and procurement
- product customisation
- BoM, change and maturity management
- project management
- no prototype.

PLM is central to BAE Systems Naval Ships achieving its transformation objectives, with the iBoM being a critical enabler. In partnership with the University of Strathclyde a framework to successfully implement PLM on ETO products will be developed using Enterprise Architecture principles.

7. REFERENCES

[1] R.L. Nolan, Ubiquitous IT: The case of the Boeing 787 and implications for strategic IT research, The Journal of Strategic Information Systems, 21 (2) (2012) 91-102.

[2] C. Hicks, T. McGovern, Product life cycle management in engineer-to-order industries, International Journal of Technology Management, 48 (2) (2009) 153-167.

[3] A. Saaksvuori, A. Immonen, Product Lifecycle Management, Springer, New York, 2008.

[4] S. Terzi, A. Bouras, D. Dutta, M. Garetti, Product lifecycle management - from its history to its new role, International Journal of Product Lifecycle Management, 4 (4) (2010) 360-389.

[5] J. Brunsmann, W. Wilkes, Enabling product design reuse by long-term preservation of engineering knowledge, International Journal of Digital Curation, 4 (3) (2009) 17-28.

[6] R.G. Fichman, S. Nambisan, Deriving Business Value from IT Applications in Product Development: A Complementarities-Based Model, Information Technology and Product Development, (2009) 19-47.

[7] D.K. Oh, Y.H. Jeong, Y.G. Kim, J.G. Shin, Y.H. Yeo, C. Ryu, Development of product model management system for naval shipbuilding, Journal of Ship Production, 24 (2) (2008) 82-91.

[8] J. Stark, Product Lifecycle Management: 21st century paradigm for product realisation, 2nd ed., Springer-Verlag, London, 2011.

Science in Engineering, 5 (3) (2005) 227-237.

[9] A. Matsokis, D. Kiritsis, An ontology-based approach for Product Lifecycle Management, Computers in industry, 61 (8) (2010) 787-797.

[10] D. Tang, X. Qian, Product lifecycle management for automotive development focusing on supplier integration, Computers in Industry, 59 (2) (2008) 288-295.

[11] R. Oliva, R. Kallenberg, Managing the transition from products to services, International Journal of Service Industry Management, 14 (2) (2003) 160-172.

[12] A. Ball, M. Patel, C. McMahon, S. Culley, S. Green, J. Clarkson, A grand challenge: Immortal information and through-life knowledge management (KIM), International Journal of Digital Curation, 1 (1) (2006) 53-59.

[13] B.J. Hicks, S.J. Culley, R.D. Allen, G. Mullineux, A framework for the requirements of capturing, storing and reusing information and knowledge in engineering design, International Journal of Information Management, 22 (4) (2002) 263-280.

[14] S. Sivaloganathan, T. Shahin, Design reuse: an overview, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 213 (7) (1999) 641-654.

[15] R. Roy, E. Shehab, A. Tiwari, Y. Mey Goh, C. McMahon, Improving reuse of in-service information capture and feedback, Journal of Manufacturing Technology Management, 20 (5) (2009) 626-639.

[16] T.L. Briggs, T.C. Rando, T.A. Daggett, Reuse of ship product model data for life-cycle support, Journal of Ship Production, 22 (4) (2006) 203-211.

[17] G. Schuh, H. Rozenfeld, D. Assmus, E. Zancul, Process oriented framework to support PLM implementation, Computers in Industry, 59 (2) (2008) 210-218.

[18] M. Bokinge, J. Malmqvist, Challenging Requirements Management Issues in PLM Implementation-Findings from a Retrospective Case Study, in, 8th International Conference on Product Lifecycle Management-PLM11, Eindhoven, The Netherlands, 2011.

[19] R.M. Rangan, S.M. Rohde, R. Peak, B. Chadha, P. Bliznakov, Streamlining product lifecycle processes: a survey of Product Lifecycle Management implementations, directions, and challenges, Journal of Computing and Information

[20] M. Bokinge, J. Malmqvist, PLM implementation guidelines - relevance and application in practice: a discussion of findings from a retrospective case study, International Journal of Product Lifecycle Management, 6 (1) 79-98.

[21] R.B. Handfield, Effects of concurrent engineering on make-to-order products, Engineering Management, IEEE Transactions on, 41 (4) (1994) 384-393.

[22] A. Haug, K. Ladeby, K. Edwards, From engineer-to-order to mass customization, Management Research News, 32 (7) (2009) 633-644.

[23] J. Wikner, M. Rudberg, Integrating production and engineering perspectives on the customer order decoupling point, International Journal of Operations & Production Management, 25 (7) (2005) 623-641.

[24] J.H. Lee, S.H. Kim, K. Lee, Integration of evolutional BOMs for design of ship outfitting equipment, Computer-Aided Design, 44 (3) 253-273.

[25] A. Van Marrewijk, S.R. Clegg, T.S. Pitsis, M. Veenswijk, Managing public–private megaprojects: Paradoxes, complexity, and project design, International Journal of Project Management, 26 (6) (2008) 591-600.

[26] S. Floricel, R. Miller, Strategizing for anticipated risks and turbulence in large-scale engineering projects, International Journal of Project Management, 19 (8) (2001) 445-455.

[27] R. Sharma, T.W. Kim, Development of a logic-based product life-cycle management (LBPLM) system for shipbuilding industry—conceptual development, Journal of Ship Production and Design, 26 (4) (2010) 231-251.

[28] E.W. Merrow, L.M. McDonwell, R.Y. Arguden, Understanding the outcome of Megaprojects, in, Santa Monica, USA. The Rand Corporation, 1988.

[29] E.W. Merrow, Industrial megaprojects: concepts, strategies, and practices for success, Wiley, Chichester, UK, 2011.

[30] L.K. Griffin, Analysis and comparison of DoDAF and ZACHMAN framework for use as the architecture for the United States Coast Guard's maritime patrol (WPC), in, Naval Postgraduate School, Monterey, USA. , 2005.

[31] R.M. Foorthuis, F. Hofman, S. Brinkkemper, R. Bos, Assessing business and IT projects on compliance with enterprise architecture, Proceedings of GRCIS 2009, CAiSE Workshop on Governance, Risk and Compliance of Information Systems, (2009).

[32] Y.E. Chan, S.L. Huff, D.W. Barclay, D.G. Copeland, Business strategic orientation, information systems strategic orientation, and strategic alignment, Information Systems Research, 8 (2) (1997) 125-150.

8. AUTHOR'S BIOGRAPHY

Danny McKendry holds the position of Product Lifecycle Management (PLM) and Integrated Bill of Material (iBoM) Engineering Manager at BAE Systems Naval Ships. Prior to his current role he was the Information Management and Technology (IM&T) Manager for the Type 26 Global Combat Ship with BAE Systems Naval Ships. Danny has over 25 years' experience in large-scale, complex, Engineer to Order products. He has a BSc in Computer Aided Engineering, an MSc in Manufacturing: Management and Technology and an MBA. At the time of publication he is a 4th year part-time PhD student with the DMEM faculty of the University of Strathclyde with research focusing on PLM implementation in Engineer to Order products.

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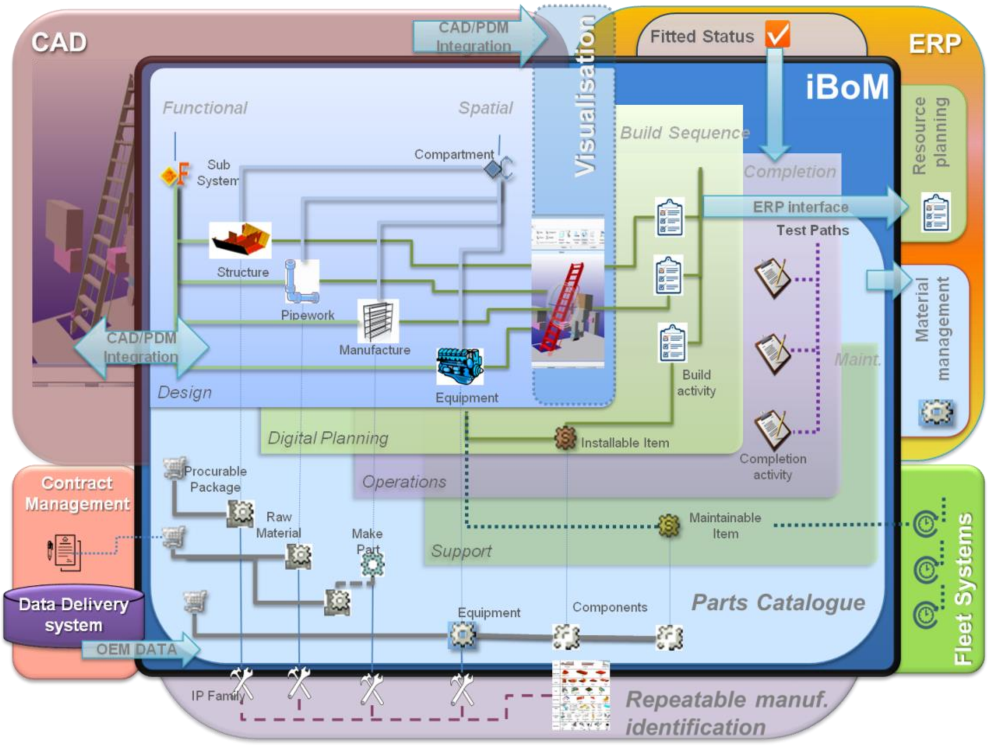

Figure 1 the iBoM and its relationships within the BAE Systems Naval Ships PLM concept

Appendix H Published conference papers from research - International Conference on Manufacturing Research 2017, London

Key Findings to Support the Development of a Framework for the Implementation of Product Lifecycle Management in Engineer to Order Products

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Abstract. BAE Systems Naval Ships has undertaken a comprehensive overhaul of all aspects of its approach to the engineering, design and manufacture of complex warships. Through a partnership with the University of Strathclyde, research has been completed on the implementation of Product Lifecycle Management (PLM) to meet organisational objectives in the development of Engineer to Order (ETO) products. Engineer to Order (ETO) products include characteristics such as high capital value, large-scale, long-life, no prototype, highly customised and few or one off. An overview of PLM is provided highlighting the challenges specific to the characteristics of ETO products. The paper then provides a summary of the key findings of approximately 30 semi-structured interviews with leading industry personnel, in the UK and internationally, on PLM implementation in ETO products. These participants are engaged with PLM in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation. The findings have been used to support the development of a framework to ensure that PLM implementation supports the business objectives of ETO product development.

Keywords. Product Lifecycle Management, PLM, Engineer to Order, ETO

1. Introduction

BAE Systems Naval Ships is the UK's leading provider of complex warships and through-life support, a world-class industrial partner for the UK Ministry of Defence and a leader in the global market for warships and innovative naval warship support.

At BAE Systems Naval Ships, a comprehensive overhaul of all aspects of its approach to the engineering, design and manufacture of complex warships has been undertaken. Significant investment in technology, infrastructure, people and processes is enabling a step change in efficiency, quality and safety, helping to ensure Naval Ships remains competitive and delivers the best value for money to its customers.

BAE Systems has established a long-term partnership with the University of Strathclyde, one of the UK's top centres for engineering research and education. The partnership aims to encourage close co-operation in the development of advanced maritime research and technology. This paper describes research collaboration between BAE Systems and the University of Strathclyde on the implementation of Product Lifecycle Management (PLM) on Engineer to Order (ETO) Products. The paper demonstrates that a tailored approach to PLM implementation is needed for ETO products to ensure that PLM aligns with the organisation's strategic objectives, related processes, requirements and technology. The paper provides an overview of PLM followed by a description of specific PLM challenges on ETO products compared to other product types. The paper summarises the key findings of approx. 30 semi-structured interviews with leading industry personnel, in the UK and internationally, on PLM implementation in ETO products. These participants are engaged with PLM in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation. The findings have been used to support the development of a framework to ensure that PLM implementation supports the business objectives of ETO product development

2. PLM Overview

Sääksvuori and Immonen describe the benefits of PLM as providing easy access to up-to-date, relevant and configured information [1]. This enables tasks such as design or planning to be improved and timescales reduced as the approved information can be presented, used and reused in a more efficient way. PLM supports the extended enterprise by ensuring not only that information is available to all those who require it, but at the same time controlling access to only those who have authority to view or update this information. This is especially true in BAE Systems Naval Ships where the design and build takes place across multiple locations with multiple stakeholders. Information access must be carefully analysed, configured, implemented and managed, to ensure quality and that the organisation is compliant with its security and regulatory obligations.

Information management in the context of PLM is not only to aid the delivery of a product configuration chosen by a customer, but to ensure the design, build, support and disposal is robustly managed. PLM ensures that during the product's lifecycle, the information is properly structured and that any design changes are highlighted and effectively communicated, aiding improved decision making, decreased approval time, decreased rework and improved quality as relevant information is presented to those who need it when it is required [1]. Robust Configuration Management processes and technology across the entire project and supply chain are needed, which is a requirement from the high volume of evolving information which affects the design of Naval Ships, resulting in a critical need to capture, understand, communicate and action new information concurrently with the design, manufacture and support phases. A full audit history of the timing and responsibility of change is critical for decision traceability. This not only contributes to the organisation's knowledge but is also necessary for managing the maturity of the design and to support business measurement for targeting areas for improvement.

These descriptions and benefits can be summed up as PLM being a product centric business model which is supported by Information Management Technology (IMT) across the entirety of a product's lifecycle, involving people, processes and organisations in order to achieve a product performance or service goal [2]. Brunsmann and Wilkes describe the main goal of PLM as supporting the integration of people, information, process and systems, to provide an information backbone to the business [3]. What is certain is that "IT Applications that support PLM have assumed critical importance as companies focus on enhancing the efficiency and effectiveness of their innovation across the enterprise" [4]. These benefits are especially important for major defence products given the limited budgets but increasing demand for advanced capability [5].

When implementing PLM, the organisation should first understand its strategic objectives and core processes and use this to decide on the PLM approach, which in turn should influence the PLM system implementation.

3. Challenges with Engineer to Order New Product Development

Engineer to Order products, such as first of class Naval Ships, require careful consideration of the PLM implementation approach due to their unique characteristics and challenges. The unique nature and related challenges require PLM implementation to be tackled differently compared to other product types, e.g. aerospace or automotive [6]. A summary of ETO challenges are described below.

3.1. Complexity and uncertainty

The level of complexity is one of the greatest challenges to manage within the development of ETO products as they have a large number of different types of elements interacting across its lifecycle in difficult to predict ways.

3.2. Customer interaction and procurement

The customer in ETO products commits to the order early in the design lifecycle and therefore has a significant input into the design, manufacture and procurement strategies, such as the supplier tendering process for each programme.

3.3. Product Customisation

ETO products have a high level of customisation due to their low volume and high-complexity [7]. If incorrectly managed this will result in higher levels of risk relating to longer lead times and increased costs.

3.4. Bill of Materials (BoM), change and maturity management

Customer commitment early in the design lifecycle requires significant product information management to ensure the evolution of the design is managed to conform to their specific requirements. Naval ship products have an evolving Bill of Material (BoM) where the product information gradually matures and requires careful configuration and change management.

3.5. Project management

Amongst the challenges of ETO delivery are the complexity of the product due to emerging patterns which impact the initial cost estimations and requirements resulting in cost increases and schedule overruns [8].

3.6. No prototype

With ETO products there is a critical need to ensure that it is 'right-first-time' due to the lack of a prototype which in turn is due to the small number of similar products produced [5]. Typically physical prototyping allows error removal and efficiency improvements through their various iterations, this includes aspects relating to the design, manufacture and in-service support which are not possible for ETO products.

4. PLM Implementation Research

BAE Systems Naval Ships has made significant improvements on its approach to PLM including process, information and toolset integration, and its data quality methodology [6]. Through the partnership with the University of Strathclyde, research has been completed to create a framework for PLM implementation guidelines for large-scale, complex, long-life, no prototype, highly customised, one-of/few-of a kind Engineer to Order products to meet organisational objectives. This section will provide a high level summary of aspects of the research findings.

4.1. The approach undertaken to capture PLM Implementation findings

Approximately 30 semi-structured interviews on PLM implementation were undertaken with senior personnel from 10 ETO related organisations in the UK and internationally. A set of questions were developed to identify the key objectives and challenges of PLM implementation on ETO products as well as the enablers to ensure their success. The interviewees were selected based on their relationship with PLM in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation. To generate the results of the interviews, Thematic Analysis was used as a means to codify and generate themes [9]

4.2. Summary of selected findings

The findings were categorised into those related to information, process, people and technology and are in line with Brunsmann and Wilkes recommendations. A summary of the findings for PLM implementation enablers are stated below.

4.2.1. Information

- Develop a policy to capture what information is required and how it will be used for an evolving complex product. This is to ensure organisational resources are focused on the capture, management and presentation of meaningful information.

- Create a central team with suitably qualified and experienced personnel (SQEP) for PLM information integration, policy development, standardisation, learning from experience (LFE) and adherence across the organisation.

- Develop a Data Quality and Governance policy, team and adherence approach. This is to ensure when PLM is implemented those data rejections and errors across an integrated environment are captured, analysed and rectified.

- Develop a Configuration and Change Management approach across ETO product classes and variants. Configuration Management is a mandatory requirement in major new product development but this must be focused on the specific challenges in ETO products as described in this paper.

4.2.2. Process

- Create a central team with SQEP for PLM business process ownership, development, standardisation, LFE and adherence across the organisation.

- Implement guidelines and governance over processes to ensure they are simple and usable thereby reducing complexity. This is due to overly complex processes often being introduced to manage the challenges in ETO product development, such as with electronic workflows.

- Mandate utilisation of PLM processes internally, for partners and the supply chain. This should be embedded with the engineering business model, and its related processes, and is to ensure that all stakeholders adhere to the PLM approach introduced into the programme.

- Implement sustainable benchmarking across related industries and vendors for ongoing business improvement and confidence. This is to ensure that the PLM approach undertaken is tested against best practice to maintain quality, reduce risk and to provide ongoing confidence.

4.2.3. People

- Capture and provide continuing evidence of PLM benefits to senior management to enable support and maintain sponsorship. PLM implementation is costly and high risk, therefore senior management must not only be convinced of the benefits initially, but must continually be presented with the benefits of the approach across the ETO lifecycle.

- Develop and implement a comprehensive business change initiative on PLM. The implementation of PLM will result in new processes, information and toolsets which will have an impact on the people within the organisation such as those moving from another ETO product where they have used a different approach for many years.

- Develop and implement a cross functional PLM education programme, embedded within the core business training approach, emphasising core values and objectives. This is to ensure that PLM education is not just focused on processes and toolset training but is integrated with the business culture.

- Provide PLM support and training to partners and the supply chain. It is often the case that those outside the core organisation are not given the required support to ensure the success of the PLM implementation.

- Create a central team with SQEP to develop PLM objectives, education and support to the business. This will assist in utilising key resources to deliver the enablers for successful implementation of PLM.

4.2.4. Technology

- Identify and implement configurable PLM toolsets with minimal customisation. Due to the long lifecycle of ETO product development, customisations will otherwise impact the ability of the toolsets to be maintained and upgraded, resulting in considerable risk to the programme.

- Drive integration of information through toolset rationalisation. This will force otherwise disparate information sources to be integrated into the core toolsets

- Focus toolset development on business objectives, priorities and ease of use to reduce complexity of technology and processes. This should be managed through a central PLM approval authority.

- Scale and implement IT architecture improvements to support new ways of working and ensure toolset performance, especially focusing on large volumes of data. This is to ensure IT architecture is maintained against information growth and toolset integration.

5. Conclusion and next steps

ETO products have considerable challenges to overcome when implementing PLM to meet organisational objectives. PLM is central to BAE Systems Naval Ships approach to delivering world class products and through the partnership with the University of Strathclyde a framework to successfully implement PLM on ETO products has been developed and validated.

References

[1] A. Saaksvuori, A. Immonen, Product Lifecycle Management, Springer, New York, 2008.

[2] S. Tersi, A. Bouras, D. Dutta, M. Garetti, Product lifecycle management - from its history to its new role, International Journal of Product Lifecycle Management, 4 (4) (2010) 360-389.

[3] J. Brunsmann, W. Wilkes, Enabling product design reuse by long-term preservation of engineering knowledge, International Journal of Digital Curation, 4 (3) (2009) 17-28.

[4] R.G. Fichman, S. Nambisan, Deriving Business Value from IT Applications in Product Development: A Complementarities-Based Model, Information Technology and Product Development, (2009) 19-47.

[5] D.K. Oh, Y.H. Jeong, Y.G. Kim, J.G. Shin, Y.H. Yeo, C. Ryu, Development of product model management system for naval shipbuilding, Journal of Ship Production, 24 (2) (2008) 82-91.

[6] McKendry, D., R. Whitfield, and A. Duffy, Business and information management architectures for delivering Product Lifecycle Management (PLM) in Engineer To Order (ETO) products, International Conference in Computer Applications for Shipbuilding. 2015, RINA: Bremen.

[7] Hicks, C. and T. McGovern, Product lifecycle management in engineer-to-order industries. International Journal of Technology Management, 2009. 48(2): p. 153-167.

[8] A. Van Marrewijk, S.R. Clegg, T.S. Pitsis, M. Veenswijk, Managing public–private megaprojects: Paradoxes, complexity, and project design, International Journal of Project Management, 26 (6) (2008) 591-600.

[9] Braun, V. and V. Clarke, Using thematic analysis in psychology. Qualitative research in psychology, 2006. 3(2): p. 77-101.