Product Lifecycle Management implementation for high value Engineering to Order programmes: an informational perspective.

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Abstract

This paper presents the first ever framework for implementing Product Lifecycle Management within high value Engineering to Order programmes. 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 system implementation. The research first 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. Thematic analysis of 27 semi-structured interviews was used to develop the framework to address these challenges. The interviewees were selected based on their relationship with PLM on ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation. The framework themes were described in relation to information, process, people and technology and were defined as being either objectives, challenges or enablers. 19 participants were selected from seven ETO organisations to validate the framework using statements that assessed the quality, structure, and versatility. 95% of the participants' responses either agreed or strongly agreed with the statements. This research contributed to the updated BAE Systems Naval Ships PLM strategy for the design, build and in-service support for the First of Class new generation Royal Navy vessel for a recent shipbuilding programme.

Keywords

Product Lifecycle Management implementation; Engineering to Order; Information management.

1 Introduction

Sääksvuori and Immonen described a key benefit of PLM as the ease of 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 and reused in a more efficient way. PLM supports the extended enterprise by controlling access of information to only those that have the authority to view or update it, which is required within defence programmes where the secure management of information is critical [2]. The design and build of large-scale, complex, long-life products such as naval ships takes place within a geographically dispersed extended enterprise requiring access to highly sensitive information. 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. PLM is a key enabler in supporting these export obligations and managing sensitive information.

It is also necessary to manage the Intellectual Property Rights (IPR) of the information within the extended enterprise. Collaboration results in sensitive commercial information being managed and shared across multiple partners who may also otherwise be competitors [3]. The enterprise's PLM system can be used to effectively manage IPR and ensure it does not get shared inappropriately [4].

PLM also aims to ensure that information is correctly configured, duplicate information is reduced, and is current and consistent providing design clarity with respect to applicability and context. Robust

This is a peer-reviewed, accepted author manuscript of the following article: McKendry, D. A., Whitfield, R. I., & Duffy, A. H. B. (2021). Product lifecycle management implementation for high value engineering to order programmes: an informational perspective. Journal of Industrial Information Integration, [100264]. https://doi.org/10.1016/j.jii.2021.100264

information authorisation and approval procedures, governed by integrated workflows and change management processes are required to maintain the configured product definition. This ensures that a particular product configuration can be correctly designed to satisfy the customer's requirements.

During the design stage, PLM allows the structuring of information to support effective communication of design changes, improving decision making quality and decreasing approval time and rework volume by presenting the correct information to the correct individuals at the correct time [1]. Quality issues can otherwise emerge throughout a product's lifecycle leading to costly rework when discovered in later life phases [5]. The design of large-scale, complex products typically involves high volumes of change necessitating the capture, understanding, communication and management of change concurrently with the design, manufacture and support phases [6]. Auditing the change history can help provide understanding in terms of the associated decision making and can provide a basis for knowledge capture and reuse. This also supports the management of design maturity and presents opportunities for business process improvement.

PLM can be described as being a product-centric business model, supported by Information Management Technology (IMT) across the entirety of a product's lifecycle that involves people, information, processes and organisations to achieve a product performance or service goal [7]. As such, the concept of PLM can be differentiated from the supporting technology. PLM is commonly regarded as being technology only, whereas the technology should be configured to support the product lifecycle requirements of the people, process, information and product within the context of the organisation. The PLM technology is commonly viewed as a Commercial off the Shelf (COTS) single vendor integrated solution, which should satisfy all of the organisation's PLM needs, typically through the integration of smaller commercial solutions into the suite of systems. It would be more accurate to regard a PLM system as a series of interconnected applications, or system of systems, configured to provide supporting functionality throughout the lifecycle of the product across the extended enterprise [7].

Achieving a PLM implementation that is correctly aligned to the requirements of the people, process, information and product is extremely challenging and expensive, with $29.9B invested globally in 2011 of which $19.1B was in the technology [6]. Few companies have however realised the projected benefits [8]. The complexity of implementation results in a broad range of reasons for the varying degrees of success, including for example, the organisation focusing on individual aspects of PLM rather than taking a holistic approach. This may be due to the organisation not understanding what PLM implementation means [9], which is confounded by a lack of detailed research in this area [10]. The challenge of understanding which functionality should be adapted to support the business processes, and which processes should be adapted to support the functionality also remains to be addressed [1]. Often organisations turn to technology providers to solve their PLM problems, leading to customisation, resulting in the organisation taking more ownership of the technology and impacting support and future upgrades [11].

When implementing PLM, the organisation should first formalise its strategic objectives and core processes to inform the PLM approach, which subsequently influences the PLM technology implementation. This is not trivial as the alignment of strategic objectives, process and functionality is one of the key challenges to PLM implementation [12], and is an area that PLM technology providers have difficulty in resolving [9]. This dichotomy may be due to a lack of understanding of the PLM technology providers about their customer's needs, which may in turn be due to the customer's inability to understand their own relationship between strategic objectives, process and technology requirements. This research addresses this challenge by developing a PLM implementation framework to align the technology with the product lifecycle requirements of the people, process, information and product.

2 PLM challenges with Engineering-To-Order products

When investigating PLM implementation challenges it is important to consider it within the context of the product being developed. Whilst each product type has their own PLM implementation challenge, this research focussed on the unique challenges affecting Engineer-To-Order products. Product development 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 receipt from the customer [13]. With MTS, the order is ready to go upon receipt whereas MTO usually requires some manufacturing before shipment [13]. ATO supports a degree of customisation by the customer but generally only in relation to assembling pre-manufactured parts [14]. Within ETO product development, the order is received before the design stage and the customer is typically involved in defining requirements and the resultant function of the product [13]. ETO products tend to be one or few-of-a-kind products that are large-scale, complex, long-life, and highly customised [15]. A First of Class (FOC) naval ship may be characterised as being large-scale, complex, long-life, one/few of a kind, customised and not cost effective or practical to construct a prototype to demonstrate the design. These characteristics distinguish it from other large-scale, complex, long-life products such as commercial aircraft which may otherwise be described as ATO products.

This research focuses on ETO and the unique PLM implementation challenges in comparison to other product types. These challenges are in relation to the design, manufacture and in-service support life phases of the product. It highlights that the size, complexity, long-lifecycle and lack of the ability to prototype necessitates a tailored approach to PLM implementation.

2.1 Complexity and uncertainty

The level of programme complexity is one of the greatest management challenges for ETO product development as they typically have a large number of different types of elements interacting in a large number of different ways across their lifecycles [16]. Sargut Gökçe described complex systems as being unpredictable resulting from the constant operating environment changes, 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 [17]. An FOC naval ship can be described as complicated in its operational behaviour, but highly complex in its design and manufacture due to the unpredictability and emergent behaviour within these life phases.

These complexities create challenges in ETO product development particularly in relation to cost, lead times and quality expectations [18]. Known and emergent interrelated elements relating to the product require careful management, for example, changes to supplier interface requirement. These emergent elements have interrelations with other design aspects which can go unnoticed and exacerbate the product development complexity [19].

2.2 Customer interaction and procurement

The delivery lead-time for ETO products is considerably longer than other product types as the design and procurement is developed specifically to the customer's requirements [20], and is related to the customer commitment for the order. The greater the lead-time the earlier a commitment from a customer is required, and is often termed the customer order de-coupling point [21] or order penetration point [14]. Customer commitment to the order is early in the design life phase, providing significant input into the design, manufacture and procurement strategies [16]. Other product types (such as ATO) have customer commitment when the design is mature, limiting any customer inputs to configuration of the completed design.

Rahim and Baksh stated that the customer has a high degree of negotiating power over the requirements, price, delivery dates and product performance, which should be balanced against the prime contractor's need to generate profit and reduce risk. These early customer engagements typically have considerable focus on defining requirements [22], which often evolve necessitating appropriate management. Requirement change has a direct effect on the evolving design and may introduce high levels of design change due to the inherent product complexity.

Requirement capture should ideally be early in the development process and not subject to change. This can be challenging within ETO product development whereby the requirements may be difficult to accurately define, or articulate to a level that can be captured and agreed. 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 product development process.

2.3 Product customisation

Hicks and McGovern stated that ETO products have a high level of customisation due to their low volume and high-complexity [15] increasing the risk to lead time and cost. They also stated that the structure of ETO products consists of supplied systems that are bespoke or heavily customised to perform a specific function. They can be subject to a unique and specific set of requirements, for example, for a weapons system on a naval ship. Other systems may be more commercially available and subject to more general requirements, such as valves. This mixture results in differing degrees of complexity where the design is managed through interaction with suppliers to ensure coherence with the overall design of the product. This is achieved using contract management principles and sporadic data drops through the lifecycle of the product [16].

Interaction with bespoke suppliers would be collaborative with product information communicated in both directions, whereas interaction with COTS suppliers would be cooperative with information communicated from the supplier to the prime contractor, once the requirements are defined. Bespoke systems require the use of enterprise tools during design, such as Product Data Management (PDM) or Contract Management Systems (CMS) and during manufacture, such as fitting specialised Government Furnished Equipment (GFE). Lee et al. stated: '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' [23].

2.4 Configuration, change and maturity management

The Bill of Material (BoM) is well defined once manufacturing begins within MTS and ATO products, resulting with fewer emergent patterns within the manufacturing planning and execution phases [23]. ETO products have an evolving dynamic BoM where the product information gradually matures, and requires specific management due to emerging variables [23]. These variables include changes due to the evolving supplier information which impacts the design, for example increases to the size of a gas turbine affecting the space allocated in the compartment [16].

Manufacturing typically starts before the BoM is fully mature in order to reduce the overall design and manufacturing life phases within ETO products. BoM changes that have manufacturing implications can therefore have extensive impact to schedules and costs due to rework if not managed effectively [23]. The impact of these changes increases as the design and manufacturing life phases evolve due to the locked-in costs and greater maturity.

PLM in ETO product development must support evolving maturity, quality, change, configuration, integration and relevance of the product. Methodologies used on MTS, ATO and MTO do not meet these challenges [23]. ATO industries focus on variant management while ETO products such as naval shipbuilding and AEC have an emphasis on project management and BoM traceability [23]. Current PLM methodologies are designed more for ATO and MTO industries [23], presenting a gap in research for PLM implementation for ETO product delivery.

2.5 Project management characteristics

The recognition of the need for robust project management reflects a history of considerable schedule and cost overruns on ETO products which results in a need for more advanced project management principles beyond those normally applied to less complex products [24]. The project management methodologies require the interlinking of risk, schedule, resource and governance management [24].

This is required to support specialised production processes which possess widely varying operational types dispersed across an activity-driven schedule, based on the lifecycle of the product [18]. The challenges relate to the difficulty in taking a bottom-up approach to estimating and establishing plans for these products, which is the norm in other engineering and construction projects [19]. This 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 that are difficult to predict and manage. The lifecycle of these products means that the requirements are at a very high-level before a gradual transformation into a physical product over a long period of time. This transformation introduces changes to the product which affect the cost and schedule estimates [19]. 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 [25].

2.6 Lack of physical prototype

The lack of a physical prototype raises a critical need to ensure that the ETO product is 'right-first-time' due to the small number of similar products produced [26]. Prototyping allows error removal and efficiency improvements with respect to design, manufacture and support through their various iterations. Prototypes are used to verify the design and manufacturing process, and demonstrate 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 prototype as well as a delivered product [16]. 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.

3 Definition of requirements for PLM implementation

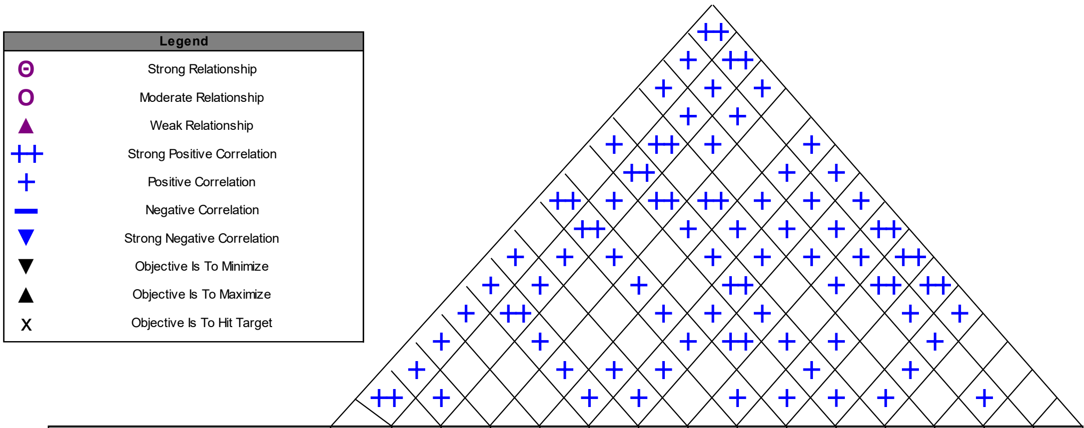
A series of workshops and focus groups were undertaken to identify the key BAE Systems Naval Ships business objectives for PLM to support current and future shipbuilding programmes. These sessions included representation from the functions of the business including Engineering, Supply Chain, Programme Management, In-service support, and Manufacturing. The aim was to identify how PLM would meet their objectives and to create a strategy to realise them. An output of these focus groups was the House of Quality illustrated in Figure 1 which describes those objectives identified by the stakeholders, the demanded quality and the functional requirements. Some of the key requirements are discussed below in terms of their PLM consequences. These requirements also formed the basis for a case study PLM implementation which is reported in [16],[27].

These requirements formed the basis for PLM for the design, build and in-service support for the FOC next generation Royal Navy vessel. The results informed the updated BAE Systems Naval Ships PLM strategy, and provided the basis for the PLM implementation framework discussed within Section 5. This strategy related the findings from semi-structured interviews, of which a significant proportion were senior personnel with an interest in PLM, and triangulated with individuals from other ETO programmes.

A key requirement of the PLM approach is an integrated Bill of Materials (iBoM), which should evolve throughout the product's lifecycle to enable the business objectives of all of the stakeholders. This requires the creation of BoMs for each life phase that are aligned, integrated, are timely and do not need translating at the point of use.

To achieve this, the iBoM is required to consist of hierarchies that break the product definition down to achieve different business needs including design, planning, manufacturing and support. A common set of configured items would uniquely identify every usage of each part across multiple hierarchies within the Parts Catalogue and link to applicable hierarchies to create a cross functional product definition. This allows information to be reused for different purposes and be fully integrated but viewed differently depending on the users' roles.

The requirement for improved information quality could be achieved by reducing duplication through integrating the CAD, PDM and Enterprise Resource Planning (ERP) systems. This would reduce rework from misalignment of the product data, especially between the CAD and PDM systems. Without integration between CAD and PDM, the system and detail designs can become misaligned through design evolution and emergent change, resulting in significant cost and rework, especially in manufacturing. Improved integration across CAD/PDM and ERP enables improved processes for change and configuration management as the data and toolsets can be better aligned.



Row #	Weight / Importance	Column # → Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1 Cross functional BoM ownership and Improved BoM level of detail	2 Improved data integration/alignment (PDM/CAD/ERP)	3 Association of related Design artefacts (modules, mounts, cabinets, Planning paths, test paths, etc.	4 Improved supplier data capture	5 Create views of product data which will evolve through product lifecycle for different stakeholders needs	6 Improved access to the right configured information	7 Centralisation of Product management processes, and capability provision	8 Toolset rationalisation	9 Digital (model based) Planning	10 Improved identification of change affected items	11 Enable single point of truth and a reduction in data duplication	12 Capturing, management and presentation of maturity information	13 Classification of design artefacts based on design, supply chain, manufacturing processes	14 Identification of BoM artefacts to enable repeatable manufacturing	15 Integrate the BoM with configuration and change management across CAD/PDM and ERP
		Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▲	▲	▲	▲	▲	x	▲	x	▲	x	x	▲	▲	▲
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	5	5	5	4	4	5	3	3	4	5	5	4	3	5	5
		Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	7	10	7	6	8	6	6	7	9	8	9	8	7	8	10

Figure 1. House of quality for PLM to enable shipbuilding programme objectives.

Providing the product breakdown to an installable level within the iBoM and accurately describing maturity should enable manufacturing planning activities to be undertaken 18-24 months earlier than is traditionally the case. With digital planning, the full engineering BoM could be published via CAD/PDM along with 3D visualisations of the BoM in the CAD model. This allows BoM items to be linked to work packages in a sequence informed by the CAD model, resulting in the creation of a manufacturing BoM. The CAD visualisation allows stakeholders to provide feedback on the build sequence many months before the build is due to start, and helps manage manufacturing challenges with not being able to prototype the build. It also assists the programme management team in verifying and managing the schedule.

There is a requirement to reduce manual data entry and improve data quality, particularly with supplier information which is used to evolve the design through-life. Mechanisms to support the receipt and verification of supplier equipment information are required to allow the capture of supplier equipment attributes and parent/child breakdown. Integrating the engineering and in-service BoMs would reduce the time required to conduct supplier reviews and enable more efficient input of data into the programme, therefore increasing maturity to support the design and build schedule.

Supporting the identification and management of repeatable manufacturing processes is a requirement to reduce the number of bespoke activities during build. This provides a reduction in build timescales due to the identification of standard manufacturing processes in the design lifecycle. Product customisation would typically result in specialised processes that are difficult to manage and do not deliver economies of scale. Standardisation enables simplified manufacturing planning processes as the team have familiarity from past experiences, as opposed to attempting to understand how a bespoke manufacturing product should be processed.

There is a key requirement to manage the ongoing completion of the product through the various phases of the programme. These completion activities may span many years from completion planning, to installation, commissioning and acceptance and should be integrated with the master engineering BoM. Without an iBoM, the completion activities would use BoM data in a disparate system potentially causing misalignment between the master engineering BoM, which is subject to design evolution and change, and the completion activities, resulting in quality issues and rework.

4 Data gathering approach

Semi-structured interviews were used to capture data for the development of the PLM implementation framework. The questions were structured to elicit a comparable set of results to allow for analysis, whilst providing flexibility to enable information that was not obvious to surface.

The interview schedule was based on the characteristics of PLM for ETO. The questions included within Table 1 were designed to relate to the challenges identified from the literature earlier, and allowed the elicitation of the interviewees' thoughts and concerns without leading them towards a constrained response. Context to the research was provided at the interview start, including the challenges of PLM implementation in ETO products, the research aim, and how the responses could contribute to the development of a PLM implementation framework.

Question	Rationale
Q1 – Have you encountered any of the key challenges described? Would you add or remove any?	To further support the gap in knowledge identified in relation to the characteristics of PLM implementation for ETO.
Q2 - What are the typical key business objectives which you require a PLM environment to support?	To stimulate the interviewee into considering why they need PLM and provide a basis for responding to the following questions. The responses to these questions will form the basis of the PLM objectives section of the framework.
Q3 - Describe your current PLM environment from your perspective?	To stimulate the interviewee into considering the PLM environment within which they work and to provide a link between the objectives, challenges and enablers, and the following questions.
Q4 - Describe the typical challenges you experienced with utilising PLM?	To capture what the interviewee believes is their typical challenges with utilising PLM, based on their PLM environment. This will set the basis for the following questions as to what improvements can be enabled.
Q5 - What improvements would you make to a PLM environment to ensure it meets your business objectives and why?	The interviewee has considered the challenges with utilising PLM and this question is designed to capture what improvements can be made to the PLM environment to meet their objectives.
Q6 - Can you prioritise the improvements in terms of business impact?	Only used if there are a number of responses to Q5 to allow the interviewee to convey what improvements are more critical.
Q7 - Can you prioritise the improvements in terms of effort required?	Only used if there are a number of responses to Q5 to allow the interviewee to convey the improvement effort required.

Question	Rationale
Q8 - How could you better enable the implementation of these improvements?	To stimulate the interviewee into considering the business implications of 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)?	To capture the enterprise-level considerations required for an improved PLM implementation. The results may follow on from Q4, for instance, the interviewee may have people challenges, which may impact the implementation of improvements.
Q10 - Can you prioritise the challenges in terms of business impact?	Only used if there are a number of responses to Q9 to allow the interviewee to convey what challenges are more critical.
Q11 - Can you prioritise the challenges in terms of effort required?	Only used if there are a number of responses to Q9 to allow the interviewee to convey what the effort required to address the challenges.
Q12 - How could you overcome difficulties associated with these challenges?	To supplement Q8 in terms of enablers but specially to elicit any which may arise in the implementation of the PLM improvements not yet considered.
Q13 - Would a framework assist with the transition from as-is to the to-be, if so how?	To elicit whether a framework is an appropriate means of assisting PLM implementation. Also capture the ways the framework would assist and any features of its design and use.
Q14 - What other ETO industries would benefit from a framework?	To assist in identifying further interviewee candidates, areas with which the research could be targeted to improve industrial performance, and also, for future research opportunities.

Table 1. PLM implementation questions.

27 semi-structured interviews on PLM implementation were undertaken with senior personnel associated with eleven ETO product development programmes in the UK, France, Australia, USA and Canada. The interviewees were selected based on their PLM experience in ETO products either as an implementer or as a key stakeholder with an interest in its successful use within their organisation, and held positions such as chief engineer, head of programme, and senior systems engineer. The interviewees (coded A1 to A27) 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.

The results of the interviews were captured and analysed to provide PLM implementation recommendations. The responses were classified into categories (codes and themes), which provided a structure through which further analysis took place [28]. 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 that allowed the analysis and recommendations to be drawn. The phases of thematic analysis used are shown in Table 2 and illustrated in Figure 2.

No	Phase	Description of the process
1	Familiarisation with the data.	Transcribing the data, 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 framework.	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 2. Phases of Thematic analysis [29].

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', but also highlighted potential hazards that may impact the quality of the research [29]. 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. It is also possible that the themes do not directly relate to the research goals, therefore, consideration was given to ensure that the key themes captured relate to forming the basis of the PLM implementation framework. Also, the themes should be supported by the data itself to ensure that they are not generated based on weak data, therefore, there should be data to support each of the themes [29].

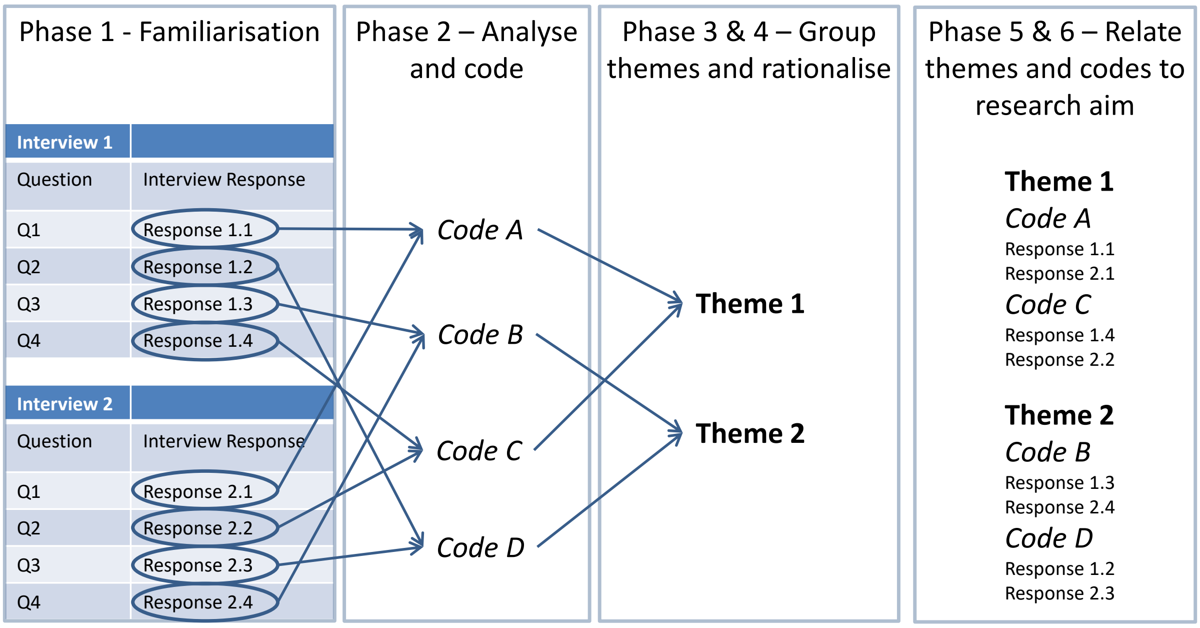


Figure 2. Approach to thematic analysis.

To illustrate this thematic analysis, the following responses are reflective of answers to questions Q1 to Q3: "change, configuration, maturity, BoM management"; "huge focus on risk […] BoM maturity - the procured BoM didn't align with the design BoM"; "BoM integration - the flow [of information] through into production"; "track the information - not data but information, what does that mean - maturity, quality, risks, performance measure"; "consistent and controlled BoM through the lifecycle, PLM enables this through product structures [… and] meta data"; "[…] how we structure our data, engineering build data for breaking down into manageable chunks - leads to the creation of our engineering BoM". 378 responses in total were received from the interviews, which were analysed, coded and themed. These responses related to product information contained within the BoM; the integration of this information; and the use of information at different stages of the product's life. 23 interview responses, including the six responses included above, were analysed and coded as being related to "through life capture, integration and management of all evolving product information", which along with other similar codes was rationalised into the theme of "information objectives".

5 PLM implementation framework

This section describes the findings from the semi-structured interviews including the main themes derived from the interview responses that are used to develop the PLM implementation framework. The themes identified were supported by relevant interview responses from the analysis undertaken. The responses were grouped and common themes derived in relation to: information, process, people, and technology as illustrated in Figure 3. The research reported here focusses specifically on the information theme. The interview responses also highlighted commonality in relation to how the interviewees responded to the PLM implementation questions. These responses across all themes, prompted by the questions, typically took the form of discussing either: an objective for successful PLM implementation; a challenge faced during PLM implementation; or, an enabler or means of supporting implementation. Consequently, this aspect of the PLM implementation framework focusses on information objectives, challenges and enablers derived from the interview responses. A summary of the supporting interview statements for the framework's information objectives, challenges and enablers is provided within Sections 5.1, 5.2, and 5.3, along with recommendations in relation to implementation. These sections do not include all interview responses used to derive the themes, instead focussing on key points in order to get a broader illustration of information objectives, challenges and enablers.

	Objectives	Challenges	Enablers
Information	• Through life capture, integration and management of all evolving product information from all stakeholders. • Single point of truth to capture evolving product information once and use many times • 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 3. PLM implementation framework for ETO products.

5.1 Information objectives

The management of information is a fundamental requirement of PLM in any New Product Development (NPD) environment. The information objectives in ETO products differ at a detailed level as they must manage large volumes of information with various levels of importance that are not stable throughout the product's life phases. This section describes those information objectives for the implementation of PLM on ETO products, which were identified through thematic analysis. This section describes the six findings for meeting the organisational information objectives related to the themes identified from the interview responses.

5.1.1 Through life capture, integration and management of all evolving product information

This element explains the importance of the objective of capturing, integrating and managing the information as it evolves through the product's lifecycle. The relevance of BoM management as a key business requirement for PLM was confirmed by A2. A25 discussed their role as understanding the programme performance from a design perspective, and while operating within project management there was a significant risk in relation to BoM management and maturity. A22 highlighted the importance of information management procedures including configuration, change and BoM integration as well as the flow of information into the production environment. A key objective of A24 was to understand the meaning of information with regard to quality, risk, and overall performance measures for the programme. BoM enablement through-life was identified by A9 as an objective with PLM providing the required support through product structures and associated metadata. A7 reinforced this by stating the importance of understanding how to structure information by breaking it down into manageable chunks to support the build.

A18 defined one aspect of the importance of PLM as providing a means to integrate product artefact information such as schematics to ensure that the design 'hangs together'. PLM allows the business to react to emergent challenges due for example to information provided by the supplier. A23, A22, and A27 all discussed the importance of PLM through the lifecycle: ensuring that it promotes integration of information throughout the lifecycle to in-service support and disposal. A5 specifically discussed the significance of accurately controlling information through the design and build phases, and the lead-time in realising the benefit of this investment when the product is in-service and operating precisely to specification. A10 stated the importance of being able to retrieve information on components in order to establish when they require maintenance and also to replace the item with another with the same form, fit and function.

5.1.2 Single point of truth to capture evolving product information once and use many times

A3 identified a key objective providing an immediate response to business need through capturing, organising, and sharing information. A7 highlighted a need to collect and review information across the product's lifecycle such as concept, build and commissioning. A1 stated a key objective was to source everything from their PLM environment through writing once, using many times, and having a single point of truth. A2 discussed the importance of being able to trust information and how this relates to single source, which was embellished by A4 who described problems their business faced with using multiple non-COTS data sources as motivation for moving towards a single integrated approach. A25 described experiences with misalignment of information within the BoM using an example of lack of alignment between the procured BoM and the design BoM. Each BoM is managed at a different level: the procured BoM managed at the parent level, whilst the design BoM is decomposed to support manufacturing. Misalignment due for example to design change, can cause quality issues and rework which has significant cost and schedule implications.

5.1.3 Management of product configuration and emergent change

Configuration and change management was identified as an important objective in multiple interview responses. The configuration of the design as it evolves was stated as a requirement of PLM by A14 due to the time it takes for the design to evolve through the lifecycle. A11 described how the management of multiple configured baseline versions should be from cradle to grave. A8 agreed that this supports information coherence, completeness and correctness with a key objective being a design with the minimal number of iterations after the design is constrained into change management. Configuration and change management ensures that the customer receives an agreed upon design with any differences subsequently managed through a robust process. A4 stated that effective configuration and change management ensures the information delivered meets the customers' expectations. A11 stated the importance of configuration management in the context of variant and applicability management: both commonality and individuality of systems need to be appropriately managed across design variants.

5.1.4 Management of security, export and IPR obligations

For BAE Systems Naval Ships, PLM is required to support security, export and Intellectual Property Rights (IPR) information. The management of export and IPR in ETO products increases when there are multiple variants. The UK, Australia and Canada for example 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

These aspects were not discussed in detail by the interviewees although A23 stated that PLM is required to manage ITAR, whilst A20 discussed the importance of managing security and resilience. The lack of elaboration was most likely due to focussing on PLM objectives, with security, export, and IPR regarded as normal expectations. These obligations are a critical requirement particularly when the business is dependent on being able to manage security and export regulations. Information access must be carefully analysed, configured, implemented, and managed, to ensure quality and compliance with security and regulatory obligations. An example is with A1 who raised IPR as a PLM challenge but did not raise it as a PLM objective.

5.1.5 Management of evolving product maturity

The management of maturity for ETO products is an objective and a challenge in comparison to other product types due to their long lifecycle and sporadic data drops from suppliers. A2 stated that at design reviews they use information maturity levels to understand risk, and determine whether a level of maturity is sufficient to pass the review or is too immature to proceed. 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 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. A5 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.

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

PLM must support the ETO programme to 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. A2 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, where any changes to the information must be communicated to those who are utilising it for downstream activities, such as engineering changes that 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.

Stakeholders require efficient and easy access to information across the entire lifecycle and extended enterprise. A17 described the need for helping to enable geographically dispersed teams to collaborate, which is important in an extended enterprise. A3 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.

A6 described how the ETO product is developed based on information provided by suppliers and that the PLM environment assists them with reacting to unanticipated problems. Ensuring that all business functions communicate effectively through PLM was raised by A15 as being a key objective.

5.2 Information challenges

The section describes the three information challenges relating to information for the implementation of PLM to meet business requirements in ETO products.

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

This challenge relates to the difficulties with identifying the necessary product and programme information in the PLM environment for management decision making, when there are large volumes of information related to aspects of significant programme importance. A5 stated that turning data into management information is problematic, and commented that they are better at capturing data as opposed to turning it into management information to support decisions. A13 described that their product is data rich and people lose sight of what is important and elaborated that the challenge of identifying when data becomes useful information; otherwise it is just data with limited value and with a big overhead to maintain. Whilst it is difficult to identify management information to see problems before they arise or to make considered decisions to resolve emergent issues, there is also the problem of managing large amounts of data to support the programme.

A6 discussed the challenge of the lack of alignment between resolving product issues and project progress. The ETO product schedule is aligned with the product development lifecycle: emergent product issues have a direct impact on the schedule. A26 stated that there were different approaches to supply chain procurement across partners within their project that affected production activities.

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

This challenge relates to that of integrating large volumes of evolving information on ETO products across multiple stakeholders within various functional roles, in many different locations through the lifecycle of the programme. A5 stated that their single biggest challenge was providing a single point of truth at any one time and A18 elaborated this with a need to see the 'big picture'.

Throughout the product lifecycle, it is increasingly challenging to establish where the relevant and updated information can be viewed. A12 stated the challenge of how information flows from the engineering environment, to the ship build, and how information is utilised throughout the lifecycle of the programme. A15 stated that there was a challenge with integrating in-service support requirements as they focus the PDM environment on the engineering lifecycle. The engineering lifecycle can be close to a decade in duration, which is challenging in identifying and enabling information management strategies for downstream activities when there is so much uncertainty in the programme's lifecycle. A24 stated that not only is it difficult to manage each other's data, but this is compounded as the team grows in numbers.

Ineffective information management and integration may result with duplication occurring through the lifecycle of the programme, as there will be thousands of staff creating and consuming information over many years. A9 stated the problems of data accuracy on previous programmes, but believed that integration across CAD, PDM and ERP will assist in eliminating manual translation and data integrity issues. A16 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 programmes as the lifecycle includes years of design with overlapping phases.

5.2.3 Management of product information maturity and its relationship to change, configuration, schedule and cost

This challenge relates to the difficulties with managing maturity and its relationship with placing the product information under change control through configuration management. Maturity supports decision-making and is used to manage the status of the programme. When elements of the key maturity targets for the product are reached, configuration management rules can be established to constrain the product into change control, providing a mechanism for stability for the next phase of the programme.

There was a belief by A25 that maturity can over-complicate the programme, including in the system and physical designs – maturity management adds value but the progressive refinement of a system design does not necessarily mean that it is immature. This is a difficult challenge as if a design is sufficiently mature to pass the review 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 must be applied. This is due to the level of complexity in ETO products where it is difficult to quickly understand the impact of a design update to the various interconnections throughout the lifecycle of the product. This was supported by A18 who indicated how technology cannot be used to understand the impact to product relationships and how they have been affected, which instead requires manual investigation.

A9 stated a challenge relating to how and when change management is implemented in the product's lifecycle, as inadequate information which was used to progress design and immaturity issues has resulted in change. The relationship between what is design evolution and what is change was also stated by A16 as a challenge with PLM. As emergent changes affect the design, the agreed schedule and budget is impacted, as work that was deemed complete then has to be updated. Therefore the challenges of maturity, change and configuration management are not just with developing the product but also with ensuring that the product can be delivered to cost and schedule.

5.3 Information enablers

The section describes the enablers for implementing PLM in ETO products relating to information.

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

The importance of 'boiling down' the information to understand the status of the programme so that risk, safety, and schedule status can be understood to articulate this to the customer was discussed by A24. It was asserted that an improvement would be to make the PLM data more "digestible" to allow better and faster decisions to be made.

A18 described the importance of information and its impact on the programme using examples of product changes that initially had little impact but could have subsequently had huge repercussions. This was elaborated with the proposal that guidance to help understand the implication of changing information and its effect on the product would be an enabling feature. The importance of being presented with the right information on the change as well as standardising the change impact would allow it to go through the change management system quicker was also identified by A18.

A policy to capture what information is important could be used not only to aid the stakeholders but also to add valuable attribution to the objects within the PLM environment. Attribution with a PDM system is common place, the key enabler is the policy which identifies what information is important. A18 also stated how reports are important 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 could be configured to provide the information required by the programme.
A17 identified product change and an accurate understanding of its impact on the supply chain as an improvement to their PLM environment. The supply chain business function has a particular challenge in that they are responsible for the procurement of materials required to support product development. 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, 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.

5.3.2 PLM information integration, policy development, standardisation, learning from experience and adherence using suitable expertise

This section describes how a dedicated cross-functional team with Suitably Qualified Experienced Personnel (SQEP) can enable PLM information integration, information policy development and information standardisation. The team should enable learning 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 should also ensure that the information-related policies and procedures are adhered to across the extended enterprise of the ETO programme.
A27 used examples of when not enough attention had been given to the design of the PLM environment and stated that an improvement would be the upfront design of the PLM system. A central PLM team with SQEP provides the basis for the effective management of these improvements. The team should have experience from previous programmes and across industry to understand the objectives and challenges to produce appropriate policy. The team should be cross-functional to ensure that the information interconnections across the business functions are understood and correctly managed. They should also 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.

5.3.3 Develop a data quality and governance policy and adherence approach

In order to meet the information objectives and overcome the challenges of PLM implementation in ETO products, an approach to data quality and governance is required. A2 highlighted data quality as an improvement to their PLM environment to meet their business objectives. As ETO products have large volumes of items, including equipment, pipe spools, steel piece parts and HVAC, problems arising from information integration can take a considerable amount of time to resolve.
CAD/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 in the CAD system. However if data quality is not managed then significant issues will occur at this interface. These challenges are compounded by the level of emergent change that can affect CAD/PDM, for example, large volumes of data may have been published from CAD to PDM that 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.
A9 stated the importance of master record management with integration, which is important to understand where the master source of the data resides. A10 also highlighted the relationship between PLM and quality which was supported by A3, stating 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 that 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.

5.3.4 Develop a configuration and change management approach across ETO product classes

This section relates to the development of a configuration and change management approach aligned to the objectives discussed earlier. 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 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, which requires identification of the affected items that are related to the change objects.

A18 stated the importance of understanding how various design artefacts are affected by a change, which can often take days to complete. 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 that 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.

A13 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 affects the flexibility and speed of response from the programme.

A16 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.

Whilst configuration and change management is a well-researched topic, ETO products have specific challenges that require careful consideration. The change and configuration management approach must 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.

6 Validation and Evaluation

A questionnaire was used to capture the opinion of senior stakeholders in ETO programmes who have an interest in the successful implementation of PLM. This allowed the elicitation of responses in relation to framework quality, structure, and versatility using the statements shown in Table 3. Interviews were considered, however it was decided that they might result in conversations that were not related to the framework validation, and were therefore not pursued.

The responses relate to the validation 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 elicit responses, eight statements relating to the validation 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. All aspects of the PLM framework were assessed as illustrated within Figure 3.

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 3. Statements in the questionnaire related to validation objective.

The validation and evaluation approach consisted either of identifying participants who would attend a one-hour briefing session, 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. The roles within these ETO organisations were selected to represent stakeholders who have business objectives required to be met by a successful PLM implementation. These roles include: Head of manufacturing planning (B1); Engineering manager – in-service support (B2); Engineering manager – Design (B3); Manufacturing planning manager (B4); Engineering manager – BoM (B5); Engineering manager – PLM (B6); IM&T Manager (B7); PLM consultant (B8); PLM architect (B9); Design authority (B10); Operations manager (B11); Head of engineering (B12); Head of Enterprise Architecture (B13); Head of IM&T (B14); Underwater systems specialist (B15); Programme director (B16); Deputy head of programme management (B17); Systems engineering manager (B18); and, Engineering director (B19). The 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 PLM implementation framework was described using supporting materials in the form of a poster and presentation. The participants were requested to rate their level of agreement or disagreement towards the statements using a five-point Likert scale: strongly disagree; disagree; neutral; agree; and, strongly agree.

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 validation using the questionnaire. The participants were a mix of those who had previously been interviewed, and those who had not. This approach ensured that there was a balance in the results from those who had been involved and would see their input in the framework, and those who had not previously been aware of the research.

The responses indicated that the questionnaire statements supported the objectives of quality, structure and versatility with 95% of the responses either agreeing or strongly agreeing with the statements as summarised within Figure 4. The comments included within the questionnaire responses also supported the value of the framework. B1 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. B1 added that it is refreshing to see this represented in the framework. B15 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 B16 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'. B17 highlighted that 'securing the support of the business is, and will always be, a key challenge and a very important enabler'.

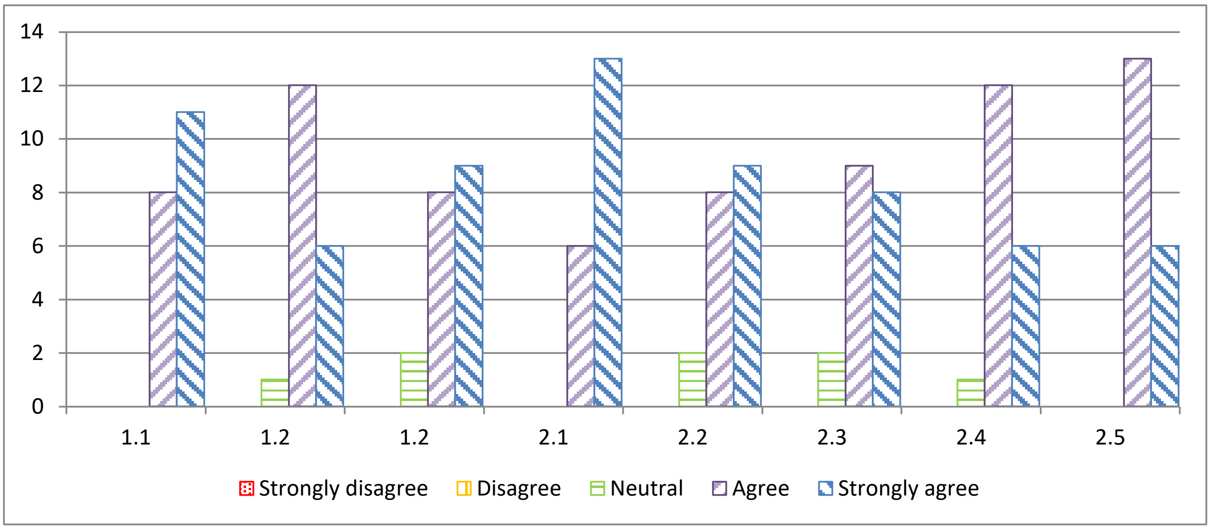


Figure 4. Framework statement responses.

The comments also highlighted the importance of versatility, with B2 stating that tailoring was important, whilst acknowledging that the framework described their business challenges. B12 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.

The framework was described by B3 as being 'an invaluable asset to any business embarking on the implementation of PLM'. It was also highlighted by B3 that the wide and varied research approach as a strength, which included different ETO products, and which recognised key themes that B3 identified with during their PLM implementation. The systematic way with which the framework considered the key elements in PLM implementation was identified by B6 and which was supported by B10 who described it as robust and well considered.

B11 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 B12 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 process'.

7 Discussion

The developed framework provides information, process, people, and technology objectives, challenges and enablers that were identified as being necessary to manage the large number of product artefacts of varying complexity and volume to support the product development and build programme. The findings captured the importance of managing information throughout the lifecycle of the programme from all of the stakeholders, and to ensure that duplication was minimised in order to improve data quality.

The importance of information quality was demonstrated repeatedly from the findings including how it is affected by disparate data sources. The integration of information is a significant challenge on FOC naval shipbuilding programmes due not only to its instability throughout the lifecycle but the necessary requirement to consume the information to progress the design and build. This presents further challenges due to the huge volumes of information published across the CAD/PDM/ERP interfaces and requires all of the information enablers identified in the findings to be applied.

Whyte et al. described a greater requirement for configuration management in complex projects in order to manage their large volumes and various interconnections, and to ensure their integrity. 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 change in interconnections within the systems [30].

There is a delicate balance between when to apply configuration management against the defined maturity criteria to provide stability to downstream activities, and the burden of applying change management processes to add product information to evolve the design. 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 product development. The reason for applying configuration control is to provide stability for this next phase but, when it is applied, there is a change management overhead to all involved in the design and build programme.

Maturity management must inform the configuration management approach to ensure that the timing of constraining the design is appropriate: constrain too early and there is a change overhead applied to the programme; leave it too late and the stability of the design and build life-cycle is affected. Identifying what is design evolution with minimal impact and what is a major product change is difficult.

Due to the complexity of the product, the overhead to the programme is with identifying the impact of the change. There are significant amounts of data published across the interface and, if configuration management is not applied effectively, it puts a burden on organisational resources, including people and IT infrastructure, to ensure the information integrity. This requires multiple stakeholders across all the functions in the programme to be involved in the processes.

Once constrained, the product artefacts require an approved change request to unlock the information from under the configuration control rules applied in the PLM environment, which are typically managed through the PDM system. The configuration control on a product artefact is automatically unconstrained once change is approved.

The framework identifies that a policy is required to establish what information is important, who owns it and how it will be used in the programme. Understanding what information is required to have its maturity managed is necessary to enable the development of the maturity management criteria. Therefore, PLM does not solve all of the challenges in an ETO product, such as an immaturity, but enables the programme to have consistent, valid and reliable information which can be used to make decisions on the programme.

If the information management approach is not managed in a robust PLM environment then the programme would struggle to manage its status against the agreed plan. It will also align with the configuration management approach which will determine when, how and what information will be constrained into change management. The findings concluded that having consistent information through a single point of truth, which would allow maturity and levels of correctness to be understood, is required.

The lack of prototype means that ETO products cannot test the outcome of their PLM approach before initialising design and production. Therefore, the research has highlighted that information integration to ensure right-first-time quality is necessary to support the programme. There are methods that 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 [31]. 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 for data quality and reporting activities once an ETO information policy has been created. As shown in Figure 5, a combination of understanding the information objectives, what information is required, who owns it, how it will be applied, measured, integrated and the alignment with the configuration and change management approach will enable the information challenges, identified in the research, to be overcome.

Figure 5. Stakeholder oriented integrated information approach.

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 working within a central PLM team who will have responsibility regarding where the information is mastered, defining what is to be published, where it will be published and, critically, monitoring its quality and publication success. The findings also state that the team must also 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.

8 Conclusion

This paper presents the first framework to implement Product Lifecycle Management (PLM) in Engineer to Order (ETO) products. It describes the unique challenges of ETO products and why a specific approach to PLM is required. These challenges within ETO relate to: complexity and uncertainty; customer interaction and procurement; product customisation; configuration, change and maturity management; project management; and, lack of physical prototype. Due to sparsity of published research relating to PLM implementation for ETO, the paper discusses the related literature on PLM and from the perspective of these challenges for ETO products.

The requirements for PLM implementation were elicited through workshops and represented within a House of Quality and used to relate the demanded customer requirements to the functional requirements of the PLM implementation. These requirements are described from the perspective of the concept of an Integrated Bill of Materials, which represents a key vision for the PLM philosophy of the organisation.

The approach to developing the framework involved the use of a semi-structured interview to elicit responses to PLM implementation questions. 27 interviews were conducted with senior personnel from eleven ETO organisations in Australia, Canada, France, UK and USA. 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.

The findings were used to create the framework using thematic analysis. The framework provides objectives, challenges and enablers for information, process, people and technology to support the implementation of PLM on ETO products. This paper presents those findings relating to information. Each theme generated in the framework was supported by multiple interview responses, to ensure that the findings were triangulated across multiple sources.

The framework is structured to focus on each key element of PLM: information; process; people and technology. There are common themes through these elements, such as with a PLM team enabling the key objectives and overcoming their challenges.

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