Analysing the factors affecting engineering change implementation performance in the engineer-to-order production environment: case studies from a Norwegian shipbuilding group

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Analysing the factors affecting engineering change implementation performance in the engineer-to-order production environment: case studies from a Norwegian shipbuilding group

Engineering changes (ECs) are unavoidable in the engineer-to-order (ETO) environment. ECs improve products and bring additional profit to ETO companies if effectively negotiated and implemented. Despite the abundant relevant literature on EC management, ETO companies still report cost overruns owing to ECs. Here, a multiple case study conducted in a Norwegian shipbuilding group was used to investigate the factors affecting EC implementation performance in complex ETO environments. The factors were examined by a cross-case analysis of six ECs occurring in the shipbuilding projects. Eleven factors were identified and analysed; their impact on EC cost was assessed by experts. The factors were ranked; the ranking shows three factors having the highest impact: time of EC occurrence, competence and experience of engineering and production staff, and degree of vertical integration in a supply chain. Finally, the study recommends EC management practices and tools to reduce the negative impacts of the identified factors.

Keywords: engineering change management; engineer-to-order; engineering change cost; case study

1. Introduction

Engineering changes (ECs) occur throughout the lifecycle of products; for most companies, ECs are the rule rather than exception (Clark and Fujimoto 1991; Hamraz, Caldwell, and Clarkson 2013). EC is a modification to the structure, behaviour, and function or to the relations between the structure, behaviours, and functions of a technical artefact (Hamraz, Caldwell, and Clarkson 2013). ECs occur as a consequence and desire to improve the product, adapt it to new requirements, or eliminate past mistakes (Jarratt, Clarkson, and Eckert 2005). They can be triggered by customers, company’s internal departments, suppliers, market drivers such as technological and commercial needs, and government regulations (Yap et al. 2018).

ECs are introduced to products in all production environments, but their implementation in the engineer-to-order (ETO) environment is distinctive compared with, for example, make-to-stock (MTS) and mass production. This study deals with a complex ETO archetype, where products are 'one-of-a-kind', require high engineering effort, are ordered in low volumes, and are managed on a project basis (Willner et al. 2016). In MTS and mass production, ECs are planned in advance, batched, and implemented into the next product version or production run (Wänström, Lind, and Wintertidh 2006). In ETO, there is generally no next product run or version – production is discontinuous (Gann and Salter 2000) and ECs are implemented to the one-of-a-kind product during its development and production. ECs need to be immediately implemented because project activities constantly progress and late ECs are usually more disruptive than early ECs (Fricke et al. 2000).

Research on ECs in the ETO environment shows that ECs often have negative consequences. Love et al. (2017) demonstrated that changes in construction projects after a contract is signed lead to an almost 24% increase in project cost. Love et al. (2019) noticed that in addition to the identifiable negative impact of changes on profit, considerable hidden loses might occur because not all rework is documented in ETO projects. Yap, Abdul-Rahman, and Chen (2017) estimated that ECs delay construction project time and increase project costs by 10%–20%. These studies show that coping with ECs is still a major issue in companies.

EC management (ECM) tools and practices help companies reduce the negative impacts of ECs. The overview of ECM practices and tools is presented in the theoretical background section of this paper. Why then, despite all the available ECM practices and tools, are ETO companies still reporting considerable negative impacts of ECs?

Contingency theory suggests that situational (or contingency) factors often affect the use of management practices and the associated performance outcomes (Sousa and Voss 2008). The purpose of this study is to identify such factors in the ETO context and analyse their impact on EC implementation performance. The research questions are as follows: *(1) What are the contingency factors affecting EC implementation performance in the complex ETO production environment? (2) How do the contingency factors affect EC implementation performance?*

The paper is structured as follows. First, the theoretical background on ECM research is provided. Next, the research methodology employed is described, followed by the summary of the six studied ECs. Then, the results are analysed and discussed. Propositions regarding the contingency factors and their impact on EC implementation performance in the complex ETO production environment are developed. The last section concludes the paper and provides suggestions for further research.

2. Theoretical background

2.1. Defining an engineering change

In this study, EC is defined as a modification to the structure, behaviour, and function or the relations between the structure, behaviours, and functions of a technical artefact (Hamraz, Caldwell, and Clarkson 2013; Jarratt et al. 2011). ECs can occur at any stage of the product lifecycle after the design release. Design release indicates when all the design data and documents are decided upon and formally released to engineering teams (Clark and Fujimoto 1991). Any changes before the design release are considered to be ‘design iterations’ needed for the creative design process (Hamraz, Caldwell, and Clarkson 2013).

ECs are of two fundamental types: coming from the product (mistakes and errors) and from external sources (e.g., customer changes) (Jarratt et al. 2011). In academic literature, such changes are called emergent and initiated, respectively (Eckert, Clarkson, and Zanker 2004).

An EC can propagate – that is, it can spread from one affected part of the product to other parts and systems. It can also spread to other departments in the organization and to other actors in the supply chain (Jarratt, Clarkson, and Eckert 2005). Such a phenomenon is called ‘change propagation’ (Eckert, Clarkson, and Zanker 2004).

2.2. Engineering changes in the engineer-to-order production environment

In an MTS and mass production environment, products are gradually improved through the planned development process. ECs are usually planned before the production starts, with the only exception of changes owing to safety issues, which are immediately implemented. Other changes are implemented in the next product version or production run; updated design and engineering drawings are made, the inventories are gradually phased out, and new parts and components are ordered from suppliers.

Handling of ECs in the ETO production environment is different from that in the MTS and mass production. This study deals with ETO companies that belong to the complex ETO archetype as classified by Willner et al. (2016). Companies of this archetype produce traditional one-of-a-kind products with high engineering complexity (>2,000 hours per unit) in low volumes (<750 units per year). Examples of such products are ships, plants, and oil platforms (Willner et al. 2016).

In this environment, each customer order is handled as a separate project, including tendering, design, engineering, purchasing, production, assembly, testing, and commissioning activities followed up by the delivery and guarantee period (Bertrand

and Muntslag 1993; McGovern, Hicks, and Earl 1999). The projects often have long durations with overlapping design, engineering, production, and procurement processes to reduce the total delivery time of the product (Adrodegari et al. 2015; Semini et al. 2014). Under these circumstances, even a seemingly simplistic EC can have several effects: it can influence the ongoing production, assembly processes, and current inventory because the ECs must be immediately implemented and cannot be postponed until the next product version or production run. Often, the work-in-process inventory needs to be disposed and parts and components need to be reworked or scrapped. Owing to the high product complexity and high degree of component interdependence, ECs can propagate deep into the product, requiring many other parts – often already produced – to be changed (Leng et al. 2016).

2.3. Engineering change management

ECM refers to the organization and control of the processes of making alternations to the product: ECs (Jarratt, Clarkson, and Eckert 2005). ECM addresses five strategies: less, earlier, effective, efficient, and better (Fricke et al. 2000). The ‘less’ strategy aims to reduce the number of ECs. The ‘earlier’ strategy aims to detect and implement ECs early and avoid late, more disruptive ECs. The ‘effective’ strategy aims to improve the assessment of ECs to ensure that implementation of the changes in question is necessary and beneficial. The ‘efficient’ strategy aims for an EC implementation with the best use of resources. The ‘better’ strategy aims to improve and continuously learn from EC implementation processes.

Table 1 gives an overview of the existing ECM practices and tools and links each of them to the corresponding ECM strategies. For a more extensive review, the reader is referred to the works of Hamraz, Caldwell, and Clarkson (2013) and Storbjerg, Brunoe, and Nielsen (2016).

[Table 1 near here]

Table 1. Engineering change management practices and tools

ECM practices and tools	Description of the existing ECM practices and tools and supported ECM strategies	References in literature
ECM practices		
Establishment of a clear ECM process	A clear ECM process should comprise the following steps: (1) raise EC request, (2) identify possible solutions to change request, (3) assess impacts of possible solutions, (4) select and approve a solution, (5) implement the solution, and (6) perform EC post-implementation review. *Supported ECM strategies: effective, efficient, and better.*	Jarratt, Clarkson, and Eckert (2005); Wickel et al. (2015)
Appointment of a coordinator of EC activities	A responsible person following and coordinating the ECM process should be appointed. *Supported ECM strategies: effective, efficient, and better.*	Huang and Mak (1999)
Establishment of a cross-functional team to work on ECs	Cross-functional teams should comprise representatives from different disciplines, such as design, engineering, production, purchasing, and planning. *Supported ECM strategies: earlier, effective, and efficient.*	Huang and Mak (1999); Sjögren et al. (2018)
Involvement of production early in the design and engineering process	Production function should be involved at the early stages of the design and engineering process to determine future production non-conformances and implement necessary changes at early stages. *Supported ECM strategies: less and earlier.*	Huang and Mak (1999); Jarratt et al. (2011)
Involvement of suppliers in the EC assessment and implementation process and the cross-enterprise ECM process	Suppliers affected by an EC should be involved early in EC assessment and implementation for early detection and assessment of all EC propagations. Furthermore, a common cross-enterprise ECM standard should be established to ensure timely and accurate EC assessment and implementation processes. *Supported ECM strategies: earlier, effective, and efficient.*	Rouibah and Caskey (2003); Wasmer, Staub, and Vroom (2011)
Separate meetings to work on ECs	Established cross-functional teams should have meetings dedicated to ECs. This ensures that all information regarding ECs is taken into consideration and is available in a timely manner to all involved functions. *Supported ECM strategies: effective and efficient.*	Huang and Mak (1999); Sjögren et al. (2018)
Documentation and centralized access to EC status and history	Information about ECs should be properly documented and centrally stored to ensure that it is available to all functions and departments at any time. The information should be presented in a way that allows users to track EC history. *Supported ECM strategies: effective, efficient, and better.*	Morris et al. (2016); Sivanathan, Ritchie, and Lim (2017)
Making decisions regarding ECs at the lowest possible managerial level	Decisions regarding ECs should be made at the lowest possible managerial level to save resources used for EC implementation. Different approval levels can be assigned depending on EC cost or level of risk. *Supported ECM strategy: efficient.*	Stevens and Wright (1991)
Computer-based tools to support ECM		

Dedicated IT systems for ECM	Dedicated IT systems developed by academics and practitioners support EC-related documentation flow, capture knowledge related to ECs, support EC assessment, and allow collaboration on ECs. *Supported ECM strategies: effective, efficient, and better.*	Chen et al. (2015); Sivanathan, Ritchie, and Lim (2017)
Configuration management systems	Configuration management systems establish and maintain the integrity of the product and associated information to effectively control the changes in the product. These systems support EC assessment as well as storing, tracking, and updating EC-related information. *Supported ECM strategies: earlier, effective, efficient, and better.*	Jarratt, Clarkson, and Eckert (2005); Whyte, Stasis, and Lindkvist (2016)
Product data management (PDM)/product lifecycle management (PLM) systems	PDM and PLM systems help to efficiently manage and share product development data and processes among stakeholders. These systems can be used to support EC planning, approval, and implementation. *Supported ECM strategies: effective, efficient, and better.*	Do (2015); Wu et al. (2014)
Building information modelling (BIM)	BIM is a multidisciplinary, collaborative environment containing the digital representation of physical and functional characteristics of a product. Use of BIM reduces the number of emergent ECs and supports EC propagation assessment. *Supported ECM strategies: less, effective, and efficient.*	Francom and El Asmar (2015); Saoud et al. (2017); Matthews et al. (2018)
Change reduction and front-loading tools		
Quality function deployment (QFD)	QFD is used to translate customers' requirements into engineering characteristics of the product. QFD helps to understand customer needs and wants at an early stage, therefore reducing future customer-initiated changes. *Supported ECM strategies: less and earlier.*	Eckert et al. (2009); Huang and Mak (1999)
Failure mode and effect analysis (FMEA)	The FMEA method identifies and reduces potential problems in a product. If performed early in the design process, FMEA reduces the number of internal ECs occurring owing to errors and front-loads changes to early design stages. *Supported ECM strategies: less and earlier.*	Braaksma, Klingenberg, and Veldman (2013); Eckert et al. (2009)
Design tools		
Design for manufacturing and assembly (DfMA)	DfMA is an approach aimed at designing products for easy and economical production. DfMA prevents the occurrence of emergent changes at the production and assembly stages. A common approach for DfMA is the integration of manufacturing and assembly requirements early in the design process. *Supported ECM strategies: less and earlier.*	Das and Kanchanapiboon (2011); Jarratt et al. (2011)
Design for changeability (DfC)	DfC is aimed towards designing systems and products such that future ECs can be easily and rapidly implemented or avoided altogether. Changeability can be achieved through the principles of simplicity, independence, and modularity. *Supported ECM strategies: less and efficient.*	Fricke and Schulz (2005); Ross, Rhodes, and Hastings (2008)

Design freeze	Design freeze is the end point in the design activity at which evolution of the design is stopped and design documents are handed over to production. This limits the number of occurring ECs. *Supported ECM strategy: less.*	Dieter (2000); Eger, Eckert, and Clarkson (2005); Gosling, Naim, and Towill (2013)
Change propagation and impact assessment tools		
Change prediction methods (CPM), design structure matrices (DSM)	CPM and DSM are tools that include a matrix to represent the dependencies between the components of a product and a technique to predict and analyse the impacts of change propagations. *Supported ECM strategies: earlier and effective.*	Hamraz et al. (2015); Zhao et al. (2010)
System dynamics (SD) models	SD is a modelling framework that can be used to analyse ECs by considering the dynamic behaviour of project feedback loops causing delays and disruptions. It provides insights into how ECs propagate in a project and influence project performance. *Supported ECM strategies: earlier and effective.*	Ansari (2019); Love et al. (2002)

3. Research method

In this study, the necessity of in-depth investigation of the contextual conditions (i.e. contingency factors) affecting EC implementation performance in the ETO production environment strongly advocates for the selection of a case methodology (Eisenhardt 1989; Voss, Tsikriktsis, and Frohlich 2002; Yin 2013). In addition, case research is applicable when 'how' questions are asked (Yin 2013). The data collection and analysis were performed in two steps as shown in Figure 1 and elaborated further.

[Figure 1 near here]

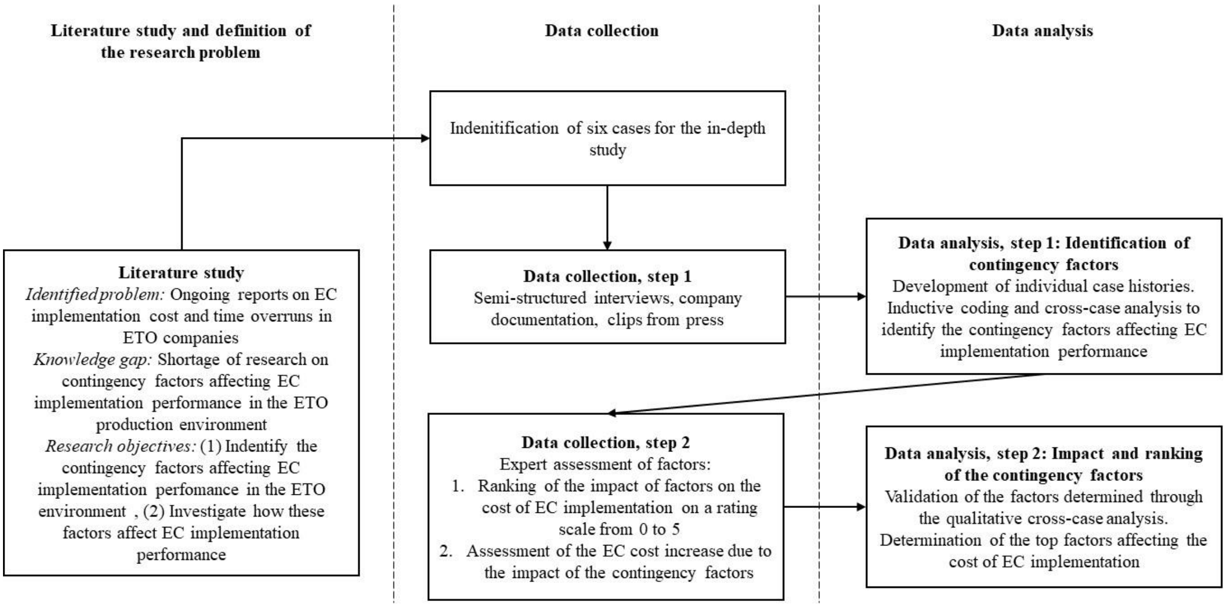

Figure 1. Research process

3.1. Unit of analysis and case selection

In this study, the case represents an EC that occurred in a shipbuilding project. The data were collected from a Norwegian shipbuilding group (focal company) comprising several business areas including ship design, shipbuilding, ship equipment solutions, and shipping. The projects in which ECs occurred also involved companies external to this group. Each shipbuilding project and built vessel has characteristics that distinguish it from other projects and vessels. Vessels are tailored for each customer and produced in small series of 3–5 new buildings. Each ship production project lasts for around two years and requires up to 40,000 engineering hours. From this perspective, shipbuilding is a suitable representative setting to study the complex ETO context as defined by Willner et al. (2016).

In a multiple case study research design, the selection of cases should be guided by theoretical interests rather than statistical sampling logic (Eisenhardt 1989; Yin 2013). Based on the available theory, ECs vary based on the time and source of occurrence. Based on discussions with the shipbuilding group, where the data were collected, it was decided that ECs from different projects must be considered because project and product characteristics also constitute the contingency factors important for the research. Hence, our search criterion was to sample ECs that vary based on: (1) time and source of occurrence – initiated or emergent ECs occurring at different stages of the project, (2) projects in which they occur – projects with different levels of vertical integration in a supply chain and (3) product characteristics: type of vessel, vessel complexity, and maturity of the design. This allowed the evaluation of the EC implementation process in different contexts.

The focal company was known to the authors through previous collaborations. Before visiting the company, excerpts from the research protocol, including the data collection plan and interview questions, were sent to the company. During the visit, an experienced managing director and business analysists helped the authors to select ECs suitable for the study. The final sample included six cases. This number is in line with general recommendations that between four and ten cases work well for case-based research (Eisenhardt 1989; Yin 2013). Table 2 details the studied cases.

3.2. Data collection and analysis

Data collection, step 1

In the first step, the data were collected via interviews with persons most knowledgeable about the ECs in question. In total, six interviews were conducted with the managing director, business analyst, deputy Chief Executive Officer (CEO), senior advisor, design manager, and innovation and development manager because they were directly involved in the EC implementations selected for the study. Each interview lasted for 2–3 h. A mix of viewpoints from the participants helped to develop a deep understanding of the factors affecting EC implementation performance. This also allowed the comparison of interpretations of the people involved in the EC implementation process. The interview guide was designed to help in conducting interviews (Appendix A) and was intended to cover *ex ante* identified project and product characteristics that might affect EC implementation and leave room for participants to suggest additional factors affecting EC implementation. The participants were asked, to the extent possible, the same questions to increase the reliability of the collected interview data. The interviews were audio-recorded with the permission of the participants. Interview transcripts were written and sent to the participants for verification.

The interviews were supplemented by the collection of additional data. First, during the interviews, the participants were asked to check the information regarding ECs in their records. The following documents and records were checked: change evaluation spreadsheets, change order request forms, and records in the project planning and enterprise resource planning (ERP) system. Second, the project database from the company's website and articles from maritime magazines were used to check information about the projects. Finally, any additional clarifications were obtained through phone calls and e-mails.

Data analysis, step 1

Recommendations by Eisenhardt (1989) and Miles, Huberman, and Saldana (2014) were followed to analyse the collected data. The interview transcripts, together with the collected documents and excerpts from the media and company website, were synthesized into individual case histories containing narrative descriptions of cases, summaries, and tabulations summarizing the key facts about the cases. The cases were then coded to determine the contingency factors affecting EC implementation performance.

Next, a cross-case analysis was performed. Using the methods suggested by Miles, Huberman, and Saldana (2014), the authors looked for the presence of same factors across multiple cases and examined whether familiar themes emerged in multiple settings. To aid the analysis at this stage, all cases were combined in a meta-matrix created by assembling each case in a common format and displaying them together in one large table. Reformatting and resorting the cells and rows in the table helped the authors to identify patterns in the cases and determine whether new observations can be constructed. Then, a summary table was created by partitioning data according to the factors affecting EC implementation performance. Through this process, a list of contingency factors affecting EC implementation performance was obtained. Only the factors mentioned by two or more interview participants were included in the list.

Data collection, step 2

In step 2, the data were quantified. Miles, Huberman, and Saldana (2014) argue that linking qualitative and quantitative data in research is important. This study adopts their suggestion of quantifying data by converting qualitative information into magnitudes of ranks: the list of contingency factors is converted into rating scales. Miles, Huberman, and Saldana (2014) state that for such purposes, three- to five-point scales seem the easiest and most reliable. Hence, the following rating scale was adopted for this study: 0 = no impact, 1 = very low impact, 2 = low impact, 3 = medium impact, 4 = high impact, and 5 = very high impact. The factors were ranked according to their impact on EC implementation cost. Measuring EC performance in terms of EC implementation cost and time (Alblas and Wortmann 2012) or project cost and duration (Love et al. 2017; Love et al. 2019; Yap, Abdul-Rahman, and Chen 2017) is common. In the studied cases, however, separating the impacts of one specific EC on the total project cost and duration was often difficult. In addition, the time required to implement ECs is not always known. Hence, the decision to measure the impacts of the contingency factors on the EC cost was made.

Three experts from the focal company – deputy managing director and two senior business analysts – were asked to rank the factors. They were chosen based on their profound knowledge of all studied ECs. Moreover, the experts were asked to estimate the increase in the EC cost owing to the contingency factors.

Data analysis, step 2

Based on the importance given to each factor by the participants, the mean value of impact for each case and for all cases combined was calculated. The factors were ranked based on the mean value. The results were compared with the qualitative cross-case analysis results, which allowed the validation of the list of factors. Quantitative data further allowed the authors to formulate several propositions describing the impact of factors on EC implementation cost.

3.3. Validity and reliability

The quality of the case study is assessed on the basis of external validity, construct validity, internal validity, and reliability (Yin 2013). The cases studied here cover a good range of data in terms of EC varieties, projects, and product characteristics, which strengthened the external validity of the results. The external validity was further strengthened by setting the research in a complex ETO context, of which shipbuilding is a suitable representative. The construct validity was enhanced by asking information from several participants and sources, inquiring additional clarification, and asking the participants to review the interview transcripts and case study reports. Internal validity was ensured by employing cross-case analysis with a matrix approach to determine patterns in data. The internal validity was further strengthened by supplementing qualitative data with ranking of factors by experts against EC implementation cost (Miles, Huberman, and Saldana 2014; Yin 2013). The issue of reliability was addressed by creating a case study protocol and a case database. The case study protocol, as recommended by Yin (2013), included research questions and theoretical base, data collection procedures and questions, and a tentative plan for a case study report.

4. Case studies

Following hereon is a description of a typical shipbuilding project to provide the reader with a general understanding of the actors involved in the EC implementation process. Next, the six cases examined in this study are described.

4.1. Shipbuilding project

The shipbuilding project is a complex interaction between the ship designers, shipyards, suppliers, ship-owner, classification society, and authorities. Main project activities include design, engineering, production and assembly, procurement, commissioning, planning, and coordination. For the future discussion on ECs, understanding the difference between the design and engineering activities in a shipbuilding project is important for the reader. Design and engineering are two considerably different activities and are handled by separate business units or even by separate companies. The task of the design team is to satisfy the ship-owner's requirements and to create the information needed to build a ship. The outputs of the design stage include ship specifications, lines drawings, general arrangements, capacity plan, and structural design criteria. During the engineering stage, all the ship design information is translated into a form suitable for production, including parts lists, process instructions, welding plans, hull fitting drawings, and numeric data (Gale (2003). The engineering activities are performed by the engineering teams at the ship design firm or the shipyards.

Figure 2 shows the different supply chain structures observed in the studied cases. From the perspective of the focal company, the design activities can be performed internally or by other ship designers. The vessel can be engineered and built either at the focal company's own yard or at the partner yards. In case of using a partner yard, a ship designer sells the design to the yard and ship-owner signs the contract with that yard. The yard has the final responsibility for the vessel to be delivered on time and meet all contractual requirements.

[Figure 2 near here]

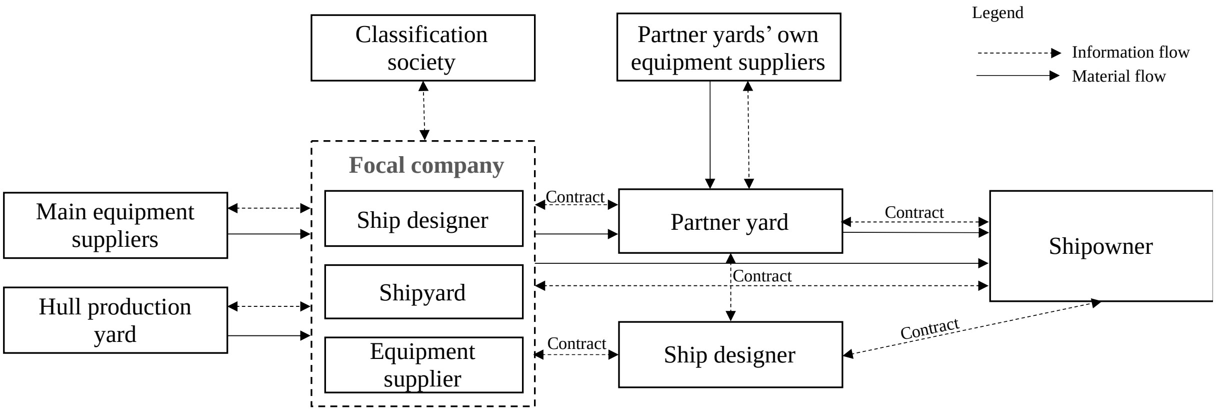

Figure 2. Ship production supply chain

4.2. Case studies

The cases are presented to contextualize the factors affecting EC implementation performance. Table 2 summarizes the cases.

Case 1

EC1 occurred in the technologically complex subsea vessel intended for several operations. After the steel cutting activities had already started at Shipyard B, the decision to increase the deck area and tank capacities was made, leading to the increase of vessel length and width. The solution to this change was to add a new section to the hull. Design recalculations and engineering of a new section and interfaces between the sections were performed by Shipyard A. During this time, steel work at Shipyard B was stopped to wait for the updated drawings.

Case 2

EC2 occurred in a service operations vessel for the offshore wind industry. This was one of three sister vessels built by Shipyard A. In general, sister vessels require a limited amount of design and engineering work between them because they have similar designs. In this case, more work was required because the customer wanted to equip the vessel with a helicopter deck. By installing the helicopter deck, new escape routes and safety plans had to be designed, increasing the design and engineering workload. However, because all the EC adjustments were made before the start of production, the shipbuilding group only incurred costs connected to the design and engineering work.

Case 3

EC3 occurred in a plug-in hybrid ferry. Shipyard A had never engineered and built this type of vessels. After both engineering and steel production in Country B had started, the engineering team discovered problems with vibrations in the aft ship. To reduce the amount of rework in both design and production, the problem was decided to be solved by welding smaller parts to the steel structure to avoid vibrations during vessel operation instead of changing the entire structure. Although the designer company made the mistake, Shipyard A decided to solve it with their own resources to avoid further cost increase and delays.

Case 4

EC4 occurred in the first ever luxury yacht engineered and built by Shipyard A. The design of the yacht was a collaboration between Ship designer A and Superyacht designer D. When the vessel was already taken out of the dock, vibrations from water intake grids were detected. The grids were created in the same way as they would have been for an offshore support vessel, which proved to be unsuitable for the yacht. The water intake grids were changed. The change itself was minor, but because the vessel had to be taken back to the dock, a small job turned out to be very expensive.

Case 5

EC5 occurred in one of the twelve platform supply vessels designed by Ship designer A and built at Shipyard E. The design of this vessel was not new for Ship designer A, but the vessel was designed from scratch. In one of the vessels, new technology was added: exhaust to waterline. Shipyard E did not have experience with this technology that required special pipe arrangements. The arrangement was not properly done: a bending pipe was added to the exhaust end, which gave back pressure to the engine. The problem was solved by rearranging the pipes and going back to the funnel solution. The Ship designer's assistance was required to solve this problem.

Case 6

EC6 occurred in the first expedition cruise vessel designed by Ship designer A. It was engineered and built at Shipyard F. However, the two companies had different understandings of the boundaries between design and engineering. The engineering department at the shipbuilding group could work with a much more basic design, as compared with the engineering department at Shipyard F. In this environment, when the customer asked the yard to implement several modifications, the yard could not implement them without Ship designer A.

[Table 2 near here]

Table 2. Characteristics of the cases

Cases		Vessel type	Design company	Engineering and production company	Design maturity	Time of EC occurrence	EC type
Case 1 (EC1)	Vessel size change	Subsea	Ship designer A (Country A)	Shipyard A (outfitting, Country A), Shipyard B (hull, Country B)	Similar designs were created by the designer	Engineering, steel cutting at Shipyard B	Customer-initiated
Case 2 (EC2)	Adding helicopter deck	Offshore wind	Ship designer A (Country A)	Shipyard A (outfitting, Country A), Shipyard B (hull, Country B)	Second sister vessel	Design/engineering stage, before the start of production	Customer-initiated
Case 3 (EC3)	Modifications to the steel structure	RoPax (hybrid ferry)	Ship designer C (Country A)	Shipyard A (outfitting, Country A), Shipyard B (hull, Country B)	First vessel of this type	Engineering, steel structure construction at Shipyard B	Mistake in design
Case 4 (EC4)	Change of water intake grids	Luxury yacht	Ship designer A (Country A), Superyacht designer D (Country D)	Shipyard A (Country A)	First vessel of this type	Vessel out of the dock	Mistake in design
Case 5 (EC5)	Exhaust to waterline	Platform supply	Ship designer A (Country A)	Shipyard E (Country E)	Similar designs were created by the designer	Production	Mistake in engineering
Case 6 (EC6)	Several modifications	Cruise	Ship designer A (Country A)	Shipyard F (Country E)	First vessel of this type	Engineering and production	Customer-initiated

5. Results

The analysis of the ECs described above has led to the identification of 11 contingency factors affecting EC implementation cost. These factors are presented in Table 3 and are described in what follows. Table 4 presents the results of the factor ranking by the experts.

5.1. Factors affecting EC implementation performance

[Table 3 near here]

Table 3. Factors affecting EC implementation

Factor	Explanation
1. Time of EC occurrence	Represents the stage of the project when an EC occurred: design, engineering, procurement, and production phases
2. Maturity of the product design	Represents how novel is the product for the design, engineering, and production staff working on it
3. Maturity of a technological solution	Represents how novel is the changed technological solution for the design, engineering, and production staff working on it
4. Competence and experience of focal company's design, engineering, and production staff	Represents the professional competence and experience of the designers, engineers, and production staff at the focal company
5. Competence and experience of partner yards' engineering and production staff	Represents the professional competence and experience of the engineering and production staff at partner yards
6. Degree of vertical integration in a supply chain	Represents an arrangement in which the supply chain of the focal company is owned by it
7. Contractual distance between project actors	Represents the contractual distance between the different actors involved in the project – that is, absence of direct contractual relationships between some actors involved in the project
8. Physical distance between project actors	Represents the physical (geographical) distance between the different actors involved in the project – design, engineering and production companies
9. Cultural and organizational distance between project actors	Represents the cultural, linguistic, and organizational (i.e. organizational structure and different understanding of boundaries between design and engineering) proximity between project actors
10. Degree of overlap between project stages	Represents the concurrent execution of design, engineering, procurement, and production activities
11. Formal, contractually binding professional culture	Represents the extent to which customers rely on formal, contractually binding procedures compared with relationships of trust and informal problem-solving

Factor 1: Time of EC occurrence

ECs 1, 3, 4, 5, and 6 occurred after the production had started. A common view amongst the interview participants regarding ECs 1, 3, 4, 5, and 6 is regarding the uncertainty of rework activities in production. The further in production an EC is implemented, the more physically constrained are the work conditions aboard a ship: workers have to work in closed rooms, and many passages are closed. The workers are considerably slowed down and the risk of damage to the already installed equipment is high. The further the production progresses, the more 'vulnerable' are the already installed components.

Factor 2: Maturity of the product design

This factor was mentioned by the interview participants in Cases 1, 3, 4, 5, and 6. The ECs in these cases occurred in the vessels with completely new designs: the focal company had never designed or built these types of vessels before. ECs 1 and 5 occurred in the subsea and platform vessels, respectively. These types were not new to the design company, but these vessels were designed from scratch. When changes were required in the vessels with low design maturity, more time and resources than usual were used to develop and implement the solution.

Contrary to these cases, in Case 2, the EC occurred in the vessel with the most mature design among all vessel designs in the studied cases: a second sister ship. The only difference between the sister ship designs was the added helicopter deck. The design and engineering teams knew well what needed to be done to implement the change.

Factor 3: Maturity of the technology

This factor concerns how specific technological solutions employed where EC was implemented affected the implementation of this change. The effect of this factor becomes visible when comparing Cases 3, 5, and 6 with Cases 1, 2, and 4. In Case 3, the vessel was designed in a way that led to vibrations in the ship aft. This immature design was given to Shipyard A for further engineering and production. Engineers at Shipyard A, who lacked experience in working with large open spaces in ship hulls typical for passenger vessels, noticed the vibration issue after the production had started. To avoid redesigning and reengineering, steel stiffeners were cut and welded to strengthen the structure. Case 5 best presents the situation wherein a technological solution with low maturity was implemented. The exhaust to waterline system was designed by Ship designer A, which was further engineered by Shipyard E. This yard had never worked with this technology before. Consequently, the pipe arrangements were not correctly engineered, giving back pressure to the engine. The issue was only resolved by involving the design and engineering teams at the focal company. Case 6 also exemplifies the situation wherein the technologies used in the design developed by Ship designer A were not mature from the yard's perspective. When the customer requested changes, the shipyard needed support from Ship designer A to find solutions to the requested changes.

In comparison, Case 1 concerned ship size rather than specific technology. Case 2 is an implementation of a mature system: helicopter deck. Case 4 is an example where mature technology was used in the design where it was unsuitable.

Factor 4: Competence and experience of the focal company's design, engineering, and production staff

Comparison of Cases 3 and 4 with Cases 1, 2, 5, and 6 shows how the competence and experience of the engineering and production staff of the focal company affected EC implementation. The staff noticed issues with vibrations at a late stage, after the aft was built and water intake grids were installed (Cases 3 and 4). They lacked experience in working with passenger vessels, where vibrations need to be carefully accounted for. In Cases 1, 2, 5, and 6, the design and engineering staff of the focal company were competent and sufficiently experienced to provide the needed support to the external engineering and production teams.

Factor 5: Competence and experience of partner yards' engineering and production staff

The influence of this factor is visible in Cases 5 and 6, where the responsibility of implementing the changes was on Shipyards E and F. The rest of the changes occurred in projects where ECs were the responsibility of the focal company. The engineering and production staff at the focal company had more experience than the staff at Shipyards E and F. Decisions regarding changes at a focal yard are often made by engineers and shop-floor workers without the involvement of upstream functions. Designers and engineers at external yards are often less experienced and need support to solve ECs. In addition, when ECs occur at these yards, engineering and production activities are often stopped to obtain exact instructions on how to proceed, which further increases the EC implementation time and cost.

Factor 6: Degree of vertical integration in a supply chain

ECs 3, 5, and 6 occurred in projects with low degree of vertical integration. The design and engineering of the hybrid ferry (Case 3) were completed by separate companies located in the same country. The platform supply and cruise vessels (Cases 5 and 6, respectively) were designed in Country A but engineered and built in Country E. These cases show that in vertically disintegrated supply chains, EC implementation processes are longer and more expensive because achieving effective and efficient collaboration on ECs between the project actors is often difficult. In contrast, the ECs in Cases 1, 2, and 4 occurred in projects where the design, engineering, and most of the production were performed by the companies belonging to the same group.

Factor 7: Contractual distance between project actors

Case 6 exemplifies a situation wherein contractual distance negatively affected EC implementation performance. The customer could not directly contact the focal company because the contractual relationships were established between the design company and the yard and between the yard and the customer, making the communication process distorted, long, and expensive.

Factor 8: Physical distance between project actors.

Cases 5 and 6 are representative of the physical distance undermining EC implementation performance. In such cases, ECs are jointly resolved by the ship designer and shipyard located in different parts of the world and different time zones, which slows down the communication process when resolving ECs.

Factor 9: Cultural and organizational distance between project actors

Cases 5 and 6 are also examples wherein the design and engineering teams belong to different cultures and have a different understanding of boundaries between design and engineering. Shipyards in Country E expected the design drawings to be much more specific than the ones they received from the designer in Country A. When the customer required a range of ECs, the yards had to contact the design and engineering teams at the focal company for clarifications and explanations.

Contradictory examples of contractual, physical, cultural, and organizational distances are Cases 1–4. In Cases 1 and 2, the designers and engineers belonged to the same organization, were co-located, and had similar understandings of the boundaries between design and engineering. Communication between the two was efficient. In Case 3, although the design and engineering teams belonged to different companies, they were both located in Country A; therefore, physical and cultural distances played a lesser role. The same applies to Case 4. Although the collaborating designers belonged to different organizations, this did not have a considerable influence on EC implementation.

Factor 10: Degree of overlap between project stages

In the focal company, the design, engineering, procurement, and production activities overlap to shorten the delivery time. The influence of overlapping stages is visible in Cases 1 and 3. The ECs in both cases occurred when the steel production had started but engineering drawings were not finished. When implementing both changes, the engineering team had to deal with an unfinished set of documents, which made the detection of EC propagations difficult. Furthermore, steel production had to be stopped while the drawings were updated.

In Case 2, the engineering activities were already in process, but they had just started; therefore, the effect of overlapping stages was minimal. In Case 4, all design and engineering activities were finished when the change occurred, and the vessel was already out of the dock. Finally, in Cases 5 and 6, all project stages were sequential rather than overlapping: Ship designer A completed the design documents before sending them to the engineering teams at Shipyards E and F.

Factor 11: Formal, contractually binding professional culture

The focal company has established relationships with its customers in the offshore vessels market. Their customers are often local ship-owners with whom they have developed relationships based on mutual trust and support. When customer-initiated ECs occurred, they were quickly resolved by telephone calls without delving into contract specifications (Cases 1 and 2). The situation is different in the new passenger vessels market, where customers are contract driven. EC negotiation processes with these customers were long and formal and required the assistance of legal advisers (Case 6). Cases 3 and 5 represent mistakes in design and engineering that are resolved without customer involvement. An exception is Case 4, where the customer demanded the yacht to be taken to the dock to change the water intake grids. This was done despite the fact that the grids could be changed at a quay.

5.2. Ranking of factors affecting EC implementation cost

Table 4 shows the results of the expert assessment: mean scores and ranking for each case and factor. EC cost increase (%) at the bottom of the table shows the increase in the cost of each EC under the influence of the identified factors. The results are further interpreted and discussed in the next chapter.

[Table 4 near here]

Table 4. Ranking of the factors affecting EC implementation cost

Factors affecting EC implementation cost	Case 1 (EC1)		Case 2 (EC2)		Case 3 (EC3)		Case 4 (EC4)		Case 5 (EC5)		Case 6 (EC6)		All cases	All cases
	Mean score	Rank	Mean score	Rank	Mean score	Rank	Mean score	Rank	Mean score	Rank	Mean score	Rank	Mean score	Rank
1. Time of EC occurrence	4.67	1	2.67	1	3.67	3	4.33	1	4.33	1	4.00	3	3.94	1
2. Low maturity of the product design	2.33	4	2.00	3	4.67	1	2.67	4	2.67	5	2.67	6	2.83	4
3. Low maturity of the technology	2.33	4	2.00	3	3.00	5	2.00	6	3.67	2	2.67	6	2.61	6
4. Lack of competence and experience of the focal company's design, engineering and production staff	1.67	6	1.33	4	4.00	2	4.00	2	3.00	4	2.33	7	2.72	5
5. Lack of competence and experience of the partner yards' engineering and production staff	2.33	4	1.33	4	3.67	3	2.67	3	4.33	1	4.67	1	3.17	2
6. Low degree of vertical integration in a supply chain	2.67	3	2.33	2	3.67	3	2.33	5	3.33	3	3.67	4	3.00	3
7. Contractual distance between project actors	1.00	8	1.33	4	1.67	7	2.67	4	2.00	6	3.00	5	1.94	9
8. Physical distance between project actors	1.33	7	0.67	5	2.00	6	2.67	4	3.00	4	4.33	2	2.33	8
9. Cultural and organizational distance between project actors	2.00	5	1.33	4	1.33	8	2.67	4	2.67	5	4.00	3	2.33	8
10. High degree of overlap between project stages	3.00	2	2.33	2	3.33	4	2.67	4	2.00	6	2.33	7	2.61	6
11. Formal, contractually binding professional culture	1.67	6	2.00	3	2.00	6	3.67	3	2.00	6	3.67	4	2.50	7
EC cost increase, % of total ship cost price	***10%***		***30%***		***20%***		***5%***		***10%***		***5%***			

6. Discussion

Based on the above results, six propositions were developed. The propositions describe the relationships between the identified factors and EC implementation cost from the perspective of shipbuilding companies.

Factor 1: Time of EC occurrence

The results show that the time of EC occurrence is the most influential factor contributing to the increase in EC cost. This result supports the Rule of Ten idea that the cost of an EC exponentially increases with each phase of the product lifecycle (Fricke et al. 2000). Such increase is often explained by the fact that more coordination is needed to implement changes at later stages because more functions and people are involved (Fricke et al. 2000; Mello, Strandhagen, and Alfnes 2015; Mello et al. 2017). This study provides additional explanation for the increase in EC implementation cost in the production of ETO products: high risks of demolition, rework, and product damage, constrained working conditions, and longer travel distances.

Proposition 1: In a complex ETO environment, the further into production an EC is implemented, the higher is its implementation cost owing to increasing risks of demolition, rework, and product damage, constrained working conditions, and longer travel distances.

ECM research recommends avoiding late and expensive ECs by front-loading them to earlier stages (see ‘earlier’ strategy in Table 1). Customer-initiated changes, however, are often difficult to predict. For such changes, which are paid for by the customer, the correct assessment of EC cost is important. After the price is agreed upon and paid by the customer, any unpredicted expenses are paid by the company producing the product, thus eroding their profit margins. To avoid this, all EC propagations must be taken into consideration. Therefore, ETO companies may use ECM practices and tools to support accurate EC assessment: 'effective' strategy. These include 'soft' practices, such as the use of change propagation and impact assessment tools, and computer-based tools (see Table 1). A note of caution is due here. Both change propagation and impact assessment tools and computer-based tools merely *support* EC assessment, but it is people who feed data, create structure matrices, and make final decisions. Next, creating change prediction methods (CPM), design structure matrices (DSM), and system dynamics (SD) models are resource consuming and therefore can only be built on a high product level for complex products such as ships: EC propagations at lower levels might go unnoticed.

Factors 2–5: Maturity of the design/technology. Competence and experience of the focal company's and partner yards' design, engineering, and production staff

Cases 3, 4, 5, and 6 clearly show that the maturity of the design/technology and competence of the design, engineering, and production staff working on EC implementation are closely related. In these cases, low maturity product/technology designs were given to the yards for further engineering and production. The yards lacked experience with the given designs. Consequently, they were not properly engineered and produced, leading to either additional work (Case 3) or demolitions and rework (Cases 4–6). Negative influence of the lack of experience in terms of time and cost in construction projects is indicated by Yap, Shavarebi, and Skitmore (2020), who emphasize the importance of learning from previous project experiences.

By comparing Cases 3 and 4 with Cases 5 and 6, we noticed that the lack of competence and experienced of shipyards in Cases 5 and 6 had a higher impact on EC implementation cost. In Cases 3 and 4, the shipyard at the focal company was able to independently develop solutions and implement ECs, whereas Shipyards E and F (Cases

5 and 6) required the involvement of the ship designer, increasing the number of administrative hours used for EC implementation. This result suggests that EC implementation cost depends on the experience, competence, and *autonomy* of the engineering and production staff.

Proposition 2: In a complex ETO environment, the lower the levels of competence, experience, and autonomy of the engineering and production staff working on the ECs, the higher the EC implementation cost.

ECM research states that communication of ECs upstream to the design and engineering teams is necessary to guarantee that mistakes are not repeated in future and that all involved staff learn from the EC implementation process (Fricke et al. 2000; Yap, Abdul-Rahman, and Chen 2017). Mello, Strandhagen, and Alfnes (2015), on the contrary, emphasized the importance of the ability of the production staff to resolve emergent problems without involving the design team. This, according to the authors, reduces coordination effort. However, this does not mean that ECs should not be communicated to the upstream functions at all. Engineering and production staff can still develop solutions and independently implement ECs while directly reporting it later to the design team or centrally storing EC data to be available for everyone. For this purpose, ECM practices and tools ensuring centralized access to EC history can be used (see 'better' strategy in Table 1).

Factor 6: Degree of vertical integration in a supply chain

Overall, this factor is very influential in increasing the EC cost. In Cases 3, 5, and 6, the design and engineering/production were conducted by separate companies. The low level of vertical integration in these cases had a high impact on EC implementation cost, compared with Cases 1, 2, and 4, where most of the design and engineering/production activities were performed by the focal company. In Cases 1 and 2, part of the hull was produced by the external yard, and in Case 4, part of the design process was performed by the external designer. Consequently, the impact of vertical integration is low to medium in these cases. The results can be explained by the idea of integration and coordination difficulties in vertically disintegrated supply chains (Cigolini and Rossi 2008; Mello, Strandhagen, and Alfnes 2015; Gosling et al. 2014; Weck 2005). Cigolini and Rossi (2008) determined that coordination costs are lower when there is a high level of vertical integration and when business activities occur within few business units. Gosling et al. (2014) talked about the necessity of having minimum number of echelons in the ETO supply chains. They state that ETO companies should strive to reduce the number of handovers and interfacing issues between actors in the supply chain to avoid project failures. Weck (2005) also notes that the greater number of interfaces, the more complex it is to cope with changes in projects.

Proposition 3: In a complex ETO environment, the lower the degree of vertical integration between the design, engineering, and production functions, the higher the EC implementation cost.

ECM literature highlights the importance of integration and coordination between project actors. It suggests the establishment of cross-enterprise ECM processes (see Table 1). The issue with such processes in the ETO environment, however, is that some relationships between actors exist only for the duration of one project, making establishment of such processes unprofitable.

Factors 7–9: Contractual, physical, organizational, and cultural distance between project actors

The results show that these factors overall have relatively low impact on EC implementation cost. Cross-case comparison, however, shows that the impact of these factors was medium to high in Cases 5 and 6. In both cases, the design and engineering/production companies were in different countries: Countries A and E. In

Country E, the shipyards' expertise is developing fast. They are, however, not as experienced as the shipyards in Country A. In Case 6, the companies had a different understanding of the boundaries between design and engineering; engineers in the focal company were able to work with a much more basic design, as compared with their colleagues in Country E. This was especially visible when ECs occurred at the engineering stage and Shipyard F needed support from the focal company, increasing the administrative costs of ECs. Next, organizational structures in Shipyard A are flat; engineers and yard workers have autonomy to resolve ECs without approval from different managerial levels. In Shipyards E and F, the structures are more hierarchical, and ECs require management approval, which sometimes is a lengthy and expensive process. Necessity of managerial approval of all, even smallest issues, can be explained by the societal acceptance of unequal distribution of power (e.g. power distance) in counties where Shipyards E and F are located (Chipulu et al. 2016). In Cases 5 and 6, the design company and shipyards were in different time zones and the staff spoke different languages, which also added time and effort in the EC implementation processes. Finally, the communication between the design company and customers occurred through the yards owing to contractual restrictions, making the EC process more biased and expensive.

Proposition 4: In a complex ETO environment, the higher the contractual, physical, organizational, and cultural distance between project actors, the higher the EC implementation cost.

It is possible to argue that in Cases 5 and 6, the focal company should not bear any expenses related to ECs because the company was not responsible for EC implementation: all design drawings were sold to the external yards having contractual responsibilities to the customers. The final product, however, carries the stamp of the focal company; therefore, it is important for the company that the vessel of the highest quality is delivered to the customer, although it is not engineered or built in their own yard. That is why the focal company is actively involved in EC implementation. From the perspective of a focal company, such risks should be included in the design cost or addressed in a contractual agreement. From the perspective of external yards, these factors should be taken into consideration when assessing the EC implementation cost.

Factor 10: Degree of overlap between project stages

Comparison of Cases 1 and 3 with Cases 2, 4, 5, and 6 suggests that if ECs occur at a time when design, engineering, and production activities are simultaneously performed, EC implementation cost increases. This result might be explained by the information uncertainty. Under overlapping project activities, when moving from design to engineering and from engineering to production, design and engineering documents are released in batches; some components and systems are already engineered, whereas information on neighbouring systems and system interfaces is not yet available. In this situation, the assessment of EC propagations is based on the experience of the people involved rather than actual design and engineering data. Undetected propagations are discovered at later, more expensive project stages. These findings are in line with Hicks, McGovern, and Earl (2001) and Mello, Strandhagen, and Alfnes (2015), stating that ECs combined with missing information are major sources of increased coordination efforts in ETO projects with concurrent execution of design, engineering, and production activities. This study also suggests that EC cost increase is explained by the fact that under occurring ECs, the production had to be stopped to wait for the updated drawings. Later, to catch up with the schedule, additional resources were used.

Proposition 5: In a complex ETO environment, concurrent execution of design, engineering, and production activities increases EC implementation cost owing to high information uncertainty.

From the perspective of ECM research, ‘earlier’ strategy can be used to front-load ECs to early design stages, before engineering and production activities start (see Table 1). This is not always possible, especially in case of customer-initiated changes. In this case, the company needs to accurately assess ECs by taking the discussed factor into consideration.

Factor 11: Formal, contractually binding professional culture

The expert assessment of this factor confirmed the initial cross-case analysis. This factor had a considerable impact on the cost of ECs in Cases 4 and 6 compared with Cases 1, 2, 3, and 5. In Case 6, customer-initiated changes were implemented after long negotiation processes and the involvement of legal advisors. Case 4 is an example when the customer (private person) needed to dock the vessel at the yard for as long as possible to avoid payments for docking it elsewhere. They used the change as an opportunity to extend this period. Hence, the yacht was taken back to the dock, even though technically the EC did not require it. Contractual specifications, however, allowed the customer to delay the process.

Proposition 6: In a complex ETO environment, formal, contractually binding professional culture between the customer and companies undertaking the project increases the cost of customer-initiated ECs owing to long negotiation processes, involvement of legal advisors, and development of suboptimal EC implementation solutions.

Customer-initiated ECs can be partially reduced by change reduction and front-loading tools (Table 1). However, this can only be partially done; in long ETO projects, such ECs are unavoidable. It is important for complex ETO companies to take note of this factor and possibly review their contractual agreements if they consistently lose money on EC implementation owing to legal disputes.

7. Conclusions

7.1. Contributions and managerial implications

This study reported the results of a multiple case study investigating the contingency factors affecting EC implementation performance in the complex ETO environment. The first research question asked: *What are the contingency factors affecting EC implementation performance in the complex ETO production environment?* Through cross-case analysis, 11 contingency factors were identified (Table 3). These factors indicate the importance of taking production and supply chain characteristics into consideration when implementing ECs: risks of demolitions, rework, product damage and constrained work conditions at late production stages, degree of vertical integration in a supply chain, and contractual, physical, organizational, and cultural distance between project actors involved in a ship production supply chain. The results show that failing to take these factors into consideration leads to EC implementation cost overruns: by as much as 30% of the product cost price. This is an important contribution because pervious ECM research is focused on the design domain. For example, available change propagation and impact assessment tools are built based on DSM without taking the production and supply chain into consideration. Another example is computer-based tools, whose main objective is to maintain the integrity of the design and engineering drawings.

The second research question investigated the identified contingency factors in depth by asking: *How do the contingency factors affect EC implementation* *performance?* The answer comprises two parts. First, the ‘how’ was answered by measuring the degree of influence of each factor on the EC cost. The results show that overall, among all the studied cases, three factors had the highest influence on EC implementation cost: (1) time of EC occurrence, (2) lack of shipyards’ competence and experience, and (3) degree of vertical integration in a supply chain. Second, the mechanism of influence of each factor was described and discussed. As a result, six propositions describing the impact of the factors on the EC cost were formulated along with recommendations as to which ECM practices and tools can be used to reduce the negative impact of these factors. According to Love et al. (2019), empirical research examining the impact of changes on the cost performance of companies carrying out projects is limited. This study contributes to literature by considering EC implementation cost from the perspective of companies undertaking shipbuilding projects.

The results suggest that front-loading as many ECs as possible to the earlier stages of the project is important to avoid high production- and supply chain-related costs at later project stages. Next, the study emphasizes the importance of engineering and production staff’s ability to independently implement ECs, without unnecessary involvement of the design and management teams. The information on these ECs, however, should still be made available for everyone to avoid similar ECs in the future. In vertically disintegrated supply chains, cross-company EC processes should be established between project actors. If this is not possible (e.g. actors are working together only for the duration of one project), the risks associated with disintegrated supply chains should be taken into consideration when assessing the EC implementation cost. These include contractual, physical, organizational, and cultural distances and low levels of expertise, experience, and autonomy of project actors.

In conclusion, relating to the large problem of cost overruns in ETO projects, the study suggests that failing to take the identified factors into consideration reduces the profit of the companies undertaking the project. First, emergent changes are fully covered by the companies themselves and the later into the production they are discovered, the higher is the cost of these changes and consequently the higher is the decrease in profit. Second, even though customer-initiated changes are covered by the customers, any costs not included in the change order request are covered by the companies themselves.

Regarding the managerial implications for this research, we believe that this study will help practitioners operating in the complex ETO environment to (1) more accurately assess EC implementation cost by considering the factors described and (2) make informed decisions when choosing ECM practices and tools – know what practices and tools can eliminate or reduce the negative effects of the identified factors.

7.2. Study limitations and suggestions for further research

The study has limited generalizability because only the ECs occurring in shipbuilding projects were studied. Generalizability can be increased by adding ECs occurring in project undertaken by companies of the same archetype (complex ETO) and/or different ETO archetypes – basic and repeatable ETO.

The impacts of contingency factors on EC implementation performance are considered based on the subjective opinions of the interview participants. To address this issue, an in-depth longitudinal case study might be performed, where researchers follow several ECs from their initiation to implementation. Researchers should try, with the help of the project team, to collect accurate quantitative data on occurring ECs. A longitudinal study might also bring to light additional contingency factors.

The results of this study suggest that contingency factors directly affect EC implementation performance. However, EC implementation performance might also be affected by the ECM practices and tools used by the companies. Hence, future research could investigate the possible links between contingency factors, ECM practices and tools adopted by the company, and EC implementation performance.

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[Appendix A near here]

Appendix A. Interview Guide

Project and product characteristics

1. What kind of vessel was built in the project? How many of such vessels were previously built by the companies involved in the project?

2. How would you estimate the innovativeness and complexity of this product? How much of the product design was re-used and how much was designed from scratch?

3. What companies (design, engineering, production) were involved in the project? Where are they located? What is the nature of the relationships between these companies?

EC characteristics

4. Please describe the EC. Who initiated the change? What exactly was changed in the product and why? What was the solution to the change? Who developed the solution?

5. At what stage of the project did the EC occur?

6. Did the change propagate to other parts, components, or systems of the product? What are these parts, components, and systems?

7. What departments, functions, and companies were affected by the change? How were they affected by the change? What were their roles in EC assessment and implementation?

EC impacts

8. What was the initially assessed cost and time needed to implement the EC? What was the actual cost and time needed to implement the change?

9. What were the impacts of an EC on the project cost and duration?

10. Who took the financial responsibility for covering the expenses connected to the change? Was there any profit earned on this change?

11. Were there some impacts you did not account for during the EC assessment and implementation (e.g. unexpected propagations, delays, and rework)? Did they affect EC implementation cost and time or project cost and duration?

Factors affecting EC implementation

12. Were there any specific product, project, or EC characteristics that contributed to the increase in EC implementation cost and time or project cost and duration?

13. Were there any other factors that contributed to the increase in EC implementation cost and time or project cost and duration?

14. What contributed to the occurrence of the change? Do you think this EC could have been avoided?