Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 51-11 (2018) 144–151

Managing engineering changes in the engineer-to-order environment: challenges and research needs

Natalia Iakymenko*, Anita Romsdal*, Marco Semini*, Jan Ola Strandhagen*

* *Norwegian University of Science and Technology, S.P. Andersens vei 5, 7031, Trondheim, Norway (e-mail: natalia.iakymenko@ntnu.no, anita.romsdal@ntnu.no, ola.strandhagen@ntnu.no, marco.semini@ntnu.no)*

Abstract: Engineering changes (ECs) in companies in the engineer-to-order (ETO) production environment are practically unavoidable. It is important for ETO companies to accommodate ECs throughout the project duration, effectively and efficiently managing them in order to decrease their potential detrimental consequences. A lot of research exists on engineering change management (ECM) in general, but our study reveals a need for further investigation of ECM in the ETO sector. This theoretical study has two main contributions: (i) analysis of research on ECM, outlining general challenges and discussing these in the light of the ETO production environment, and (ii) suggestions for future research.

Keywords: engineering change, engineering change management, challenges, engineer-to-order.

1. INTRODUCTION

In the engineer-to-order (ETO) production environment, a product is designed, engineered and produced after a customer order has been received. Typical ETO products include ships, offshore platforms, power generation plants, fish farms, and original architecture houses. Production of such products is often project-based. Customers are involved throughout design, engineering and production to ensure that all specifications are met (Olhager, 2003). In such environments, engineering changes (EC) are common and inevitable (Hamraz et al., 2013). Unlike make-to-stock and mass production environments where ECs are mainly managed before the start of production, ETO companies must be able to accommodate ECs throughout the project duration, even during physical production (Semini et al., 2014).

Implementation of Engineering Change Management (ECM) practices is argued to potentially reduce the detrimental effects of ECs (Jarratt et al., 2005). The overall goal of ECM is to integrate changes into the product development cycle with as few disruptions as possible. Generic ECM process models, tools and techniques have been developed to control and implement changes, and support decision-making in ECM. However, ECM research and practice are still facing a range of challenges. In addition, limited research exists on ECM in the ETO environment. Hence, the purpose of this paper is firstly to identify the most important ECM challenges, secondly to discuss them in light of ETO production environment characteristics, and lastly to outline an agenda for future research on ECM in the ETO sector.

After a description of the research methodology in the next chapter, we define ECs, outline the characteristics of ECs in the ETO environment, and introduce ECM. Next, ECM challenges are identified and discussed, and a number of key research needs outlined before the paper concludes.

2. METHOD

This paper is based on a systematic review of literature on ECM. Literature reviews represent an important element of any research (Baker, 2000, Cooper, 1988). They 1) enable mapping, summarising and evaluating the knowledge base relevant for a studied topic, and 2) provide guidance for future studies to address knowledge gaps.

To identify relevant references in the literature, three search strategies were used. First, random search was performed to gain insights into the topic and expand the vocabulary for more precise subsequent searches. Based on the random search, a list of key words was compiled. The key words were used for the second search strategy – building blocks search (Booth, 2008), where key words were separated into three thematic blocks; changes, ETO and challenges. Each block was searched separately, then blocks were combined using Boolean operators. The search results were documented in a log book. Building block search was performed in several databases including Web of Science, Scopus, ProQuest and Google Scholar. More than 3500 papers were found. Based on titles, 224 papers were chosen for further reading. After the abstracts were read, 118 papers were left for full text reading, which further led to identification of additional 97 papers deemed relevant for the research. Only journal and conference papers have been considered. Finally, a cited reference search was performed, where key papers and literature review papers were used to identify other relevant sources. This led to another 55 papers to be included in the research.

We identified that studies on ECs have been conducted mainly within three research domains: project management, engineering design, and production management. This paper takes a holistic perspective and is not limited to any particular domain. The paper contains the main references on the topic of interest and is not a comprehensive literature review that

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2018.08.249

includes all the identified papers. Although the literature review focuses on ECM in general, the paper discusses ECM in light of the typical characteristics of the ETO production environment.

3. WHAT ARE ENGINEERING CHANGES?

Slightly differing terms for engineering changes are used in literature: engineering changes (Hamraz et al., 2015), engineering design changes (Fei et al., 2011), and product design changes (Morris et al., 2016). We use the term EC in this research. In order to cover a wide range of research on ECs, Hamraz et al. (2013) developed a broad EC definition:

"ECs are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials, etc.), behaviour (stability, strength, corrosion, etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact".

ECs can be triggered by customers, the company's management or internal departments, suppliers, partners, governmental bodies, and by market drivers such as technology and regulation.

4. ENGINEERING CHANGES IN THE ENGINEER-TO-ORDER PRODUCTION ENVIRONMENT

Implementation of ECs in mass production environments mainly takes place through the development-design process, where the product is gradually improved (Tavčar and Duhovnik, 2005). In the development-design process, ECs are often implemented in a batch technique if they are not urgent (due to for example safety issues). In other words, ECs are accumulated and realized during the next production lot, making them a part of new product version or model release (Nadia et al., 2006). This method is used in industries such as automotive, software and electronics. Applying this method in the ETO production environment is difficult, if not impossible. Instead of supplying customers directly from a finished goods warehouse, an ETO company designs, engineers, produces and commissions complex products according to highly specialized customer requirements (Caron and Fiore, 1995). Products are produced in low volumes (often volumes of one), and have a deep and wide bill of material (Hicks et al., 2000, Stavrulaki and Davis, 2010). ECs in this situation are introduced to the current customer order and cannot be postponed to the next order.

In the ETO environment, design, engineering, production and procurement activities are often performed concurrently to shorten the project duration (Bertrand and Muntslag, 1993, Semini et al., 2014). Materials used for production in the ETO environment range from commodities readily available from the market to highly customized components sourced based on specific needs of the product's design (Stavrulaki and Davis, 2010). Customized components often have long lead-times, which means they have to be ordered early in the project (Bertrand and Muntslag, 1993). In this situation, ECs can affect components that have already been ordered from a supplier, where the component might already have been

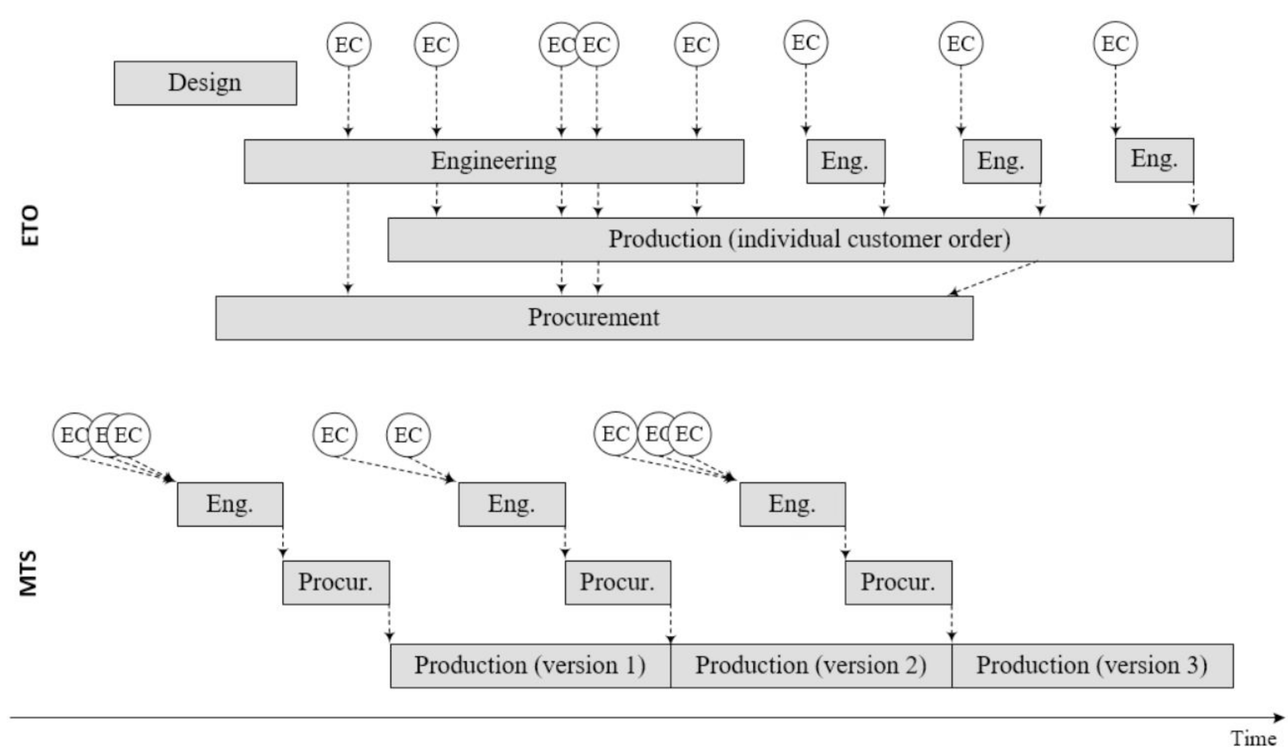

Fig.1. Engineering change implementation in ETO and MTS production environments

produced or even delivered. ECs need to be implemented immediately since production is progressing and late implementation might lead to rework, demolition, or even scrapping.

Figure 1 illustrates how ECs are implemented differently in typical ETO and MTS production environments. In MTS (bottom part of Figure 1), ECs are collected in batches, engineering drawings are revised and new updated components are ordered from suppliers. Thus, ECs are not implemented until the production of a new version of the product is started. In ETO (upper part of Figure 1), ECs are implemented throughout the duration of the project. Engineering drawings are updated based on a change request. ECs can also affect ongoing production and even procurement if the change propagates to components procured from suppliers. ECs can even have consequences for supplier components that have already been produced and delivered to the shop floor.

The above differences can be illustrated by comparing how ECs are implemented in the automotive and shipbuilding industries. Changes to a car's interior are for instance typically batched and rolled into the next lot of production. In this case, already procured components can be gradually phased-out before the company orders new ones. In shipbuilding, however, changes to a ship's size or capacity must be implemented into the existing customer order. If the production of the vessel's hull has been finished and outfitting work started, then accommodating such changes will be very complicated and might lead to a lot of scrapping and rework, in addition to considerable increases in project costs and duration.

The implications of how typical ETO characteristics impact on the management of ECs are further discussed in Chapter 6.

5. ENGINEERING CHANGE MANAGEMENT

A number of processes, tools and techniques for managing ECs exist. Companies that succeed in adopting such ECM practices can improve their competiveness in a number of areas such as cost, quality, and schedule. Thus, the benefits of efficient and effective ECM are twofold; it can avoid the significant costs caused by ECs, and it can generate additional profit by satisfying customer needs (Hamraz et al., 2013, Jarratt et al., 2011). Fricke et al. (2000) concluded that "without an adequate change management only two alternatives exist: to die of changes, or to miss the chance of a successful product".

A variety of frameworks and tools have been developed to support ECM. Generic ECM process models have been proposed, typically including the following steps: identify change, assess its impacts, implement change, and review the process (Jarratt et al., 2005, Lee et al., 2006). For each ECM stage, a range of tools and techniques to control, analyse, and predict change propagation have been suggested (listing all of the tools is outside the scope of this paper). However, despite the availability of a vast amount of tools, there are still gaps and challenges in ECM research and practice that remain to be addressed. These challenges are further presented and discussed in the context of ETO in the next chapter.

6. CHALLENGES OF ENGINEERING CHANGE MANAGEMENT

The literature review identified a number of unsolved challenges related to ECM. The most critical ones are described and discussed below. These challenges provide the basis for the research needs highlighted in chapter 7.

6.1 EC propagation control

Dealing with ECs is not straightforward. For ETO products with complex product structures, an EC is seldom limited to a single change. ECs often have knock-on effects that trigger follow-up changes in different components, subsystems and processes – which may further lead to increases in project lead time and cost. This phenomenon is known as change propagation (Hamraz et al., 2015). Change propagation can create a snowballing effect and in some cases even affect the whole system and involve many actors working on the product development (Eckert et al., 2004).

Being able to identify change propagation has been recognized as an important part of the ECM process as it enables companies to foresee unanticipated influences and act on them (Morkos et al., 2012). The difficulty in managing propagated changes stems from the complexity of product development, which typically involves most disciplines in the company, as well as external suppliers. In this situation, keeping an updated overview of the whole product and all network linkages is highly challenging.

Even though change propagation is a widely discussed topic in literature, it is mostly based on methods requiring manual input based on personal experience. The most widespread change prediction models (CPM) include the Design Structure Matrix (DSM) and the Propagation Network and Propagation Tree (see for example Hamraz et al. (2015). These are used to visualize the propagation paths, showing where components couple, as well as allowing estimation of a propagation probability for each component. The CPM is created by breaking a product into sub-systems in order to view how parts and components are connected to each other. Further, value reflecting the probability of change propagation between pairs of components and value reflecting the severity of each change are added. These models are used in practice, but they have some drawbacks. Firstly, product breakdown and risk estimations are based on the knowledge and expertise of designers and engineers. Even though experienced designers and engineers are often able to identify propagation between nonadjacent components, it is difficult to systematically evaluate all potential change options (Keller et al., 2005). For example, an Aberdeen Group report (as reported by Giffin et al. (2009)) showed that only 11 % of the questioned companies were able to provide a precise list of items affected by a change. Secondly, there are questions as to whether the generic data supplied by experts can predict specific changes (Jarratt et al., 2011). Thirdly, all these models consider individual change requests, where one change is introduced to a system at a given time – while in practice, multiple changes occur at the same time (Jarratt et al., 2011).

In addition to the issues above, there are additional specific issues for the ETO environment. Change propagation tools aim at supporting changes to a given design. The question is then if the given set of data developed for one customer order remains valid for the next one and to what extent. If the entire model has to be updated for each order, doing so for complex products would require considerable resource consumption. In addition, studies on the application of CPM tools have mainly focused on products with medium complexity (such as fans and engines). In the ETO environment, products often have a much higher level of complexity, reducing the applicability of such models.

A number of conceptual automatic decision support tools have been developed by researchers, such as the ADVICE tool developed by Kocar and Akgunduz (2010), and the framework to automate the identification of affected parts developed by Reddi and Moon (2009). The idea of such tools is to use information about previous change propagations to anticipate how new ECs will propagate. These tools show a lot of promise in theory, but there is still a lack of commercial software and industrial case studies demonstrating their usability (Hamraz et al., 2013, Jarratt et al., 2011).

Some commercial software with embedded ECM processes exist, such as Configuration Management, Product Data Management (PDM) and Product Lifecycle Management (PLM). These are however only based on direct linkages identified through the bill of material available in the system (Riviere et al., 2003) and therefore do not capture indirect propagations. Commercially available Building Information Modelling (BIM) software is able to detect some propagations, but to a limited extend. Research suggests that dependency matrices should still be used to assist with automating the propagation and impact of changes in BIM (Pilehchian et al., 2015).

6.2 EC impacts on production and supply chain

Research in the area of ECM has focused heavily on improving the approaches of modelling linkages between different product parts and components, and detailed analysis of EC propagations to determine their impacts on product design as shown in Chapter 6.1. The focus has mainly been on the engineering phase, without proper consideration of implications for the physical production phase of the project and the associated supply chain. Change propagation affects not only design processes within the product design and engineering phase, but also processes throughout the supply chain. A single change in product specifications may require adjustments in several parts of the product, which will propagate throughout the supply chain, from design and engineering departments to supply, procurement, manufacturing and post-manufacturing stages (Kanerva et al., 2002). Research on the impact of ECs on production and the supply chain is presented below.

6.2.1 Impacts on production

Wänström and Jonsson (2006) studied the impact of ECs on materials planning. They developed a framework for describing the impact of ECs on materials planning processes and the effect in terms of revenue, tied-up capital and cost. In their next paper, Wänström et al. (2006) developed a model to facilitate allocation of materials planning resources in change situations. Both studies focused on the automotive industry and assumed batch implementation of changes. In batch implementation, all changes to the product are known before production starts. This allows a company to plan the materials, parts and components to order from suppliers for the production of a new product version. Consequently, these studies are not applicable in the ETO context where ECs are often introduced to a customer order after the production of the order has started and materials, parts and components have already been ordered.

Studies in the project management research domain have addressed impacts of changes on the production phase in ETO projects. Hanna et al. (2004) presented a method to quantify the impact of changes on labour productivity. Serag et al. (2010) analysed 11 variables that might affect the percentage increase in the contract price due to change orders, where two of the variables are related to the production stage of the projects: rework and work stoppages at the construction site. Sun et al. (2009) created a taxonomy of change effects, which include logistics delays, rework, productivity degradation, and others. Even though such studies provide valuable insights into the potential impacts of changes on production, they have limitations. They take a holistic perspective on the project, which means it is often difficult to say which stage of the project is impacted by the change. They also often analyse only one parameter impacted by the change, such as labour productivity. Further, they list change impacts and develop tools to measure such impacts, but do not provide suggestions as how to minimize them. And lastly, they consider changes to include alterations to product, project program and other project aspects, of which ECs are only one part.

6.2.2 Impacts on supply chain

Lin and Zhou (2011) addressed the supply chain perspective in their study, where they identified potential supply chain risk dimensions within the context of customer-required ECs in the automotive industry. They identified that design change leads to risks in supply, delivery, policy, planning, production, information, and organization. Their work identified supply chain risks, but did not assess the severity of the risks, nor did it provide best practices or approaches to risk management in supply chains within the EC context. In addition, only customer-required ECs in the automotive industry were addressed.

ECM challenges across the supply chain were investigated by Morris et al. (2016). The study was conducted in companies producing complex, high-value products such as aircrafts, ships and trains. They identified that the main challenges were related to product information. In order to address these challenges, the authors suggested a list of requirements to better manage design changes. The requirements include integration of change management systems within and across organizations, sharing product-related information, developing transparent product data exchange standards, and improving the flow of information. The study did not provide guidelines as to exactly how these requirements can be achieved. In addition, only changes happening during operational service due to maintenance and part replacements are addressed in the paper.

The issue of production information sharing in supply chains under ECs occurrence was also addressed by Wasmer et al. (2011). They developed an approach for shared, cross-organization EC handling by a standardized data model. Their approach addresses issues related to cross-organizational design under ECs, but does not address production and logistics issues. Furthermore, their approach was only tested in the automotive industry.

Conducted studies give valuable insights into supply chain risks and challenges associated with ECs. However, more research is needed to study ECs in the ETO supply chain environment. As mentioned in Chapter 4, in the ETO environment, many parts and subassemblies are ordered from suppliers early in the project. These are often customized and can only be used for producing a single unique customer order. Unlike in make-to-stock and mass production environments, parts cannot be gradually phased-out before ordering updated parts and subassemblies. If any ECs occur that influence ordered parts, rework has to be performed on the parts or they might even have to be scrapped and produced from scratch. This potentially leads to delivery delays from suppliers, demolition, scrapping, and reordering costs. Best practices and approaches to reduce negative impacts of ECs on the supply chain need to be identified or developed.

6.3 Knowledge management

Similar ECs tend to arise in more than one project. Often, previous changes are not documented and therefore not available in future projects. Knowledge about past ECs can make it possible to avoid processing the same ECs again, thus saving time and money (Kocar and Akgunduz, 2010). Such knowledge can also help in determining EC impacts (Mehta et al., 2013).

IT systems that support ECM, such as PLM and PDM software, are capable of supporting approval of engineering change orders (ECOs), and storage and retrieval of EC documents through key word searches. However, it is difficult to trace similar engineering change cases in such systems.

There are several information system approaches to capture and reuse knowledge on ECs. For example, Fei et al. (2011) proposed a knowledge-based method to resolve design issues by reusing previous design knowledge. When a specific design conflict is identified during the change analysis, it is compared to the knowledge repository to find similar design cases. These cases are further used to solve the current design conflict. The authors developed a prototype system to show the feasibility of the method. Mehta et al. (2013) developed a knowledge-based approach for determining important EC attributes that should be compared to find similar part ECs. An example of the knowledge base was created to test their measures. Do (2015) extended the PDM database to include history of ECs for future EC analysis. They specified the attributes and behaviours of ECs and a standard data model to represent the EC and EC history in the PDM database. The authors developed a prototype system. Unfortunately, tools developed by researchers are not commercially available for testing in other companies.

Both commercially available IT systems and systems developed by researchers are able to capture only formal, structured and mature knowledge. However, there is a lot of tacit, informal knowledge in the ETO production environment, which is important for EC impact estimations. ETO projects are labour-intensive. In countries with a highly skilled workforce, shop floor operators have extensive knowledge and experience. When an EC leads to challenges in physical production, for instance due to mistakes in drawings, operators are often able to find new solutions and handle issues by themselves without involving engineers, designers or managers. When information on how previous ECs were managed is not documented or readily available, it can be lost - often leading to repetition of old mistakes, even if similar problems have been solved previously (Hölttä et al., 2010). Thus, effective tools for knowledge management is a critical part of ECM, particularly in complex production environments such as ETO - and currently, there are no such knowledge management systems commercially available.

6.4 Collaboration and integration

Companies delivering ETO products often involve various disciplines and geographically dispersed actors working together on one project. Such complex networks require effective and efficient collaboration in order to connect the actors and the product and process knowledge of their enterprises (Mello et al., 2015).

There are three main issues related to achieving efficient and effective collaboration in the ECM process. The first issue is the sequential processing of information. This typically occurs when the ECM process is either paper-based or supported by standalone IT systems used by different disciplines, without functionality for simultaneous user access. Hence, information about ECs has to be updated in each individual IT system, making it a long sequential process. This can have severe consequences in the ETO environment where changes are often introduced after production has started. In such cases, production can be progressing based on outdated versions of a part, component or subassembly because IT systems are still being updated.

Another collaboration issue related to information processing stems from the use of different engineering data formats and multi-database formats. Wu et al. (2014) developed an advanced configuration management-based ECM framework from the design and production domains based on the integration of PLM and Enterprise Resource Planning (ERP) systems. However, the framework does not address the issue of data integration between PLM and ERP. According to Rashid and Tjahjono (2016), the present architecture of ERP systems has limited capabilities for product data integration and transformation of engineering bill of materials (E-BOM) to manufacturing bill of materials (M-BOM). In addition, as Wu et al. (2014) point out, their framework needs to be further tested and expanded to integrate for example manufacturing execution systems (MES) to allow dynamic information to drive effective execution of factory shop floor operations and supply chain management (SCM) for facilitating collaboration with suppliers.

The third collaboration issue is related to insufficient communication between disciplines, noted to be one of the most frequent reasons for problems in ECM (Eckert et al., 2004, Jarratt et al., 2011, Tavčar and Duhovnik, 2005). Hölttä et al. (2010) found that roles and responsibilities in ECM are often unclear and that unclear responsibilities can delay notifying others and reacting to an EC. Hamraz et al. (2013) concluded that there is little research on how ECM can be improved through people-oriented measures. Such measures include optimization of organization and team structures for collaboration, improvement of both the quality and frequency of communication and knowledge sharing among designers, between designers and disciplines, and with customers and stakeholders, as well as development of designers' technical expertise and soft skills, work life balance and working conditions. Research shows that in the ETO production environment, poor coordination and collaboration among parties involved in the production of the product can lead to considerable delays and cost overruns (Mello et al., 2015).

7. RESEARCH NEEDS

Based on the current state of knowledge and previous research described above, we identify a number of areas for further research on ECM in the ETO environment.

Change propagation control. In the ETO environment, each product is unique and all products have a high level of complexity. This raises questions such as; would it be possible for a company to reuse CPM developed for one ETO product for another ETO product, and to what extent? Are CPMs applicable to high-complexity products or will the efforts required to build the model erode their potential contribution to project performance? We suggest that these models should be further evaluated by applying them in more ETO cases. The improvements from model application should be measured and compared to the efforts required to build the models.

ECs and their influence on production and supply chain. Very few papers were identified that go outside the engineering design domain and address the influence of ECs on production and supply chain. In the ETO environment, changes are often introduced to a customer order after physical production has started. In addition, many parts and subassemblies are ordered early in the project and might need to be altered due to ECs. Future research should investigate questions such as; what are the impacts of ECs on production processes such as materials and resources planning and scheduling, inventory management, and logistics – and what are their subsequent impacts on project performance? What are the best practices and approaches aimed at reducing negative impacts of ECs on production processes? What are the best practices and approaches for reducing supply chain risks stemming from ECs? For example, can involvement of suppliers in developing alternative solutions for ECs help in reducing their negative impacts?

Knowledge management. While the explicit knowledge on ECs is usually documented, although often in different IT systems across the company, tacit knowledge is not captured and therefore lost when an employee retires or changes work place. There is a need to develop processes and tools for capturing and reusing knowledge generated by both engineers, planners and shop floor workers during the EC implementation process. The captured knowledge might also contribute to solving ***collaboration and integration*** issues caused by insufficient communication between disciplines. For example, collecting and sharing feedback from shop floor workers on manufacturability of the changed product can help design and engineering avoid repeating mistakes and improve how ECs are managed. Human-oriented measured for improved ECM should be addressed in future studies. Research should include both internal and external collaboration issues, addressing questions such as; what are the obstacles for internal and external collaboration? What are the measures that can be adopted by ETO companies in order to improve collaboration among participants in an ECM process?

IT support tools for ECM. Several, if not most, of the above issues can at least partially be addressed by IT support solutions. Hence, there is a need for further development of IT solutions with functionality for supporting ECM by:

- automatic tracking of change propagations on products, processes and disciplines within and outside the company,
- capturing and tracking change propagations of multiple changes happening at the same time,
- updating information on what has been changed in real-time,
- integrating systems where updated product and process information is available simultaneously to avoid sequential processing of data,
- supporting decision-makers by providing knowledge on similar changes that happened before, and
- enhancing collaboration among participants within and outside the company boundaries.

The current development of digital technologies, such as virtual reality, cyber-physical systems, sensor technologies and big data analytics, are argued to provide industry with radical improvements in all business areas (Kagermann, 2015). Some researchers have already started to explore issues of applicability of digital technologies for handling ECs. For example, Aurich and Rößing (2007) suggested an approach of using virtual reality to analyse ECs and to evaluate the impact of the changes on the elements of the production system. Additional research is needed to investigate if and how these technologies can improve ECM, particularly in highly complex production environments such as ETO. For example, sensor technologies could be used to collect real-time information about the current progress of production. This information could further be used by engineers to develop EC solutions with the least negative impact on ongoing production in terms of demolition, scrapping and materials needed.

Digital tools, if correctly applied, may offer powerful new ways to manage ECs. However, tools should not drive solutions. Each company should have a clear view of their needs and find a digital solution to support them. Hence, there is also a need for more empirical research on the practical needs in different industries.

Theory-practice gap. Often there is a lack of evidence that tools developed by academics are followed-up and further tested in practice. Empirical studies are required to better understand the actual challenges and needs concerning ECM. Research is needed to better understand industrial practice, to what degree ECM tools and methods developed over the past decade have been implemented, and if they are still relevant in light of the current business environment and emergent trends, in particular digital technologies.

8. CONCLUSIONS

This theoretical study has provided some insights into ECM challenges and discussed them in light of the ETO production environment. The identified challenges form part of a future research agenda in the field of ECM. We suggest future research should focus on issues such as change propagation control, production and supply chain, collaboration and integration, knowledge management, and IT solutions to support ECM processes. There is a clear lack of papers looking at the impacts of ECs on ETO production and the associated supply chains compared to research on change propagation control at the design stage of a project. In addition, past research has focused heavily on the MTS production environment and the applicability of the findings from such studies should be tested in ETO. Further, there is a need for more empirical research comparing ECM in different ETO production environments (e.g. ships, fish farms and offshore platforms) to identify best practices and investigate how contextual factors influence ECM. Also, emerging Industry 4.0 technologies should be investigated to assess how they can support and improve ECM in the ETO production environment.

REFERENCES

Aurich, J. & Rößing, M. (2007). Engineering change impact analysis in production using VR. *Digital Enterprise Technology*, 75-82.

Baker, M. J. (2000). Writing a literature review. *The Marketing Review,* 1**,** 219-247.

Bertrand, J. & Muntslag, D. (1993). Production control in engineer-to-order firms. *International Journal of Production Economics,* 30**,** 3-22.

Booth, A. (2008). Unpacking your literature search toolbox: on search styles and tactics. *Health Information & Libraries Journal,* 25**,** 313-317.

Caron, F. & Fiore, A. (1995). 'Engineer to order'companies: how to integrate manufacturing and innovative processes. *International Journal of Project Management,* 13**,** 313-319.

Cooper, H. M. (1988). Organizing knowledge syntheses: A taxonomy of literature reviews. *Knowledge, Technology & Policy,* 1**,** 104-126.

Do, N. (2015). Integration of engineering change objects in product data management databases to support engineering change analysis. *Computers in Industry,* 73**,** 69-81.

Eckert, C., Clarkson, P. J. & Zanker, W. (2004). Change and customisation in complex engineering domains. *Research in engineering design,* 15**,** 1-21.

Fei, G., Gao, J., Owodunni, O. & Tang, X. (2011). A method for engineering design change analysis using system modelling and knowledge management techniques. *International Journal of Computer Integrated Manufacturing,* 24**,** 535-551.

Fricke, E., Gebhard, B., Negele, H. & Igenbergs, E. (2000). Coping with changes: causes, findings, and strategies. *Systems Engineering,* 3**,** 169-179.

Giffin, M., de Weck, O., Bounova, G., Keller, R., Eckert, C. & Clarkson, P. J. (2009). Change propagation analysis in complex technical systems. *Journal of Mechanical Design,* 131**,** 081001.

Hamraz, B., Caldwell, N. H. & Clarkson, P. J. (2013). A holistic categorization framework for literature on engineering change management. *Systems Engineering,* 16**,** 473-505.

Hamraz, B., Caldwell, N. H., Ridgman, T. W. & Clarkson, P. J. (2015). FBS Linkage ontology and technique to support engineering change management. *Research in Engineering Design,* 26**,** 3-35.

Hanna, A. S., Camlic, R., Peterson, P. A. & Lee, M. J. (2004). Cumulative effect of project changes for electrical and mechanical construction. *Journal of Construction Engineering and Management-Asce,* 130**,** 762-771.

Hicks, C., McGovern, T. & Earl, C. (2000). Supply chain management: A strategic issue in engineer to order manufacturing. *International Journal of Production Economics,* 65**,** 179-190.

Hölttä, V., Mahlamäki, K., Eisto, T. & Ström, M. (2010). Lean information management model for engineering changes.

Jarratt, T., Clarkson, J. & Eckert, C. (2005). Engineering change. *Design process improvement*, 262-285.

Jarratt, T., Eckert, C. M., Caldwell, N. H. & Clarkson, P. J. (2011). Engineering change: an overview and perspective on the literature. *Research in engineering design,* 22**,** 103-124.

Kagermann, H. (2015). Change through digitization—Value creation in the age of Industry 4.0. *Management of permanent change.* Springer.

Kanerva, M., Lietepohja, M. & Hakulinen, P. (2002). Shipbuilding Processes - Challenges and Opportunities. Deltamarin Ltd, Raisio, Finland: Delta Marine, IBM.

Keller, R., Eckert, C. & Clarkson, P. (2005). Multiple views to support engineering change management for complex products. *Coordinated and Multiple Views in Exploratory Visualization, 2005. Proceedings. Third International Conference on*, 33-41.

Kocar, V. & Akgunduz, A. (2010). ADVICE: A virtual environment for Engineering Change Management. *Computers in Industry,* 61**,** 15-28.

Lee, H. J., Ahn, H. J., Kim, J. W. & Park, S. J. (2006). Capturing and reusing knowledge in engineering change management: A case of automobile development. *Information Systems Frontiers,* 8**,** 375-394.

Lin, Y. & Zhou, L. (2011). The impacts of product design changes on supply chain risk: a case study. *International Journal of Physical Distribution & Logistics Management,* 41**,** 162-186.

Mehta, C., Patil, L. & Dutta, D. (2013). An approach to determine important attributes for engineering change evaluation. *Journal of Mechanical Design,* 135**,** 041003.

Mello, M. H., Strandhagen, J. O. & Alfnes, E. (2015). Analyzing the factors affecting coordination in engineer-to-order supply chain. *International Journal of Operations & Production Management,* 35**,** 1005-1031.

Morkos, B., Shankar, P. & Summers, J. D. (2012). Predicting requirement change propagation, using higher order design structure matrices: an industry case study. *Journal of Engineering Design,* 23**,** 905-926.

Morris, A., Halpern, M., Setchi, R. & Prickett, P. (2016). Assessing the challenges of managing product design change through-life. *Journal of Engineering Design,* 27**,** 25-49.

Nadia, B., Gregory, G. & Vince, T. (2006). Engineering change request management in a new product development process. *European Journal of Innovation Management,* 9**,** 5-19.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International Journal of Production Economics,* 85**,** 319-329.

Pilehchian, B., Staub-French, S. & Nepal, M. P. (2015). A conceptual approach to track design changes within a multi-disciplinary building information modeling environment. *Canadian Journal of Civil Engineering,* 42**,** 139-152.

Rashid, A. & Tjahjono, B. (2016). Achieving manufacturing excellence through the integration of enterprise systems and simulation. *Production Planning & Control,* 27**,** 837-852.

Reddi, K. R. & Moon, Y. B. (2009). A framework for managing engineering change propagation. *International Journal of Innovation and Learning,* 6**,** 461-476.

Riviere, A., Féru, F. & Tollenaere, M. (2003). Controlling product related engineering changes in the aircraft industry. *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm*.

Semini, M., Haartveit, D. E. G., Alfnes, E., Arica, E., Brett, P. O. & Strandhagen, J. O. (2014). Strategies for customized shipbuilding with different customer order decoupling points. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment***,** 1475090213493770.

Serag, E., Oloufa, A., Malone, L. & Radwan, E. (2010). Model for Quantifying the Impact of Change Orders on Project Cost for US Roadwork Construction. *Journal of Construction Engineering and Management-Asce,* 136**,** 1015-1027.

Stavrulaki, E. & Davis, M. (2010). Aligning products with supply chain processes and strategy. *The International Journal of Logistics Management,* 21**,** 127-151.

Sun, M., Vidalakis, C. & Oza, T. (2009). A change management toolkit for construction projects. *Association of Researchers in Construction Management, ARCOM 2009 - Proceedings of the 25th Annual Conference***,** 803-812.

Tavčar, J. & Duhovnik, J. (2005). Engineering change management in individual and mass production. *Robotics and computer-integrated manufacturing,* 21**,** 205-215.

Wänström, C. & Jonsson, P. (2006). The impact of engineering changes on materials planning. *Journal of Manufacturing Technology Management,* 17**,** 561-584.

Wänström, C., Lind, F. & Wintertidh, O. (2006). Creating a model to facilitate the allocation of materials planning resources in engineering change situations. *International journal of production research,* 44**,** 3775-3796.

Wasmer, A., Staub, G. & Vroom, R. W. (2011). An industry approach to shared, cross-organisational engineering change handling-The road towards standards for product data processing. *Computer-Aided Design,* 43**,** 533-545.

Wu, W.-H., Fang, L.-C., Wang, W.-Y., Yu, M.-C. & Kao, H.-Y. (2014). An advanced CMII-based engineering change management framework: the integration of PLM and ERP perspectives. *International Journal of Production Research,* 52**,** 6092-6109.