A Taxonomy for Engineering Change Management in Complex ETO Firms

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Abstract - **In this paper, we study a specific type of Engineer-to-Order (ETO) firms called Complex ETO characterized by one-of-a-kind products with high complexity and low volumes. Such firms are at high risk of encountering significant engineering changes due to their characteristics. The management of engineering changes have a large impact of time, cost, and quality of the project. The purpose of this paper is therefore to provide a holistic taxonomy for Engineering Change Management (ECM) that can guide the companies with set of actions to prevent, handle, and manage engineering changes. The study is based on literature and empirical findings from a single case study conducted in an offshore platform producer, which resulted in development and verification of the taxonomy.**

Keywords **–Engineering change management, Engineer to Order, One-of-a-kind production**

I. INTRODUCTION

Complex Engineer-to-Order (ETO) companies are characterized by one-of-a-kind products with high complexity and low volume [1], takes place with a fixed-position layout in either workshop or on site [2], and is usually managed by a project-based organization [3]. Such firms are at high risk of encountering significant engineering changes due to their characteristics of complex production value chains, high number of involved actors, complex product architectures and interdependencies, and degree of uncertainty. Engineering changes (ECs) are unplanned and non-standard elements of the complex ETO projects, initiated both from internal processes and customer requirements, and the management of engineering changes have a large impact of time, cost, and quality of the project. Engineering Change Management (ECM) encompasses the procedures, processes, and information systems to support engineering change (EC) handling in a project.

Even though ECM can have a huge impact on the performance of ETO firms, previous studies have shown that ECM is a relatively young and low-cited field of research [4]. Previous studies do not sufficiently distinguish between different contextual factors and production environments [5]. Therefore, this study aims to identify and structure critical elements for sound ECM in a complex ETO setting.

This paper provides a taxonomy for ECM, employing a holistic approach and categorizing the activities into before, during, and after occurrence of ECs. The taxonomy is developed based on a comprehensive literature review that have mainly focused on EC handling practices in complex ETO companies. Companies can benefit from this taxonomy by mapping and analysing their current state of ECM and identify potential improvement areas and actions to enhance their ECM. Accordingly, a leading producer of complex offshore platforms was involved in this study to map current ECM practices and categorize them by using the taxonomy. In such complex projects with fabricating and installing offshore platforms, ECs are inevitable and managing changes is essential. Changes can influence all parts of the project from design to installation and can put project planning at risk by deviating plans. The taxonomy further helped identifying the potential improvement areas and proposing action points to increase the efficiency of the ECM in the case company.

II. METHODOLOGY

The taxonomy is developed through a comprehensive literature study that have utilized the protocols proposed by [6] to review prior conceptual and empirical research publications on ECM domain. We have therefore first identified the research scope and strategy. Then, 62 scientific documents were selected and analysed among the 122 articles found through the initial literature search. The analysis were made using a categorization scheme [7]. For detailed assessment of the quality of the selected articles, we have evaluated each paper against measures such as clarity of research objectives, description of research design and if the proposed solution (e.g. concept, framework) adequately addresses aspects of ECM. Finally, constructs and dimensions of the proposed taxonomy were developed.

To test and verify the taxonomy, a case study was conducted with a large producer of complex offshore platforms. The study took place as part of a larger four-year research project with the company. For this study, we conducted two study visits to the company facilities within 6 months period, in which four interviews and two workshops took place.

The first study visit took place once the initial version of the framework was constructed. The duration of the study visit was two days. In the first day, the ECM practices of the company were identified through four interviews carried out with the participants listed below, while the second day was allocated for a workshop that involved all interviewees and the contact person.

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- Execution control lead that is responsible for technical follow-up of change handling in the project execution
- Employee in the engineering management department with over 30 years of experience and responsible for following the change the orders/ variation orders (VOs) in projects
- Change control employee responsible for handling the changes and presenting them to the customers
- Method leader who evaluates the changes and their consequences for the method and constructions

The second study visit took place once the framework was revised and improved based on the findings from the first study visit. This visit took one day and focused on a workshop that have also involved all the participants from the first workshop. This workshop focused on going through the revised framework and collecting the missing information on the company's ECM practices. The company has also provided relevant documentation such as EC procedures, checklists, system descriptions and organizational structure. This paper compiles the findings from the study visits and provided documentation.

III. A TAXONOMY of ECM in COMPLEX ETO

The resulting taxonomy employs a holistic approach, categorizing practices into before, during, and after occurrence of ECs, as illustrated in Figure 1. *The pre-occurrence phase* constitutes the activities done before an EC occurs. The focus is to mitigate the occurrences of the ECs, and if the EC happens to mitigate the potential impact of it. *The occurrence phase* constitutes the activities done when an EC occur. Here, the focus is to react and handle the EC effectively and efficiently. *The post-occurrence phase* constitutes the activities done after the EC is handled. In this phase, the focus is post analysis of the EC handling process to take actions for continuous improvement. The taxonomy provides description of best practice elements in each of these seven areas.

A. Classification of ECs

EC classification mechanisms are needed for appropriate prioritization and hence efficient handling of the changes. Different classification approaches are proposed in the literature, such as classification by purpose, by urgency, or by timing. In the most applied classification by purpose approach [8-12], ECs are classified as emergent and initiated changes. *Emergent changes* arise from the product itself, especially due to the problems at the design stage. Error correction, safety, change of function, and product quality problems fall into this category. Emergent changes become more costly at the later stages in the design process as the process becomes more time critical and the product becomes more integrated [9]. *Initiated changes* refer to improvements, enhancements, adaptations on the product. They can be triggered from customers, suppliers, internal functions, and legislators. They arise from the new or changing requirements of the customers.

B. Strategies

Companies should also develop strategies in advance, to have the right measures in place before the EC occurs. This is important to avoid costly change consequences. Strategies can be classified into two categories in accordance with the project stage that they are related to:

(i)*Design-stage-related strategies* address the measures taken at the design and engineering stage of the project to reduce the likelihood of the EC occurrence and/or to reduce the potential impact of ECs. By these strategies, some flexibility is introduced into the system domains such as product architecture and project plan, as such potential effects of an EC can be mitigated. Following examples can be categorized into design-stage-related strategies. Preventive strategy that refers to adding up safety margins to the initial specification of the system such as safety margin in engineering parameters Eckert, et al. [9] and safety slacks in the project plan [13]. Front-loading strategy that refers to earlier detection of the ECs [8] by some approaches such as involving users early stage of the development. Design for changeability focuses on incorporating changeability into a system's architecture by such principles as simplicity, modularity, and integrability [14].

(ii)*Production-stage-related strategies* address the measures taken to improve the conditions for handling the ECs efficiently and effectively when they occur during the production (i.e. fabrication, assembly) stage. These strategies aim to reduce the lead time for administrative EC process, such as workload balancing and optimal batching [11, 15].

C. Organization and culture

The success of ECM depends on establishing an organizational structure that ensure the efficiency of the communication, information sharing, and coordination practices across multiple functional lines, roles, and value chain partners. Poor communication is seen as a barrier to effective ECM in over 80% of UK firms [16]. In ETO projects, EC handling interdependencies can be found between tasks and

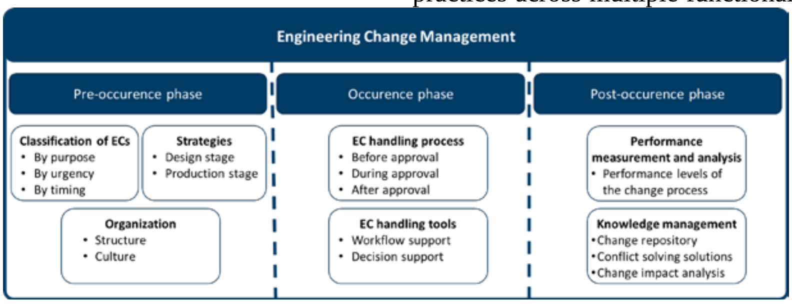

Figure 1: A taxonomy of ECM

activities, resources, people, knowledge areas, technologies, products, and components [17]. Tools such as Dependence structure matrix (DSM) and Domain mapping matrix (DMM) can help with the identification of interdependencies, relationships, and information exchange needs in multi-project environments systematically for synchronization of actions and transparency [17, 18]. Based on the DSM/DMM analysis, appropriate means (e.g. communication tools) can be applied to maximize the efficiency of communication and information sharing between the interdependent domains that require special attention.

Organizational culture is also fundamentally linked to decision making of disciplines when handling ECs [11]. Pikosz and Malmqvist [19] suggest that the key issue for this attitude variation is the cause of the change. The case study of Eckert, et al. [9] into helicopter design shows that engineers often resent changes arising from mistakes but do not show resistance to changes for product enhancement, even though the processes and tasks for handling these two types of changes are very similar.

D. EC handling process

The most standard and commonly referred EC handling process is described by Jarratt, et al. [11] who uses three formal processes - before, during and after EC approval phases, broken down into six steps and four break points (stage-gate approach) to indicate go/no-go decision points, as well as two iterations that can happen, indicated by arrows. Once the EC is triggered, an engineering change request (ECR) is raised in the Step 1, incorporating such information as what type of EC it is, at what stage it is occurring, and basic information on coupling and interfaces. At the Step 2, valuations of the different design attributes with regards to cost, time, and market needs to be carried out. Potential solutions preferably more than two should be investigated, to avoid being content with just a workable solution. Step 3 involves the impact analysis to ensure proper evaluation and assessment of the solutions and its impact on the propagation. The change can propagate to other products (e.g. other members of the product family), processes (e.g. manufacturing), and businesses (e.g. suppliers, partners, etc.). At the Step 4, The concerned board/responsible team or individuals can carry out the cost benefit analysis for the change evaluation and make the approval of the EC handling solution. Once approved, EC solution is implemented in the Step 5, and a review is carried out to see if what was intended was achieved post the implementation in the final step, Step 6.

E. EC handling tools

EC handling tools can be classified into the following two broad categories proposed by [11]:

(i) Tools for supporting the workflow in the EC handling process. These tools may address different scopes of the EC handling workflow, such as the web-based tool described by Huang, et al. [20] for managing the basic processes of ECM, including placing an EC request, keeping an EC log, and evaluating EC. Such tools allow simultaneous access to the EC workflow data, irrespective of geographic location.

(ii) Tools for supporting the decisions taken during the EC handling process, which address the decision-making process from error-recognition to impact and propagation analysis of changes and may offer potential solutions. For example, Koh, et al. [21] proposed a tool for evaluating the impact of change and assessing the dependencies across product requirements, components, attributes, and parameters. Leng, et al. [22] applied a tree-root tracking method to analyse the propagation of changes on the Bill of Materials, illustrating a case example from the aviation industry.

F. Performance measurement and analysis

ECM performance should be measured in the following four levels [23, 24].

(i) *General performance level* deals with the ECM system performance based on all development projects. The overall state of the ECM system and the role ECM plays within the organization can be analysed at this level.

(ii) *Focused performance level* deals with the ECM performance based on a single project. Here, the effects the ECs have on the course of the project are considered in terms of time and resources.

(iii) *Specific performance level* deals with the performance of one specific change process. The characteristics (e.g. type, duration) of a change process are examined at this level.

(iv) *Detailed performance level* deals with the performance of one single process step. For example, how quickly alternative solutions were found during the pre-approval stage of the EC handling.

G. Knowledge management

The knowledge management methods can be used in ECM to predict the likely occurrence, propagation path, and impact of a change, by reusing the previous DC knowledge. Depending on the analysed data, this practice can help to predict the timing, frequency, and magnitude of the ECs, as well as visualizing the dependencies between the changes, effects of changes, and information flows [25]. As an example, Clarkson, et al. [26] have analysed the change behaviour in the case study of rotorcraft design, through the development of mathematical models that can predict the likelihood and impact of change. In the same case company, Eckert, et al. [9] analysed the propagation behaviour of changes and visualized the correlation between the parts, systems and parameters.

IV. CASE STUDY AND DISCUSSION

The core products of this complex ETO company are offshore topsides and onshore processing facilities for the global oil and gas industry. Topsides are huge, unique, and complex modules fitted on permanent steel jackets or floating production storage and offloading (FPSO) vessels. Many subcontractors and suppliers are involved to deliver modules and equipment that are installed at the yard. The yard may have up to three large-scale projects at different stages in progress at the same time. Projects have significant amount of engineering hours (for example 300.000 hours in one of the observed projects). The completion time of a project is often compressed to less than three years, achieved by partially concurrent engineering and construction phases.

Concurrent phases lead to many changes, as the design of the complex products has not yet completed when fabrication starts. The most typical changes are categorized into Design Changes (DCs) that are due to mistakes and initiated from the engineering department, and Variation Orders (VOs) that are coming from customers. For example, in one of the observed projects, the company has got 205 open VOs and about 1 100 open DCs as of the time of a case study visit we have conducted.

In the strategic plans of the company, the introduction of new market segments and product solutions are important. This means that the number of concurrent projects will increase, making it even more important to manage changes effectively and efficiently. A series of observations and recommendations have been made implementing the taxonomy in the case company, as exemplified below.

A. Classification of ECs

There are different classification and prioritization approaches taken by different personnel responsible for EC handling. Changes can be prioritized based on the project stage that the change will affect (i.e. before or after fabrication), based on the urgency of the change (contractual deadline with customers in certain projects), and based on the impact in cost and delivery time. The interviews indicated that there is need for common checklists and classification scheme shared across projects and disciplines, to ensure similar use of severity categories.

B. Strategies

The main design-related strategies are prevention through safety margins, some front-loading attempts and changeability through flexible materials (e.g. stainless steel and duplex steel qualities). For example, in one of the observed projects, the main structures where designed with a 0.8 utilization factor. This means that there is a 20% safety margin built in case of changes later in the project to new and heavier equipment. The main production-related strategies are buffers in production plan, ability to add extra capacity (e.g. extra shifts, temporary employees) and resource pooling of some shared resources. Regarding improvement potentials, the communication lines with the customer and the available resources of the engineering partner makes it more difficult to work closely together in the early stages to verify concepts and designs, which should be improved for better front-loading strategy.

C. Organization and culture

The overall change management procedure is owned by the Head of Risk and Change Management in the company. However, separate procedure documents are made for each new project. The overall responsibility for the actual change process in each project is the business manager (Project Execution Manager). Each discipline has a team that is involved in the EC. Regarding the organizational culture, fear of using the change control system, and managing some of the changes outside of the system have been identified. As for improvement potentials, co-localization of a joint change team seems like a beneficial practice and could be applied to more projects. Also, training should be conducted to all parties being required to use the control system.

D. EC handling process

The company applies a very similar process to the standard EC handling process presented above in Section III. The process of registering all potential changes leads to a disproportionately high number of change objects. This contributes to complexity and a lack of overview. It is hard to determine affected disciplines for change propagation. The use of checklists and site walks are important tools to assist the decision.

E. EC handling tools

The main tool used for managing changes in the company is the so-called 'change control system'. This system should be updated when changes are registered, handled, and implemented. In some cases, late updates or skipping the registration of the actual implementation of a change may lead to double work on changes that have already been implemented. Another challenge is that the change should be formulated in accurately and with enough details, so all disciplines can understand it correctly and misunderstandings are avoided. The change control system is found to be slow, inflexible, and hard to use by many. There is a need for better access to the raw data to make specific data sets adapted to the project type.

F. Performance measurement and analysis

Performance reports on time and cost can be extracted from the change control system. However, there is no systematic approach applied for performance measurement across projects. Relevant KPIs will vary for different projects and project phases, but typically include number of VOs, number of DCs, and duration of handling VO. As an improvement potential, the company should consider tracking changes in terms of size (volume in hours) instead of numbers of changes to get a better understanding of the future workload related to changes.

G. Knowledge management

In the case company, late welding and changes to pipes can be considered as multipliers, having further impact on other subsystems such as heating, isolation, pressure testing. As an improvement potential, linking drawings and activity plans would be beneficial. There should be a long-term plan to achieve an updated 3D model with time factor and installation status. Machine learning can be of future interest for predicting outcomes and consequences of changes as well.

V. CONCLUSION

This study provides a taxonomy that prescribe the activities in which organizations and individuals should engage for efficient management of ECs. A real-life case study in a producer of complex offshore platforms verifies and expands the understanding of critical areas of the taxonomy. Further study is planned to test and verify the taxonomy in other real-life manufacturing companies possessing ETO characteristics, as well as following up on suggested improvements for the case company.

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REFERENCES

[1] O. Willner, D. Powell, M. Gerschberger, and P. Schonsleben, "Exploring the archetypes of engineer-to-order: an empirical analysis," (in English), International Journal of Operations & Production Management, vol. 36, no. 3, pp. 242-264, 2016, doi: 10.1108/Ijopm-07-2014-0339.

[2] P. Schönsleben, S. R. Schmid, and B. O. Jacobson, Integral Logistics Management: Operations and Supply Chain Management Within and Across Companies. CRC Press, 2011.

[3] M. Hobday, "The project-based organisation: an ideal form for managing complex products and systems?," (in English), Res Policy, vol. 29, no. 7-8, pp. 871-893, Aug 2000, doi: Doi 10.1016/S0048-7333(00)00110-4.

[4] B. Hamraz, N. H. M. Caldwell, and P. J. Clarkson, "A Holistic Categorization Framework for Literature on Engineering Change Management," Systems Engineering, vol. 16, no. 4, pp. 473-505, 2013, doi: 10.1002/sys.21244.

[5] N. Iakymenko, A. Romsdal, E. Alfnes, M. Semini, and J. O. Strandhagen, "Status of engineering change management in the engineer-to-order production environment: insights from a multiple case study," Int J Prod Res, pp. 1-23, 2020, doi: 10.1080/00207543.2020.1759836.

[6] S. Keele, "Guidelines for performing systematic literature reviews in software engineering," Technical report, Ver. 2.3 EBSE Technical Report. EBSE, 2007.

[7] J. Webster and R. T. Watson, "Analyzing the past to prepare for the future: Writing a literature review," MIS quarterly, pp. xiii-xxiii, 2002.

[8] E. Fricke, B. Gebhard, H. Negele, and E. Igenbergs, "Coping with changes: causes, findings, and strategies," Systems Engineering, vol. 3, no. 4, pp. 169-179, 2000.

[9] C. Eckert, P. J. Clarkson, and W. Zanker, "Change and customisation in complex engineering domains," Res Eng Design, vol. 15, no. 1, pp. 1-21, 2004.

[10] M. Giffin, O. De Weck, G. Bounova, R. Keller, C. Eckert, and P. J. Clarkson, "Change propagation analysis in complex technical systems," Journal of Mechanical Design, vol. 131, p. 081001, 2009.

[11] T. a. W. Jarratt, C. M. Eckert, N. H. M. Caldwell, and P. J. Clarkson, "Engineering change: an overview and perspective on the literature," (in en), Res Eng Design, vol. 22, no. 2, pp. 103-124, 2011/04/01/ 2011, doi: 10.1007/s00163-010-0097-y.

[12] I. Ullah, D. Tang, and L. Yin, "Engineering product and process design changes: a literature overview," Procedia CIRP, vol. 56, pp. 25-33, 2016.

[13] D. Olausson and C. Berggren, "Managing uncertain, complex product development in high‐tech firms: in search of controlled flexibility," R&d Management, vol. 40, no. 4, pp. 383-399, 2010.

[14] E. Fricke and A. P. Schulz, "Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle," Systems Engineering, vol. 8, no. 4, pp. no-no, 2005.

[15] C. Terwiesch and C. H. Loch, "Managing the process of engineering change orders: the case of the climate control system in automobile development," Journal of Product Innovation Management, vol. 16, no. 2, pp. 160-172, 1999/03// 1999, doi: 10.1016/S0737-6782(98)00041-1.

[16] G. Huang and K. Mak, "Web-based collaborative conceptual design," Journal of Engineering Design, vol. 10, no. 2, pp. 183-194, 1999.

[17] M. Danilovic and B. Sandkull, "The use of dependence structure matrix and domain mapping matrix in managing uncertainty in multiple project situations," International Journal of Project Management, vol. 23, no. 3, pp. 193-203, 2005.

[18] M. Danilovic and T. R. Browning, "Managing complex product development projects with design structure matrices and domain mapping matrices," International Journal of Project Management, vol. 25, no. 3, pp. 300-314, 2007.

[19] P. Pikosz and J. Malmqvist, "A comparative study of engineering change management in three Swedish engineering companies," in Proceedings of the DETC98 ASME design engineering technical conference, 1998, pp. 78-85.

[20] G. Huang, W. Yee, and K. Mak, "Current practice of engineering change management in Hong Kong manufacturing industries," Journal of materials processing technology, vol. 139, no. 1-3, pp. 481-487, 2003.

[21] E. C. Koh, N. H. Caldwell, and P. J. Clarkson, "A method to assess the effects of engineering change propagation," Res Eng Design, vol. 23, no. 4, pp. 329-351, 2012.

[22] S. Leng, L. Wang, G. Chen, and D. Tang, "Engineering change information propagation in aviation industrial manufacturing execution processes," The International Journal of Advanced Manufacturing Technology, vol. 83, no. 1-4, pp. 575-585, 2016.

[23] N. Kattner, T. Wang, and U. Lindemann, "Performance metrics in engineering change management-Key Performance Indicators and engineering change performance levels," in 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 2016: IEEE, pp. 1180-1184.

[24] N. Kattner and U. Lindemann, "Performance metrics in engineering change management: Towards a methodology to investigate the efficiency of handling engineering changes," in 2017 Portland International Conference on Management of Engineering and Technology (PICMET), 2017: IEEE, pp. 1-8.

[25] G. Fei, J. Gao, D. Owodunni, and X. Tang, "A model-driven and knowledge-based methodology for engineering design change management," Computer-Aided Design and Applications, vol. 8, no. 3, pp. 373-382, 2011.

[26] P. J. Clarkson, C. Simons, and C. Eckert, "Predicting change propagation in complex design," Journal of Mechanical Design, vol. 126, no. 5, pp. 788-797, 2004.