ENGINEERING CHANGE MANAGEMENT IN ENGINEERING-TO-ORDER PROJECTS FROM A MANUFACTURING PERSPECTIVE

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The purpose of this research was to investigate the engineering change management process in engineering-to-order projects while comparing the same process in traditional manufacturing. A single-case study at a engineering-to-order – engineering review office was performed and results were analysed in conjuction with literature covering the engineering change process in traditional manufacturing. Engineering-to-order projects and tradional manufacturing are different in many ways but share the need for a reliant engineering change process. This study found that engineering change management post-change analysis could benefit future projects in the form of quantifiable lessons learned from previous project's engineering change data.

Keywords: Engineering Change Management, Engineering-to-Order and Process Management.

1. INTRODUCTION

Changeability is inherent in all projects but the complexity of the same varies with e.g. project length, concurrent activities, geographical spread and organization (Dvir & Lechler, 2004; Ross, Rhodes, & Hastings, 2008). Engineering change management is the process of handling those inevitable and inherent changes. As an area of research, engineering change management, ECM, has gained interest over the past two decades as one of the answers on how to handle the increasing complexity and dynamics of product design and development. ECM is often times regarded a sub-category of Configuration Management and is also related to the disciplines of Project Management, Risk Management and in a broader sense, Systems Engineering. In engineering-to-order, ETO, projects a high level of complexity and dynamics has to be handled throughout the project execution. Despite that stakeholders and customers are involved at an early stage in ETOs and the planning is extensive, the design is frequently changed and the final design is often not reached until the physical product is completed (Hobday, 2000). The final physical appearance of the product is then documented in as-built-drawings. The strain this dynamic reality has on manufacturing in ETO projects is different from that of traditional manufacturing, e.g. automotive and other customer goods, in that, in ETO projects the prototype is the product (Tavčar & Duhovnik, 2005). The ETO industry response to challenges and set-backs has been to focus on developing project manager skills to cope with and minimize the negative impacts of change, all the while being on the lookout for opportunities in a given change situation (Olsson, 2007). Another coping mechanism in ETO projects is the product lifecycle tools and ECM-software. However much of the industry developments within the field of ECM for ETO projects remains industry knowhow and undiscovered by academia, especially matters concerning the manufacturing process (Eckert, De Weck, Keller, & Clarkson, 2009).

The research presented in this paper aims to further elaborate on manufacturing aspects in ETO projects and its relation to ECM. An overview of ECM and a single-case study analysed together, to establish consequences of ECM on manufacturing, forms the basis of this research. The single-case study was performed at a Swedish high voltage direct current, HVDC, equipment developer, at their branch that focuses on the offshore wind farm market, and the commissioning of offshore platforms for HVDC equipment. The HVDC offshore platform is a good example of an ETO project in all respects, mixing the complexity of an offshore structure with a new application.

2. METHOD

2.1. Case Study

The results presented in this paper originate from a single-case study focusing on the ECM process of the case company acting as the unit of analysis in accordance to Yin (2011). The vantage point is that of a lead engineer while conclusions are inductive and directed towards the implications for manufacturing. The research design, both exploratory and hermeneutic in its approach, has followed the framework “a Design Research Methodology” developed by Blessing and Chakrabarti (2009).

At the Swedish high voltage direct current, HVDC, equipment developer, the studied product group specializes in HVDC links from offshore wind farms to the on-shore grid. The company’s customer in these types of projects is an power transmission systems operator. The company (supplier) act both as a sub-supplier (to it-self) and project manager in these projects. The studied department at the case company has the function of reviewing documentation and perform quality control of the delivery from the offshore platform designer and fabricator.

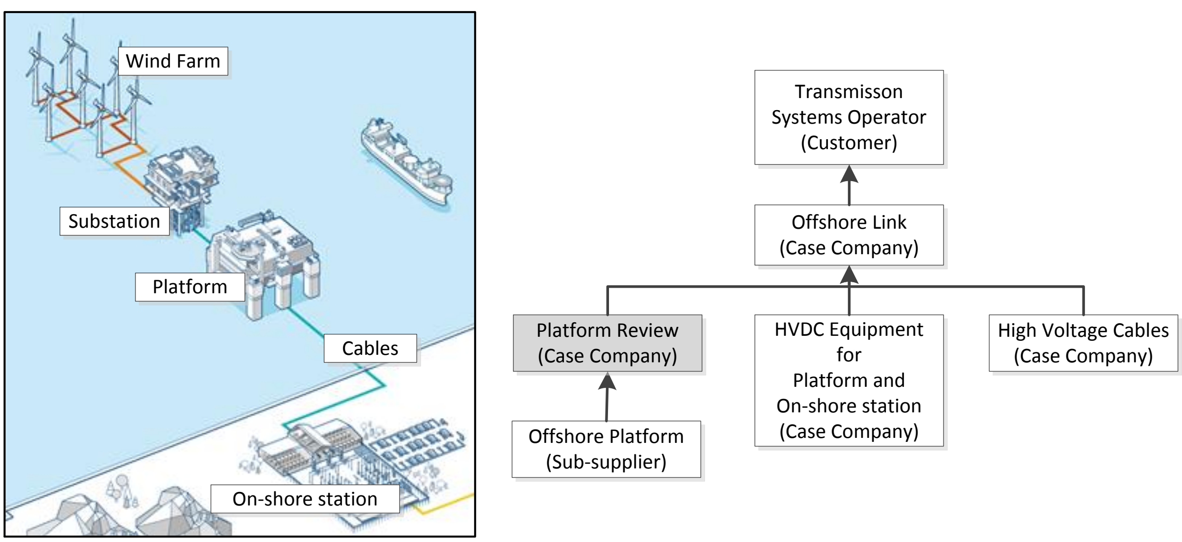

Fig. 1. Hierarchical flowchart of deliverables within the projects and schematic layout of system configuration (adapted image, courtesy of ABB).

Semi-structured interviews, based on an interview protocol, were held with nine respondents, all of which were employed at the platform review department, indicated grey in Fig. 1. Their respective roles are indicated in table 1 below. The interview protocol was complemented as knowledge about the ECM process grew with each interview. One pilot interview was held to clarify questions and ensure the understanding of the research subject. Even though the ECM process in essence is used by the case company the individuals might use a different nomenclature for concepts established in research. Statements were verified in discussion with the interviewees and archival documentation was used for verification.

Table 1. List of Interviewees responsibility and each interview's duration.

Role	*Duration [min]*	*Role*	*Duration [min]*
Project Manager	54	Lead Eng., Naval Architect	47
Contract Manager	49	Lead Eng., Piping	58
Lead Eng., Electrical & IT	48	Lead Eng., Transport and Installation	27
Lead Eng., Heating & Ventilation	59	Lead Eng., Fabrication (Pilot)	37
Lead Eng., Maintenance	39	Lead Eng., Risk & Safety	64

The researchers of this study had full access to all documentation and systems discussed in this article for the duration of the study which spanned from December 2013 to May 2014. Interviews were analysed by mapping answers of all respondents and comparing them to the established processes in the company's quality assurance system. Conclusions from the analysis were discussed with five of the respondents individually to clarify and verify the results.

2.2. ECM Overview

ECM encompasses those processes, methods, strategies, systems and organisations that govern change in product realisation, and is often regarded a sub category of configuration management. The first paper to treat the state of the art in ECM, (Wright, 1997), defined engineering change as "… a modification to a component of a product, after that product has entered production." (p.33) The same paper focused on the ECM implications for manufacturing given an engineering change. The literature treating ECM at the time was scares and Wright (1997) divided his twenty four references into two main categories: EC Tools an EC methods.

A recent literature review by Hamraz, Caldwell, and Clarkson (2013) analysed the current research body of over 400 publications connected to ECM, 384 of which were journal articles and conference papers. In conjunction with their literature review they developed a holistic categorisation framework which has been used in this research. Hamraz et al. (2013) constructed their own ideal definition of what ECM is to cover, based on the product life cycle developed by (Pahl and Beitz (1984); Ulrich and Eppinger (1995)). Their ideal definition covered the entire project envelope except planning, and emphasised the iterative nature of the ECM process. Previously engineering changes has been found to account for 5 - 15% of a project budget, which is the process of changes itself not the incurred cost of a given change (Riley, Diller, & Kerr, 2005). As with most costly project stages and entities research has been conducted on how to reduce and mitigate change in a proactive manner. Nonetheless engineering change is a necessity in most industries today. Even though the reasons for changes are similar between industries, their ways of handling changes were found different according to a study by Eckert et al. (2009). Eckert et al. (2009) conducted workshops with representatives from a variety of industries ranging from printer equipment to construction projects and concluded that a better understanding of how different industry approaches can enhance each other and be supported by tools would be beneficial to industry as a whole (Eckert et al., 2009).

Impact analysis, in the form of e.g. change predication and propagation, are among the more common research themes for ECM accounting for 12% of the journal and conference papers analysed by Hamraz et al. (2013). 51% of the journal and conference papers belonged to the in-change stage that is: ECM systems, guidelines, classification, organization implementation, documentation, ECM process and review (Hamraz et al., 2013). Post-change issues and analysis amount to a small percentage of the whole research body and manufacturing is even less represented (Hamraz et al., 2013). Post-change analysis seems to have industrial relevance particularly covered by the construction industry as a means to quantify claims in arbitration processes (Chester & Hendrickson, 2005; Golnaraghi & Alkass, 2012).

In traditional manufacturing industries ECM has been product centred as industry in general (Bellgran & Säfsten, 2010), as quantified and shown by Hamraz et al. (2013). By traditional manufacturing, referred to in this paper, we mean factory type manufacturing such as customer goods in series production. An example of this is Hua and Wemmerlöv (2006) study of personal computers and how their change intensity could be facilitated by ECM. While the implications of their study were that ECM is a great tool to deal with change and to use it as a market advantage, they omitted the complications brought on the manufacturing system. If customer requirements are allowed to be a moving target, the late changes will build up which can be harmful to manufacturing execution. Although not treated specifically, the detrimental effects of ECM on manufacturing are implied in a case study of three Swedish companies performed by Pikosz and Malmqvist (1998). Keeping control of the process from a product point of view is not a bad thing but the lacking inclusion of manufacturing aspects are eloquent for industry research in general (Bellgran & Säfsten, 2010).

3. RESULTS

3.1. Interview Responses

Responses during interviews were to a large extent focused on upstream and concurrent project practices rather than downstream. If collaborations were suggested they always included earlier engineering stages and never later manufacturing related ones. All of the engineers in the study gave witness of how the manufacturing process is often believed to be able to cope with any demand. From an engineering point of view in the ECM process the product is seen as malleable clay, and while steel and large componentry often are highly configurable, the action to e.g. change the position of a pillar can prove highly time consuming. The interviewees also told of how time expenditure is increased as a decision loop and iteration process is commenced through ECM. Distance in a global organization requires an ECM process and while this was acknowledged, the virtual process (which is ECM) was deemed insufficient to maintain the engineering quality of the project process. IT solutions as ECM have to be complemented by physical meetings. One area of improvement suggested was to couple the punch list system to the design review system, no reason could be found as to why these virtual and physical aspects of the process could not be combined.

When given the question: “In what way is change communicated throughout the projects?” Communication outside the ECM system was frowned upon by all interviewees as that behaviour compromises the traceability of any change. At the same time all engineers requested a personal dialog with their respective counterpart be it the sub supplier or the customer. In the studied project all communication regarding ECM was handled through an IT-tool, physical meetings were held on the project manager level in the case that a DRR had been escalated to that level. Engineers interviewed thus wanted the possibility of communicating change in a personal dialog while implementation and decision making should be strictly handled in the ECM software domain.

The following aspects where mentioned by the interviewees to increase the complexity or conversely changeability of the project that they were a part of (in descending order of occurrence during interviews): **Time** i.e. the duration of the project subject it to more changes than a shorter project would have to endure; **Sub-supplier layers** i.e. the complicated organization of the projects and involved companies and their related contracts; **Lessons learned** i.e. all of the interviewees responded that lessons learned process is vital and often omitted due to lack of allocated time. Lessons learned as thought by the interviewees could include, written guidelines produced either by individual engineering disciplines or project managers or both; **Culture** i.e. technological, international and company cultures; **Regulations** i.e. national authorities, classification societies and industry standards impose tough demands on all componentry that make out the HVDC platform this is combination with the immature technology aspect yield a more chaotic project environment; **Immature technology** i.e. HVDC on an offshore platform to bring energy to-shore, had not been done until 2010; **Interpretation** i.e. how parties within projects interpret contracts and decisions.

3.2. ECM Process

The ideal definition of ECM starts at the inception of a requirements list and lasts until product phase out according to Hamraz et al. (2013). Based on the ECM scope definition by Hamraz et al. (2013) and the information gathered during the case study, the ECM process is plotted in Fig. 2. from a temporal point of view against the project stages related to engineering change in the studied offshore engineering project.

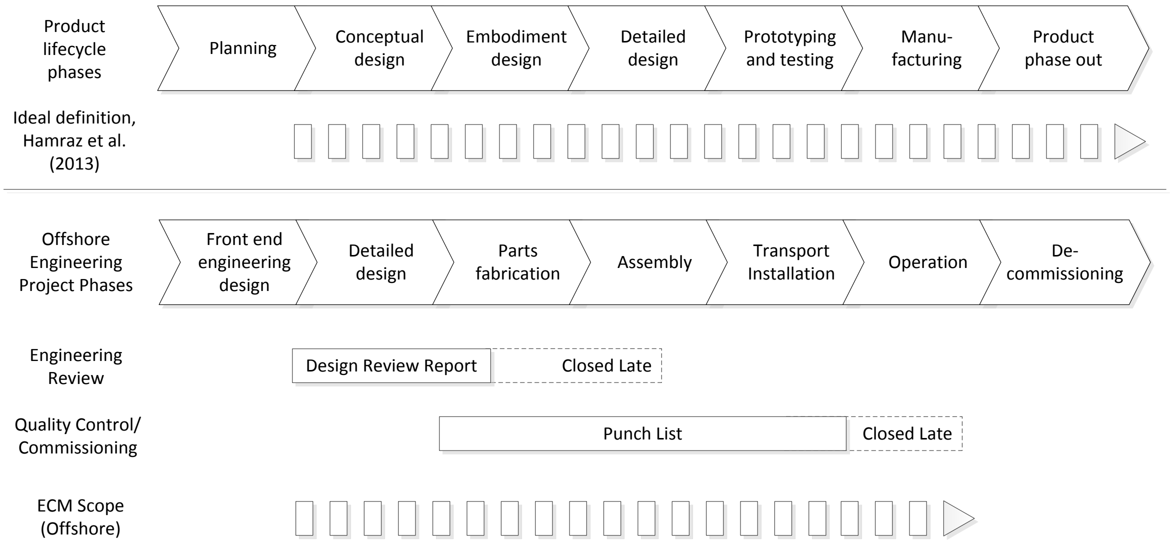

Fig. 2. Offshore project phases, established in the case study, compared to traditional manufacturing in an ECM context adopted from Hamraz (2013).

In the figure above, adopted from Hamraz et al. (2013), the gaps in the process denote the iterative nature of the ECM process. In this respect differentiation is made between ECM as a process to handle change while product lifecycle management, in the form of software, is considered a tool. In the studied case the process stages that were covered by the ECM scope for the offshore project was the detailed design and manufacturing by means of design review report and punch list systems. Both the process of design review reports and punch lists were considered processes that often got closed to late, by the interviewees.

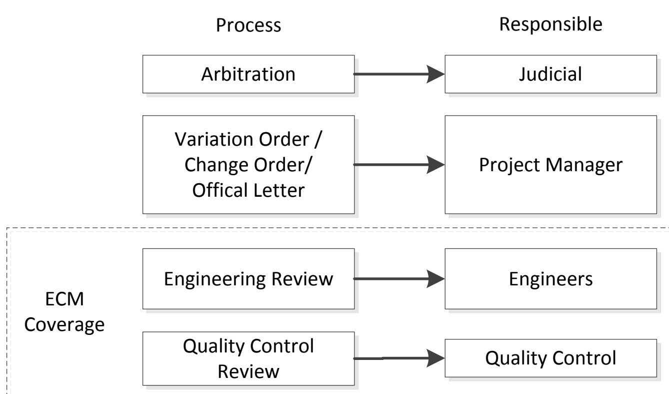

Fig. 3. The hierarchical coverage of change handling in offshore project type change management.

Expanding on the ECM process from a hierarchical point of view, shown in Fig. 3, design review reports, DRR, are started, reviewed and approved by engineers as part of the engineering review process. Punch lists are used by quality control, QC, engineers at the fabrication yard in their review process. This physical portion of the review process includes factory acceptance tests, mechanical completion and commissioning. The engineering review process is performed within the product lifecycle management, PLM, system and the QC phase is processed outside the PLM-system. As the QC review process will affect the end results, in the form of changes and deviations, documentation in the PLM-system has to be updated. This update is performed manually as the punch list system and PLM are not coupled in any way. Both punch items and DRRs, unless resolved, can be escalated to change or variation orders. Variation orders are requested by the yard and thus incur an additional cost for the company, the company then in turn can request a change order from the customer. Subsequently if a change order or variation order remain financially unresolved the issue could go to arbitration in which case it is handled in the judicial arena.

4. DISCUSSION

As Hamraz et al. (2013) suggested in their literature review, the lack of publication both associated to post completion analysis and manufacturing opens the possibilities to contribute by e.g. utilizing generated engineering change data as input for process analysis with respect to manufacturing. Extending the claims in this article to industry as a whole, what are then the implications and possibilities of using ECM-data? Other industries and the research field of performance measurement come to mind. The responses from the interviewees on their perception of manufacturing is similar to that of the study by Hua and Wemmerlöv (2006) in that it lacks the consequential thinking of repercussions for the manufacturing phase. Thus there seem to be correlation between the perceived role of manufacturing in engineering-to-order and traditional manufacturing practices.

There does not seem to be an understanding of how to use ECM-data other than what it is used for today, as a means to an end to manage change. Could ECM data be used for something else than what is being done today, to elicit change, could it be used as input for quantifiable lessons learned? With large quantities of data being generated each day in engineering-to-order projects, input for post-change analysis and the generation of quantitative lessons learned are “free”.

It should be mentioned that the investigation by Hamraz et al. (2013) was concluded with the year 2011 and that the literature reviewed was gathered from a selected group of sources, other articles can be found on the subject of manufacturing and ECM. However articles related to the other areas categorized by Hamraz et al. (2013) is still considered valid and representative of the overall body of research treating ECM.

The research presented in this paper is of a qualitative and exploratory nature and thus the company under study only represent one case and for the sake of validity this study should be part of a multiple case study. This is also the ambition of the researchers. As this is a single-case study, suggestions of improvements might already be standard practice in other project and company organisations therefore more studies related to this subject is needed for verification of empirical evidence found during the case study.

4.1. Implication for ECM Research

The arbitration process often demand the quantification of change orders and in a case study by Hameri and Nihtilä (1998) one of their case companies used ECM data from their plant design management system and a analysis revealed process improvement opportunities. The IT support systems vary along the lifecycle of the product studied in this work, much like Hameri and Nihtilä (1998) describe in their exploratory study of product data management, they can be categorised into the conceptual and detailed design, manufacturing and operations or maintenance stage.

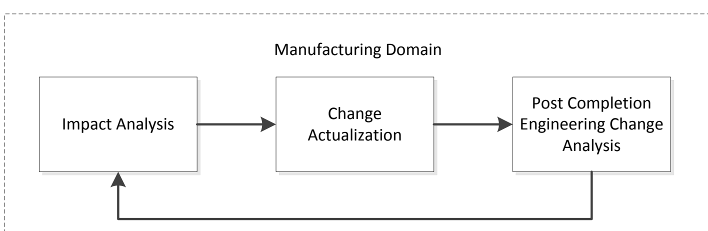

Fig. 4. The figure shows the process of using data from actualized changes as input in change propagation analysis.

Drawing from the experience of traditional manufacturing systems, what is not measured and followed-up is naturally difficult to improve (Bellgran & Säfsten, 2010). In the single-case study the measuring or rather recording of engineering change is there but the follow-up is lacking. Circumstance could be the culprit of lacking lessons learned and subsequent continuous improvement efforts as engineering-to-order are just that, a one off product, one separate from the second, often executed by different project team over long time periods. Automating the lessons learned by quantifiable data, depicted in Fig. 4, could be a way for management and individual engineers to expose and visualise pitfalls and difficult project stretches based on prior data rather than an individual's experience.

5. CONCLUSIONS

A high flexibility of a manufacturing system allow for late changes to given specification. However a subjected to late changes final solution might be suboptimal as last minute solutions often are not as thought through as an original idea. Even though the similarities are few between traditional manufacturing and engineering-to-order projects, the need for adaptation to change and subsequently agility is of importance. While ECM models are used in a traditional manufacturing context i.e. automotive and consumer goods, the need to control large projects is obvious. As reflected in the literature, engineering-to-order projects in all industries utilise ECM processes. For the body of research associated with ECM, the larger mass of publications is focusing on pre-change and in-change analysis of the alternative solutions to a change. Literature directly concerned with manufacturing is almost non-existent and outdated while post-change subject are covered to lesser extent than pre- and in-change stages. In the traditional manufacturing industries pursuit of flexible, reconfigurable and agile manufacturing systems lessons can be learned from the ETO industry and likewise engineering-to-order could stand to benefit from the respect for manufacturing difficulties shown by the traditional manufacturing industries. From the analysed case study, results showed a focus on upstream activates rather than downstream in the projects, this mind set could be one of the explanations of the congestion of change orders in ETO manufacturing.

Further research is needed to establish obstacles and reasons for not analysing EC-data post-change other than when it is required in an arbitration process. In order to process and analyse data post change efficiently the relevance, extractability and consistency of the data to be input has to be established. As found in the case study the modes of information carriage are not always established or official these realities impair the efficacy of possible EC-data post change analysis.

From the theoretical assessment and the case study the conclusion is that ECM is an essential part of engineering-to-order projects but that the present body of work connected to manufacturing and ECM could be further enriched by additional research. The research presented in this paper aspires to make available methods from various industries. This has been first attempt of showing parts of the ETO project reality Furthermore interviews conducted as part of the case study revealed engineers and project manager thought on what adds to complexity and how that effects the project execution. Hence, this research highlights possible areas of contribution to the scientific research connected to ECM, ETO and manufacturing and suggests ways forward.

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