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# Using Performance Indicators to Improve Engineering Change Management in Engineer-to-Order Companies

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# Preface

This report is the result of my Master's thesis in the Spring semester of 2016. The thesis was conducted at Department of Production and Quality Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

During the autumn semester in 2015, a specialization project was conducted, which consolidate the foundation and further motivation for this master thesis. The findings in the project revealed that there is a gap to fill for performance measurement for ECM in ETO companies. Therefore, the focus of this thesis has been extended to address the issue.

I would like use this opportunity to thank my supervisor Erlend Alfnes for giving me the opportunity to carry out my Master's Thesis with the LIFT project at NTNU/Sintef. I am very thankful for everything Erlend has done during my Master's degree student, and especially for the encouragement and the inspiration from him. All of these were valuable for me from both academic and personal experience.

I am also very grateful to my co-supervisor Pavan Kumar Sriram for all the support and supervising during my specialization project as well my Master's thesis. Pavan has been very good in inspiring me to think in the new perspective to address my research. After all, he is a very kind and caring friend of mine.

A special thanks goes to the case company-Hycast, and employee from Hycast, Ezzart Chipana, Arild Håkonsen, Turid Kjølstad, Arild Vassli, Reidar Hagen. I would like to thank them for providing me with the opportunity to study with the company and for providing me with helpful discussion and information.

Finally, I am very grateful to my mum and Ee Chee Keong. I would not be able to complete my Master's degree without their immensurable support. The love from them supports me to go through the hardest time during the two year. I have been away from home such a long time but they always have been very encouraging. Thanks to them for everything they have done.

Trondheim, June 2016

Qi Zhu

# Abstract

**Purpose** – The purpose of this thesis is to develop performance indicators that can be applied to improve the performance of ECM in ETO companies.

**Design** – The thesis is based on a structured literature study among ETO, ECM, and performance indicator together with the case study among an ETO company.

**Findings** – The findings were presented in this order: (1) the challenges that ETO companies have in terms of product, process, customer, and supply for ECM; (2) ECs in ETO companies have the complex characteristics in terms of volume, reason, occurring phase, priority, and impact which make ECM in ETO companies even more challenging. (3) Current practices of ECM varies regarding ECM process, organizational structure, and tools used to support ECM. It has further shown that despite there are various methodologies and techniques have been proposed both in theory and practice for improving ECM, few is suitable for managing complex ECs in ETO context according to their own characteristics while providing improvement in both overall and local performance of ECM process. (4) Existing performance measurements on ECM are not suitable for improving ECM in ETO because, firstly, they focus on their own contributions not for improving ECM in ETO companies. Secondly, they focus on part of the scope of ECM performance which might result the sub-optimization. Thirdly, most of them are subjective and absolute which cannot reflect the performance in an objective and relative way. (5) A reference framework was developed to visualize the ECM process, provide basis for monitoring and controlling the performance, as well as enable the flexibility to handle ECs according to their own characteristics. It can also be applied to improve the configuration of ECM process. (6) A set of performance indicators were developed based on the reference framework to assess the performance of ECM in both overall and local level, which helps the decision-making on improving ECM.

**Research limitations** – (1) The proposed methodology is applicable for ETO companies in a general situation, further adaption is required to apply it into particular company. (2) The proposed methodology is based on ETO context. Functionalities and features within the new methodology may not fit well in other production strategy. (3) A considerable workload is required to use the performance indicators in both overall and local level. Computer-aided system can be helpful to reduce the workload.

**Value –** (1) The thesis identifies the-state-of-the-art of research in ECM. (2) It reveals the current practice of ECM in ETO company both theoretically and practically. (3) A reference framework was developed to visualize the ECM process, provide basis for monitoring and controlling the performance, as well as enable the flexibility to handle ECs according to their own characteristics. It can also be applied to improve the configuration of ECM process. (4) A set of performance indicators were developed based on the reference framework to assess the performance of ECM in both overall and local level, which helps the decision-making on improving ECM.

**Keywords** – Engineer-to-Order, Engineering Change Management, Performance Measurement, Performance Indicators.

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# Abbreviations

| | |
|---|---|
| **EC** | Engineering Change |
| **ECM** | Engineering Change Management |
| **ETO** | Engineer-to-Order |
| **FAR** | Field Action Request |
| **FCN** | Field Change Notice |

# 1 Introduction

Engineering Change (EC) is one of the most important driving forces of engineering and design. Design and product are changed in order to satisfy customer requirement. EC is also applied to make adjustment on the existing function so the the product can the meet original functional requirement that fails to reach initially. Improvement and optimization in the design and product can also be realized by applying EC in order to reduce cost and time, improve the quality and reliability. During production, EC can be initiated to ensure the manufacturability hence make production easier.

Despite the benefits they brought, EC is still considered as the problem instead of the opportunity in most of the literature (i.e. Hegde et al. 1992; Huang & Mak 1999; Rouibah & Caskey 2003; Huang et al. 2003; Terwiesch & Loch 1999; Loch & Terwiesch 1999). This is because the management of EC is not as easy as expected while most beneficial ECs are not as benefit as they predicted eventually. The difficulty of engineering change management (ECM) is especially apparent in ETO companies, which is due to the characteristics of ETO in terms of product, process, customer, and supply. In product level, only very few ETO product is designed from the scratch (Hamraz 2013), most ETO products are modified based on the existing product according to customer requirements (Wikner & Rudberg 2005; Porter et al. 1999), which makes ECs unavoidable. Also, the high degree of customization in ETO product makes ECs unpredictable since it is hard to predict the need from customers (Wortmann 1992; Bertrand & Muntslag 1993). The complex and deep product structure of ETO product makes EC propagate from the original object to the other components, in the extreme case, the entire system would be affected (Eckert et al. 2006; Hicks et al. 2000; Pikosz & Malmqvist 1998). In process level, the complicated structure and relationship within the order fulfilment process makes ECM process complex. Due to the different objectives and systems between different disciplines, the communication and information sharing between ECM become challenge (Bertrand & Muntslag 1993; Pikosz & Malmqvist 1998; Chen et al. 2002; Mokhtar et al. 1998). In customer level, the high requirement for the delivery performance in terms of delivery time and product quality require the efficient and effective ECM within ETO companies (Hicks et al. 2000; McGOVERN et al. 1999; Pikosz & Malmqvist 1998). While in supply level, due to the cost and strategic issue, the trend of outsourcing results the distributed environment among ECM, which makes ECs difficult to handle (Hicks et al. 2000; Elfring & Baven 1994; McGOVERN et al. 1999; Wasmer et al. 2011).

It has been reported that ECs consumed around 30% to 50% of engineering capacity (Terwiesch & Loch 1999), which is one of the main bottlenecks in ETO companies (Grabenstetter & Usher 2015). Fail to manage ECs properly can result the loss in time and money, interrupt production schedule, as well as degrade the reliability and the quality of product, which leads to the low profitability (Rouibah & Caskey 2003). In the extreme case, the company can lost their competitive advantages in the marketplace (Huang & Mak 1998). Therefore, it is vital to have a proper ECM in order to keep the profitability as well as remain the company's competitive advantages.

Despite the importance of ECM to ETO companies, the situation of ECM in ETO is still unpleasant. This due to the lack of an appropriate technique to handle the difficulty in ECM in ETO. Another reason for this unpleasant situation is due to the low awareness of the current performance of ECM within the companies.

Various techniques and methodologies have been proposed to improve ECM, however little research focus on improving ECM by identifying the weakness and area to improve within the current performance of ECM. It is impossible to make improvement without the measuring the performance among current situation (Fortuin 1988). As the tool of performance measurement, performance indicators are used to assess the current performance of ECM process. Different from other methodologies and techniques, performance indicators can improve and optimize ECM in ETO companies by providing information about what is happening within ECM and identify where to improve rather than dealing with the problem directly. With the application of performance indicators, the current performance of ECM in the company can be assessed, which provides information for identifying the inadequacy and the weakness, and helps to make decision on where to improve among ECM. Furthermore, by benchmarking with the best practices in the similar industry, company can not only identify the inadequate and sufficient, but also reveal the reasons for the specific performance, which can eventually be used for the continuous improvement.

Another motivation for this thesis is based on the usage of performance measurement on ECM. The performance indicators for ECM can be used to evaluate the application effect of those techniques and methodologies on the performance of ECM. Thorough study on the literature in ECM, it was found that most proposed methodology have not been validated in practice. Only few methods have been further validated with performance measurement focus on their own contribution. The low validation in the proposed methodologies can be the lack of such tool that can show whether those methods have effect on the performance of ECM. Moreover, in reality, if method is decided to apply for improving ECM, a tool that can show the effect of the application on the performance of ECM is also required. Therefore, it is necessary to have indicators to show the performance of ECM.

The importance of ECM in ETO companies together with the gap within the performance measurement on ECM form the motivations for this thesis. Therefore, the objective of this thesis is to develop performance indicators that can be applied to improve the performance of ECM within ETO companies so that to keep the profitability as well as remain the company's competitive advantages.

This thesis identifies the-state-of-the-art of research in ECM through a structured literature review. It reveals the current practice of ECM through the literature review and the case study. The new methodology proposed in this thesis provides a reference framework for ETO company to efficiently and effectively manage different ECs according to their own characteristics. Meanwhile, the set of performance indicators within the new methodology assess the performance of ECM in both overall and local level, which helps the decision-making on improving ECM.

The remaining part of the thesis is presented as follows. In Chapter 2, research objectives and research questions are presented, this is followed by research scope in Chapter 3. Chapter 4 describes research methodology adapted in this thesis. Chapter 5 presents literature review on ETO, ECM, and performance measurement. The new methodology is developed based on the findings through literature review in Chapter 6. While a case study conducted in ETO company is presented and discussed in Chapter 7. The application of the new methodology for ECM in case company is elaborated in Chapter 8. The discussion of the new methodology is presented in Chapter 9. The thesis ends up with the conclusion in Chapter 10.

# 2 Research Objectives and Research Questions

The primary objective of this project is to use performance indicators to improve ECM in ETO companies. This is achieved by setting the performance objectives on the understanding of ECM in ETO context and the current practice of ECM in ETO companies. By using the findings as the best practices, performance indicators can be developed so that they can help to improve ECM in ETO companies.

The objectives of the thesis have been formulated into the following:

1. Develop an understanding of ECM and the current practice of ECM in ETO companies.
2. Develop an understanding on how to develop performance indicators and based on this, evaluate the existing research on performance measurement for ECM.
3. Set up a foundation that shows how an efficient and effective ECM looks like.
4. Use the foundation as the performance objectives to develop performance indicators that can be used to improve the performance of ECM in ETO companies.
5. Use the new methodology and findings with the case company to develop a solution that can help to improve ECM in ETO companies.

To reach these objectives, the thesis will focus on the following research questions.

**RQ1: What are the challenges of ETO for ECM?**

Definition of ETO, order fulfilment process of ETO and the challenges of ETO for ECM should be presented.

**RQ2: What are current practices of ECM in ETO companies?**

Current situation of ECs and ECM in literature is identified, the-state-of-the-art of research in ECM is identified.

**RQ3: What performance indicators can be applied for improving ECM in ETO companies?**

Definition, purposes, and principles for developing performance indicators are presented. Existing research in performance measurement on ECM is listed and elaborated. To develop performance indicators, a reference framework is developed from the current practice of ECM in ETO companies identified in RQ2. It works as the best practices for the performance objectives.

Performance indicators for improvement ECM in ETO companies is developed on the basis of the reference framework.

# 3 Research Scope

*"ECs are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behavior (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact."(Hamraz et al. 2013, p.475).* This definition successfully distinguishes ECs from design iterations. For the scope of this research, ECs is the research target while those design iterations are not the scope of this thesis. Figure 3-1 shows a clear scope for this issue. It is important to mention, for the purpose of this thesis, those field action requests (FARs), and field change notice (FCNs) are also considered as ECs.

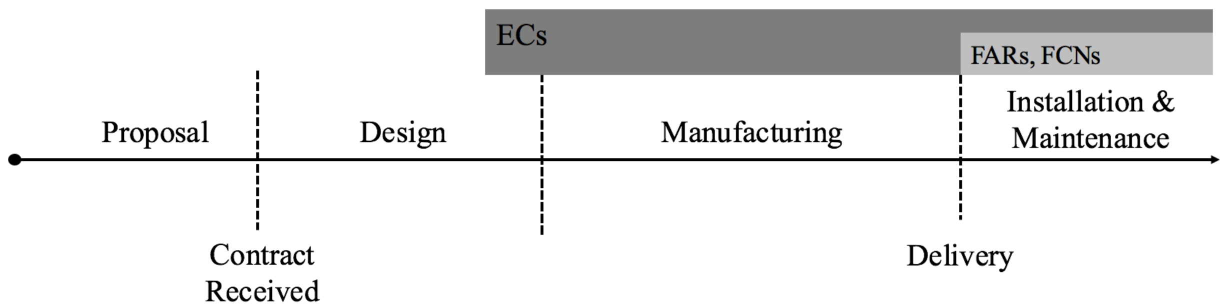


**Figure 3-1: Map for the Scope of ECs. Adapted from Subrahmanian et al. (2015)**

Managing ECs is considered as a problem in majority of the literature. Techniques and methodologies have been proposed to improve ECM. According to Jarratt et al. (2011), these techniques and methodologies can be classified into two types by their purposes. Firstly, those help to manage or document the ECM process. Secondly, those to support decision-making at a specific phase of ECM process. The new methodology proposed in this thesis belongs to previous type, which helps to improve ECM in ETO environment.

Different from other proposal that deal with the challenge directly, the new methodology developed in this thesis improve ECM in ETO companies by assessing the overall performance of ECM and identifying where to improve. In order to improve the inadequacy, further techniques and methodologies are required to deal with the corresponding problem, so that the performance of ECM can be improved.

In this thesis, the proposed new methodology provides the function for the former two steps, which means it provides the assessment of overall performance of ECM in ETO companies and helps to make decision on where to improve. The techniques and methodologies that are used to improve the inadequacy are not in the scope of this thesis.

It should be noticed that the thesis does not cover all the relevant research on the topic. However, there is still an attempt to cover the bibliography which is most important and relevant to the research objectives and questions.

# 4 Research Methodology

The methodology along with the research methods that were applied to achieve the objectives of this thesis are described in this chapter. Usually, the terms “methodology” and “method” are used without differentiation. However, there is still difference between them. A methodology is the overall understanding and picture of the applied methods, while a method is a technique of doing something, in this case, it is a techniques or a way to gather data and evidence (Bryman 2015; Greener 2008; Kaplan 1964). In general, a set of research methods form the research methodology. Before moving to the research methods applied in this thesis, it is important to describe how the research is planned and designed. Therefore, the research design is presented first.

## 4.1 Research Design

Research design is an overall plan for the conduction of research. The research conducted in this thesis follows the flow that was described by Greener (2008). At the initial stage, the exploratory research is conducted. Exploratory research is applied when there is lack of clear idea of the problems (Greener 2008). Brainstorming, discussions and extensive literature review are applied in order to define the scope of this thesis. After the deeper understanding on the direction and challenges of researching field, the research objectives and questions are clarified and defined. Then the descriptive research is conducted further among literature review and case study. Descriptive research is more formal and clear than exploratory research. With the clearly stated hypothesis or investigation questions, exploratory research is used for describing phenomena or identifying associations among different variables.

Throughout the research, the thesis closely focused on the overall objective that using performance indicator to improve ECM in ETO companies while the objectives that listed in the chapter 2 have been achieved.

## 4.2 Research Methods

Generally speaking, there are two types of research methods, namely qualitative and quantitative. Qualitative methods refer to those analysis based on text data in its textual form, they concern about constructivism, interpretation and perception (Strauss et al. 1990; Bryman 2015). Quantitative methods refer to those statistical tools and analysis based on numerical data, or textual data that can be transferred into numbers. The result of quantitative method focus on the validation of the process of the research while the replication capability is vital for the validation (Bryman 2015; Carter & Little 2007).

In this thesis, the quantitative research methods, namely literature study, and case study have been used to conducted research and achieve the objectives. These quantitative research methods will be elaborated in the following.

### 4.2.1 Literature Study

Literature study shows the state-of-the-art research in the field, it helps to understand the certain topic in academic attitude and suggest a feasible scope of the research (Karlsson 2010).

After the extensive literature search in the initial stage, the scope of literature study was narrowed down based on the research questions. Table 4-1 gives a categorization of the literature study.

Table 4-1: Literature review categories.

| **Categories** | **Sub-categories** |
|---|---|
| ETO | Definition<br>Characteristics<br>Order fulfilment process |
| ECM | EC<br>EC characteristics<br>ECM process<br>Organizational structure<br>Tools and methods<br>Performance measurement on ECM |
| Performance Indicator | Definition<br>Purposes of PIs<br>Methods and principles for developing performance indicator |

Keywords searches were made through several main databases: ProQuest, Science Direct, Emerald, Springer, NTNU BIBSYS, and Google Scholar. Two sets of keywords were created. The primary set is the main keywords while the second set is used together with the first set to narrow down the search scope. The keywords list is shown in Table 4-2.

Table 4-2: Keywords used in literature search.

| **Keywords Set 1** | Keywords Set 2 |
|---|---|
| Engineer-to-order<br>One-of-a-kind<br>Design-to-order<br>Make-to-order<br>Project<br>Customization | Typology<br>Types<br>Production environment<br>Production situation<br>Characteristics |
| Engineering change<br>Engineering change management | Definition<br>Current practice<br>Case Study<br>Characteristics<br>Process<br>Tool<br>Method |
| Performance Indicators<br>Performance Measurement | Development<br>Purpose<br>Principle |

The abstracts of found papers were read to learn purpose and content in the literature search stage. If the content of the paper is relevant, introduction and conclusion of the paper will be read. During further analyzing, the papers relevant to this project and research questions were selected based on the criteria below. More papers were selected by "snowball effect", which means that the references in these initial selected papers are traced for the papers relevant to this project. The entire process is shown in Figure 4-1.

**Selection criteria:**

1. Does the literature involve the management, order fulfilment process, and characteristics of ETO environment?
2. Does the literature involve the industrial case study among EC and ECM?

3. Does the literature involve the characteristics of ECs in terms of volume, reasons, initiator, impact, priority, occur phase?
4. Does the literature concerning on ECM and propose method for improving ECM?
5. Does the literature include performance measurement for ECM?
6. Does the literature contain performance measurement and performance indicators, does it contains the way and the requirement for developing performance measurement and PIs?

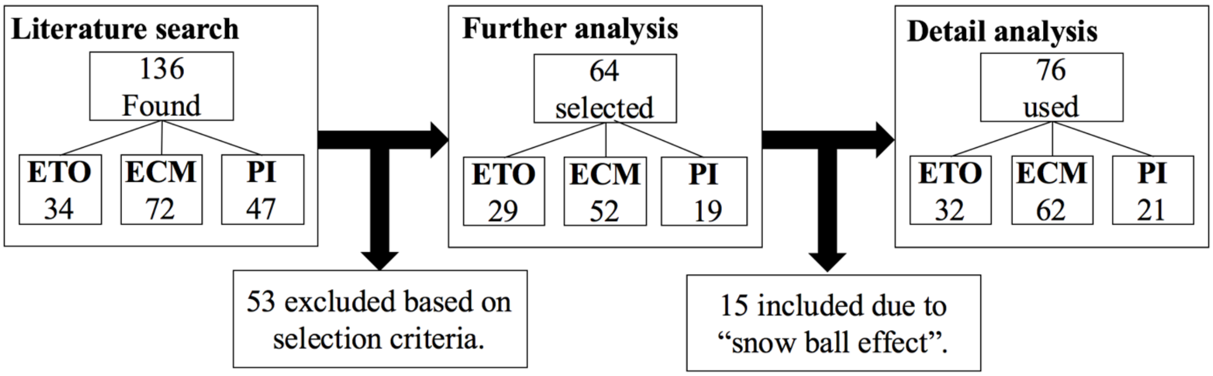


**Figure 4-1: Process of Literature Study**

# 5 Literature Review

The following chapter will present the theoretical findings of this thesis. In Section 5.1, ETO will presented with the challenges that ETO have to make ECM difficult. In Section 5.2, current practice of ECM in ETO companies will be presented, which includes several perspectives in terms of EC, ECM, and existing research in ECM. In Section 5.3 performance measurement will be presented. The three section form the theoretical findings which direct the research into next stage.

## 5.1 Engineering-to-Order

In this section, theory and findings concerning with ETO will be presented. In Section 5.1.1, ETO production strategy will be introduced with the definition to ETO. This is followed by the order fulfilment process in ETO companies. In Section 5.1.2, challenges of ETO companies that make ECM difficult will be presented and elaborated. Hence, the first research question is answered by the two sections.

### 5.1.1 Definition of ETO

Engineering-to-Order (ETO) has been mentioned by various production management literature. However, there is no consensus on the definition of ETO. Table 5-1 gives an overview on the definition of ETO among literatures.

Table 5-1: Definition of ETO among literatures

| **Description** | **Reference** |
|---|---|
| The production environment where customer order decoupling point (CODP) is located at design stage, which means the business activities downstream from design, namely, fabrication and procurement, final assembly, and shipment, are pulled by customer orders. | (Olhager 2003); (Wortmann 1992); (Giesberts & Tang 1992); (Da Silveira et al. 2001) |
| ETO was defined as a production environment where design, engineering, manufacturing has been contributed to specific customer order, it can be either a totally new design or | (Rudberg & Wikner 2004); (Wikner & Rudberg 2005); (Porter et al. 1999) |

| | |
|---|---|
| modification to existing design according to customer requirement. | |
| Pure customization where all stage of processes: from design, fabrication, to assembly and distribution are totally customized; and tailor customization where all the stage except design stage is included but products are still tailored or adapted according to specific requirements. | (Lampel & Mintzberg 1996) |
| Production environment where the amount of investments is independently from customer order. The company can make investment in product development, production process development, and resources. | (Wortmann 1992) |
| Fabricators with a high degree of customer involvement and high modularity in design and fabrication. It has early customer involvement with customized design and revisions on products. | (Duray 2002) |

Conclusion can be drawn that the definition: ETO is a production environment where the customer order decoupling point is located at the design stage is generally accepted. Different opinions exist on the degree of customization where the product is fully new design or adapted from existing product according to specific order.

In this paper, the definition that production environment where design, engineering, procurement, fabrication, final assembly and shipment are all driven by the customer order will be used. Therefore, according to the definition, ETO production environment can be either making new design or modification on existing product according to customer orders since both situations has implications for ECM process.

There are four phases in the order fulfillment process in ETO company, namely, conceptual phase, design phase, manufacturing phase, and operation phase (Hameri & Nihtilä 1998), which is shown in the Figure 5-1.

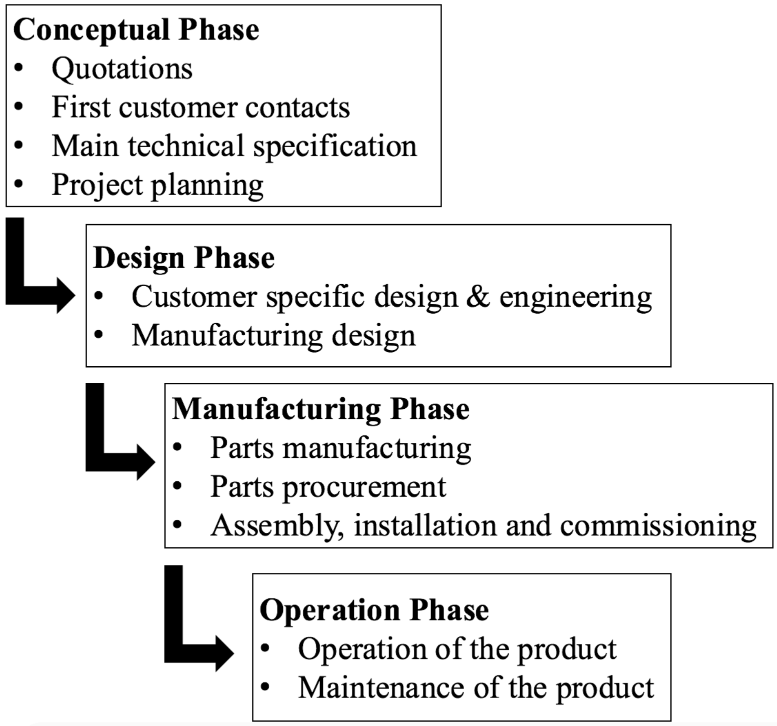


Figure 5-1:Order fulfillment process in ETO. (Hameri & Nihtilä 1998)

The activities in conceptual phase involve signing the initial customer contracts. Company need to prepare detailed offer including the main product specification and project plan. During the process, the short response time to customer requirement is critical to keep a high customer service level (Hicks et al. 2000). In the design phase, detailed designing and engineering are executed according to customer requirements while documents for manufacturing are also generated in this phase. Hence, accurately transferring customer requirements into specifications is important in this phase (McGOVERN et al. 1999). It is also normal that customers change their requirements or design during this phase, which is one of the main sources of EC in ETO companies (Sudin et al. 2009). In the manufacturing phase, production orders and procurement orders are issued according to the documents generated in the previous design phase. Since manufacturing, assembling, installation, testing are the main activities, communication and information sharing with internal department and external suppliers are essential in this phase (Hameri & Nihtilä 1998). The operation phase is the period that customer is using the product. Feedbacks from customer in this phase should be documented, which will be helpful for the product improvement.

### 5.1.2 Challenges of ETO Companies for ECM Process

Due to the position of customer order decoupling point, there is a high degree of customization in ETO product (Hicks et al. 2000; Bertrand & Muntslag 1993; Caron & Fiore 1995; Tu 1997; McGOVERN et al. 1999; Olhager 2010; Porter et al. 1999; Jin & Thomson 2003; Dean et al. 2009). This high involvement of customer in design and engineering phase results the uncertainty in product specification, which also makes engineering as the most time-consuming process in ETO (Grabenstetter & Usher 2015; Jin & Thomson 2003). The uncertainty in product specification is also the main reason for the occurrence of ECs (Wortmann 1992; Bertrand & Muntslag 1993; Hicks et al. 2000; de Carvalho et al. 2015; Caron & Fiore 1995; McGOVERN et al. 1999).

Products of ETO, in most cases, are complicated and have a deep structures combined with both standard and customized components and systems (Hicks et al. 2000; Bertrand & Muntslag 1993; Caron & Fiore 1995; McGOVERN et al. 1999; Porter et al. 1999; Lampel & Mintzberg 1996). Because of the strong couplings between components and system, change on one part will eventually results change on other parts or even the entire system. (Terwiesch & Loch 1999). This is so called change propagation (Eckert et al. 2006; Jarratt et al. 2004) or snowball effect (Terwiesch & Loch 1999). Despite current ECs may have little influence on target parts, huge impact on other parts or systems can still be incurred because of change propagation (Eckert et al. 2006; Rouibah et al. 2003). It is important to notice that in ECM process, investigations of change propagation have to cover all the affected parts or components. Failing to do so, in the worst situation, will lead to stop of production and recalling the delivered products (Pikosz & Malmqvist 1998).

The structure of each departments and the relationship between each of them are complex in ETO companies (Bertrand & Muntslag 1993; Tu 1997), which results the complexity in ECM process in ETO companies as well. In most cases, 4 to 7 different departments are involved in ECM process (Terwiesch & Loch 1999; Huang & Mak 1999), where design and engineering department is mostly involved department among others (Huang & Mak 1999). Other departments such as marketing, production and manufacturing, quality management, project management, and after-sales are also involved in ECM process. This complicated involvement of different disciplines during EC managing leads to the complex ECM process, which lower the efficiency and effectiveness of ECM process as well.

Because of the cost and strategic decision, multi-level of vertical integration ranging from totally in-house manufacturing to pure design and contract organizations is applied in ETO companies, which increases the complexity in both the structure and the relationship of companies (Hicks et al. 2000; Elfring & Baven 1994; McGOVERN et al. 1999). However, since different functional department have their own goals (Pikosz & Malmqvist 1998), the communication and information sharing between different disciplines become challenge in ECM in ETO companies (Chen et al. 2002; Mokhtar et al. 1998).

In the case studies conducted by Pikosz and Malmqvist (1998) among an ETO company, An EC was updated in several editions due to the iteration from manufacturing to design. The reason for this iteration was because of the errors such as "inability to manufacture". They argued that the updating in editions is the results of lack of communication between different functional departments. They further concluded that communication and information sharing is essential for the ECM in a distributed environment. Rouibah et al.(2003) also recognized the requirements and argued that the collaboration and the data transparency between all related department are the key factors for the fast and less-error ECM process. Fall to share qualified information across different departments may lead to the application of wrong data which eventually result the increase in change impacts (Huang & Mak 1999). In the extreme case, "air crash" will be the result of poor information quality in ECM (Pikosz & Malmqvist 1998).

Different ECM system among external disciplines is another reason that makes communication and information sharing challenging in ECM in ETO companies. According to Wasmer et al.(2011), customers and suppliers usually have their own ECM system and database in reality, which means translation and interpretation of data are necessary when ECs or change related information are sharing across the border of company. This gap between two companies can affect the effectiveness and the efficiency of ECM, which makes communication and information sharing challenging. Moreover, in ETO companies, due to the outsourcing of components or parts, design responsibility is transferred to supplier (Chen et al. 2002; Mokhtar et al. 1998), the flexibility to deal with ECs is reduced (Hicks et al. 2000; Elfring & Baven 1994; McGOVERN et al. 1999). Therefore, the main objective of ECM between companies and suppliers is to exchange information efficiently and effectively (Pikosz & Malmqvist 1998). Late information updating to suppliers will lead to interruption on manufacturing in the suppliers, which will eventually affect the delivery performance of final product.

In ETO environment, a high delivery performance in terms of delivery time and quality of product is one of the key competitive advantages for the companies (Hicks et al. 2000; McGOVERN et al. 1999). Furthermore, it is also required for ETO companies to accurately transfer customer requirements into specification. (McGOVERN et al. 1999). Therefore, as the system to process the change request from customer, it is important and essential for ECM process to be efficient and effective enough to avoid late and wrong implementation of EC, which will incur defect as well as affect delivery performance of final product (Pikosz & Malmqvist 1998; Rouibah et al. 2003). However, in ETO companies, the efficiency and the effectiveness in ECM process becomes challenging due to several reasons. For the efficiency of ECM process, complex ECM process, congestion in the flow, lack of EC handling capacity, setups and batching for EC, change propagation due to complex product structure, and organizational cost management culture can all lead to low efficiency in ECM process (Terwiesch & Loch 1999). Others such as lack of notification for the arrival of EC (Huang & Mak 1999), and lack of knowledge management system to support knowledge transfer during EC evaluation (Lee et al. 2006) are also the reasons for low efficiency in ECM process. For the effectiveness of ECM process, it highly depends on the quality of information among ECM process in ETO companies. However, as elaborated in previous paragraphs that the different objectives in corresponding disciplines as well as different ECM systems between customers, suppliers, and the companies are the main contributions to lower the information quality, which leads to the low ECM process effectiveness. Moreover, engineer who lack of knowledge and experience is another reason for the low effectiveness in ECM process (McGOVERN et al. 1999).

Table 5-2 gives an overview the challenges that ETO companies have in ECM. It can be concluded from these findings that it is the characteristics of ETO that make ECM challenging in ETO companies.

Table 5-2: Overview of Challenges that ETO companies have in ECM

| Attributes | Description | Reference |
|---|---|---|
| Product | High degree of customization in product results change in product specification, which is the main source of EC. | (Wortmann 1992; Bertrand & Muntslag 1993; Hicks et al. 2000; de Carvalho et al. 2015; Caron & Fiore 1995; McGOVERN et al. 1999). |
| | The complicated and deep product structure of ETO product makes EC propagation challenging in ECM. | (Eckert et al. 2006; Jarratt et al. 2004); (Hicks et al. 2000; Bertrand & Muntslag 1993; Caron & Fiore 1995; McGOVERN et al. 1999; Porter et al. 1999; Lampel & Mintzberg 1996); (Pikosz & Malmqvist 1998). (Rouibah et al. 2003) |
| Process | Complex structure and relationship in the order fulfillment process makes ECM process complex as well. | (Bertrand & Muntslag 1993; Tu 1997); (Terwiesch & Loch 1999; Huang & Mak 1999) |
| | Due to different objectives between different departments, communication and information sharing between different disciplines within ECM process is challenge. | (Bertrand & Muntslag 1993; Tu 1997); (Pikosz & Malmqvist 1998), (Chen et al. 2002; Mokhtar et al. 1998); (Wasmer et al. 2011); (Rouibah et al. 2003) |
| Customer | Customers require a high delivery performance in terms of delivery time and quality, which requires both efficiency and effectiveness of ECM process. | (Hicks et al. 2000; McGOVERN et al. 1999); (Pikosz & Malmqvist 1998; Rouibah et al. 2003) |
| Supplier | Increasing level of outsourcing increase the difficulties in collaboration, which reduce the flexibility in ECM process. | (Hicks et al. 2000);(Elfring & Baven 1994);(McGOVERN et al. 1999) |
| | The difference in ECM system between suppliers and ETO companies makes communication and information sharing challenge. | (Wasmer et al. 2011) |

## 5.2 Current Practices of ECM in ETO Companies

The previous chapter discussed the challenges that ETO companies have for ECM in the same context. In this chapter, a review among the literature on ECM was conducted in order to investigate further on the current practices of ECM in ETO companies. Two sections are presented to show the findings among this theme. In Section 5.2.1, EC and ECM in ETO companies is presented. This is structured in terms of definitions of ECs, volume of ECs, reasons for ECs, phases that ECs occur, priority of ECs, impact of ECs, ECM process, organizational structure, tools used to support ECM. In Section 5.2.2, the existing research in ECM are presented together with the ECM method developed in research. Two sections together answer the second research question: "What are current practices of ECM in ETO companies?"

### 5.2.1 EC and ECM in ETO Companies

**Definitions of ECs**

Scholars have proposed various definitions for EC. The following are a few of these:

- Huang and Mak (1999, p.21) as well as Huang et al.(2001, p.255) define ECs as "one kind of changes and/or modifications in forms, fits, functions, materials, dimensions, etc., of products and constituent components."

- Wright (1997, p.33) gives out the definition that: "an engineering change (EC) is a modification to a component of a product, after that product has entered production."

- Terwiesch and Loch (1999, p.160) refer ECs as "Changes to parts, drawings, or software that have already been released"

- Huang et al (2003, p.481) give out another definition that "Engineering changes (ECs) are the changes and/or modifications in dimensions, fits, forms, functions, materials, etc. of products or constituent components after the product design is released".

- Jarratt et al. (2011, p.105) define that ''An engineering change is an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time.''

Huang and Mak (1999) together with Huang et al.(2001) out a definition of EC that covers a broad scope of changes but without differentiating ECs from design iterations (Hamraz et al. 2013). Design iterations are normal in ETO companies due to the high degree of customization and the changing requirements from customer during engineering phase when the design have not been released. Despite that Wright's (1997) definition gives the distinguish, however, it restricts that ECs can only occur after the product has entered production. In other word, it ignores the occur of ECs before production. The fact is that ECs can occur during the entire product life cycle: from design, to manufacturing, and operation. This is especially the case in ETO companies because in design phase, when design has been released, ECs can still occur due to the changing request of product specification from customers (Sudin et al. 2009). Terwiesch and Loch (1999) as well as Huang et al. (2003) give a better a timeline that distinguishes ECs from design iterations. Moreover, Terwiesch and Loch (1999) also include changes to software in the scope, which is more suitable for the reality in ETO companies. Comparing with other definitions, Jarratt et al. (2011) give out a most sophisticated definition combined both a broader scope of ECs as well as the time aspects. They further define that ECs can be any size or type with different level of people's involvement and length of time. However, the definition excludes the functional ECs in the scope, which is also one of the main reasons for EC in ETO companies. Based on Huang et al. (2003) and Jarratt et al. (2011), Hamraz et al. (2013) gives a definition covering an even wider scope of ECs that is more suitable for the reality of EC in ETO companies, which is adopted in this thesis. *"ECs are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behavior (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact. "(Hamraz et al. 2013, p.475)*

**Volume of ECs**

The volume of ECs varies from ETO companies. A study conducted by Huang et al. (2003) among four Hong Kong manufacturing companies revealed that the number of existing ECs in different companies can range from five to countless. They finding is validated by a study conducted by Ahmed & Kanike (2007)), it revealed that there was over 1,500 ECs occur in an aerospace company throughout eight years of product life cycle.

Despite that there is no consistency among ETO companies, the volume of ECs can still be affected by several factors, namely, definitions of EC, the efficiency of ECM process, the stage that the volume is checked, and the complexity of the product (Jarratt et al. 2011). It was concluded by Terwiesch & Loch (1999) that too many existing ECs in companies can lead to the over occupancy of engineering capacity, which will eventually result the delay of product delivery.

**Reasons for ECs**

Product improvement and error correction are two main reasons mentioned in various literature (Jarratt et al. 2011; Eckert et al. 2004; Ahmed & Kanike 2007; Sudin et al. 2009; Vianello & Saeema 2012; Vianello & Ahmed 2008; Veldman & Alblas 2007). These reasons focus more on ECs in functional level. However, they categorize EC reasons by whether they are from internal and external sources. Another more sophisticated categorization of reasons for ECs with the same concept is accepted by various scholars (Ahmed & Kanike 2007; Eckert et al. 2004; Eckert et al. 2006; Shankar et al. 2012; T. Jarratt et al. 2011; Subrahmanian et al. 2015; Veldman & Alblas 2012). In this categorization, ECs are categorized into initiated and emergent.

Initiated ECs refer to changes apply for improvements, enhancements or adaptations of a product, which are the main reasons for ECs in ETO companies (Ahmed & Kanike 2007; Sudin et al. 2009) . The causes of these ECs are incurred from outside sources.

- *Customer requirements* are one of the most common reasons for ECs in ETO companies because of a high degree of customization in ETO (Wortmann 1992; Bertrand & Muntslag 1993; McGOVERN et al. 1999; Grabenstetter & Usher 2015). it is usual for customers to change their requirement throughout the product development life cycle (Little et al. 2000). ECs from customer are also due to the fact that only few number of product in ETO companies are designed from the scratch (Hamraz 2013), therefore, most products are modified from the existing product according to customer requirements (Wikner & Rudberg 2005; Porter et al. 1999).
- *Supplier suggestions.* Due to cost and capacity consideration, it is becoming common for ETO companies to keep their core capabilities in house and outsource some of the production. In some extreme cases, all the product development activities in companies are contracted to external organizations (Hicks et al. 2000; Elfring & Baven 1994; McGOVERN et al. 1999; Dean et al. 2009). However, it is a remarkable fact that suppliers have their own constraints (Jarratt et al. 2011), which means that supplier may propose ECs in order to comply their product standards, material specifications or

technical capabilities etc. These ECs may affect other parts or systems which might eventually affect the final product specification and delivery performance

- *Changes of regulation.* Another reason for ECs in ETO can be the changes of regulations. A case study in a helicopter manufacturer conducted by Eckert et al.(2004) revealed that the regulations for the certification of helicopter may change, so the design adhere to these regulations need to change at the same time. This finding agreed with the findings revealed by Ahmed & Kanike (2007) and Sudin et al. (Sudin et al. 2009) among an aerospace engine manufacturer.
- *Innovations and optimization* in design, materials, manufacturability and other factors which can be beneficial for both company and customer can also be the trigger of ECs in ETO companies (Jarratt et al. 2011; Eckert et al. 2004; Ahmed & Kanike 2007; Sudin et al. 2009). These kind of ECs can occur throughout the order fulfilment process in ETO companies (Ahmed & Kanike 2007).
- *Feedback from customer* during their operation of products is the important reasons for ECs in ETO companies. This type of EC reason is special in ETO due to the existing of operation phase in the order fulfilment process of ETO companies (Vianello & Ahmed 2008) Usually, these feedbacks will be transferred into the form of ECs in order to improve the performance of product in the next generation (T. Jarratt et al. 2011; Vianello & Ahmed 2008)

For emergent ECs in ETO, the reasons are due to the properties of the product itself. They are used to remove mistakes or make product work properly (Jarratt et al. 2011; Eckert et al. 2004; Ahmed & Kanike 2007; Eckert et al. 2006; Shankar et al. 2012; Veldman & Alblas 2007).

- *Error corrections* in this category refer to the removing of mistakes from parts or documents during the entire development life cycle. The mistakes include errors that affect the function of a product or faults in drawings or documents. ECs with these reasons should be process in a quicker speed in order to avoid the impact caused by them (Balcerak & Dale 1992). In ETO companies, this type of ECs accounts for around half of the total amounts throughout the entire order fulfilment process (Sudin et al. 2009).
- *Function adjustments* occur when the design of a product does not match the original functional requirements. For example, the operational temperature is not properly evaluated, so ECs are required to adjust the function of product. These ECs are common in ETO companies that fail to accurately transfer customer requirements into product specifications.
- *Quality problems* comprise failures in manufacturing, assembling, and commissioning. Inappropriate design, manufacturing and assembling can all result quality problems, which eventually lead to ECs. In ETO company, because of the phase these ECs occur, they usually have larger impact on cost and schedule (Balcerak & Dale 1992).

- *Safety reasons.* "Products must be changed if they do not meet safety requirements or are expected to kill, injure, damage property or cause commercial damage."(Jarratt et al. 2011, bk.109). However, ECs due to safety reasons are not very common in ETO companies. In design phase, calculations and simulations are executed under certain regulations. In manufacturing phase, product will be tested before delivery (Eckert et al. 2004).

**Phases that ECs occur**

ECs occur throughout the order fulfilment process in ETO companies (Jarratt et al. 2011; Sudin et al. 2009; Ahmed & Kanike 2007; Veldman & Alblas 2007; Vianello & Ahmed 2008; Vianello & Saeema 2012). They can be divided into four phases according to the order fulfilment process developed by Hameri and Nihtila(1998). It is important to notice that the volume of ECs and reasons for ECs were highly relevant to the phase that ECs occur in the product life cycle in ETO companies (Ahmed & Kanike 2007; Sudin et al. 2009). In most cases, ECs occur in early phase of an order fulfilment process were for improving the existing design while these occur in later phase were for error correction, and correct the failure in quality (Vianello and Saeema 2012). Moreover, the later ECs occur, the more time, effort, and cost required to implement them (Wasmer et al. 2011).

In conceptual phase, main technical specifications are established, which means designing are executed in a general level. Changes occur in this phase mainly from customers. Since most design have not been released in this phase, those changes are not in the scope of the definition of EC. However, it is important that company need to respond to these changes quickly enough in order to keep a high customer satisfaction level (Hicks et al. 2000; McGOVERN et al. 1999).

After conceptual phase, initial design has been released internally, which means changes occur in design phase can be considered as ECs. In design phase, detailed designing and engineering are executed. During this process, ECs occur. The main reasons for ECs in this phase can be those for customer requirement, supplier suggestion, innovation and optimization, and *function adjustments*. Hence, the initiators of ECs in design phase are customers, suppliers, as well as engineering department within ERO companies. However, in most cases, those ECs are small modification and have less impact (Rouibah et al. 2003).

ECs can also occur in manufacturing phase. Studies conducted by Ahmed & Kanike (2007) in aerospace industry revealed that most of ECs occur in this phase. The finding was confirmed by Veldman & Alblas (2007), Sudin et al. (2009), and Vianello & Ahmed (2012) in their research into electronic, machinery, oil, and gas industries. The reasons for ECs occurring in this phase can be error correction from customers, suppliers, engineering and manufacturing department, change requirements from customers, supplier suggestions, and quality problems from manufacturing (Sudin et al. 2009; Ahmed & Kanike 2007). It worth mentioning that ECs occur in this phase can have greater impact than those occur in previous phase. This can be due to the fact that in some industries every product design must be validated by certain external organizations (Eckert et al. 2004). So any EC to the approved design requires validation again. Furthermore, in this phase, production orders or procurement orders have been released, the manufacturing internally and in supplier started already. Thus, ECs occur after the release of these orders can cause huge impact on the lead time and delivery date of these parts, which ultimately affect the final product delivery performance (Jarratt et al. 2011).

In the operation or service phase, ECs occur may due to the improvement of product, which initiated from customer's requirements or engineering from companies themselves. Usually, these ECs are beneficial and should be evaluated and documented carefully. It is also important for the companies to discuss with customers and decide which ECs should be applied on the next generation of products. ECs are also incurred due to functions adjustment and quality detected during commissioning and installation. In most of the cases, these types of ECs require immediate attention and implementation to solve the problem (Vianello & Ahmed 2008).

Figure 5-2 gives a summary that covers the reasons of ECs based on the phase that occur.

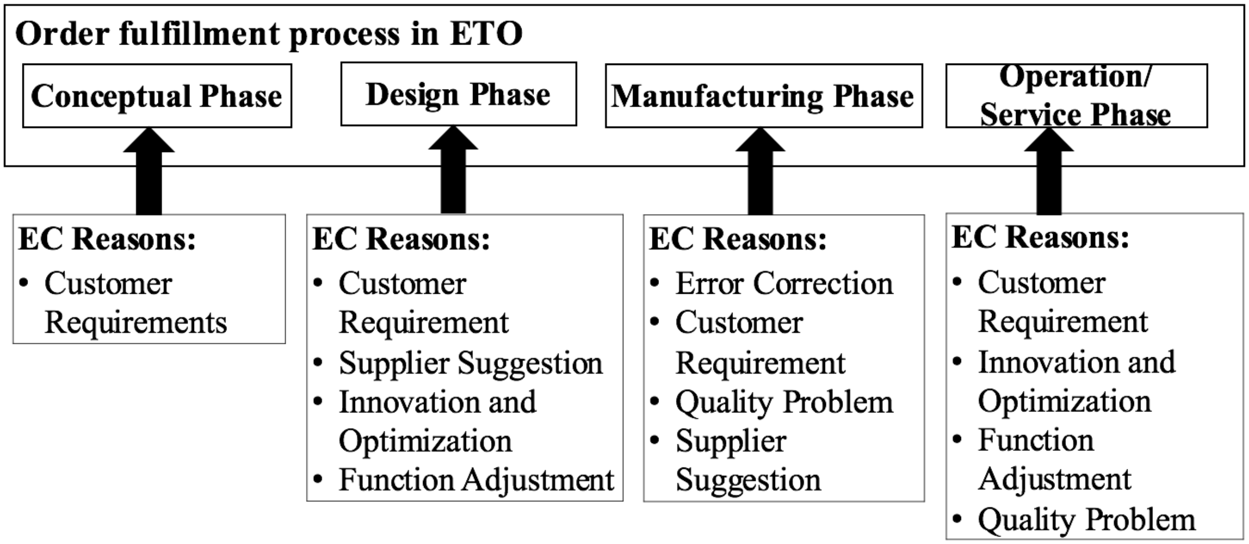


**Figure 5-2: Phases that ECs occur with corresponding reasons.**

**Priority of ECs**

Priority of EC in ETO companies highly depends on the reason for EC. Diprima (1982) proposed three categories for EC priorities on the basis of timing of EC implementation, which is also applicable in ETO context.

Immediate ECs refer to those related to safety reasons and quality problems which should be implemented immediately. These ECs have the first priority than any other categories. In some cases, companies also implement ECs proposed by customers immediately in order to keep a high service level (Diprima 1982). The implementation of these ECs require efficiency in time, in some extreme cases, stop of product is required "regardless of cost, plant disruption or obsolescence" (Balcerak & Dale 1992, p.128).

Mandatory ECs are those require implementation as fast as possible but with certain flexibility in timing (Diprima 1982). Mandatory ECs are initiated due to customer requirements, supplier suggestion, change of regulation, feedback from customer, error corrections, and function adjustments. The priority of those ECs is lower than immediate ECs. The implementation of those ECs require less efficiency in time and comprise in cost and schedule comparing to immediate ECs.

Convenient ECs are those for innovation and improvement, therefore, should be implemented in the timing when it is possible (Diprima 1982). Among other two priorities, convenient ECs have the least urgency. The implementation of this type of ECs requires planning skills from the management of the companies. In other words, the implementation of these ECs should be most efficient in cost and least disruptive in pre-defined schedule and plan (Balcerak & Dale 1992).

It worth mentioning that there is no restrict line between different priorities in ETO companies. Sometimes an EC due to mistake correction should be implemented immediately because the late correction of error could incur error in production as well, which will eventually cause scrap. The criterion for prioritizing ECs in ETO are highly dependent on how company evaluate these ECs.

**Impact of ECs**

Costs, production schedules and delivery plan are three most discussed impacts that ECs can have in ETO companies. These impacts are described in a negative aspect in most of the literature (Rouibah et al. 2003; Hegde et al. 1992; Huang & Mak 1999; Huang et al. 2003; Hanna et al. 1999; Wänström & Jonsson 2006; Fricke et al. 2000). Carter and Baker (1992) stated that ECs happen after the start of production can be ten times more expensive than those happen in the design phase. ECs can consume over 100 million dollars, which take around one-fourth to half of tool costs in the development of projects (Terwiesch & Loch 1999). ECs occur after the start of production can have impact on production schedules, which would eventually result the delay of delivery plan. Hegde et al. (1992) found that ECs created hold-ups on the shop floor and stretched lead times. As a result, vendors missed deliveries of materials and parts. In some extreme cases, due to safety reasons, companies have to recall the finished product in order to make essential changes, which can have impacts on not only costs, production schedules and delivery plan, but also on a company's reputation.

In ETO companies, ECs can also have impact on labor efficiency, which was revealed by Hanna et al (1999) in their research into 61 mechanical construction projects. By comparing the labor hours between ECs impacted projects and unimpacted projects, a difference was shown, which indicated that ECs can lower the labor efficiency in certain way. The model developed in this study provides users a quantitative method to evaluate the impacts of ECs on labor efficiency.

In product level, ECs can also result rework, in the extreme case, result scrap in the existing component and final product (Wänström & Jonsson 2006; Barzizza et al. 2001; Dale 1982). These impacts are common in ETO companies due to the changing requirement from customer (Grabenstetter & Usher 2015; McGOVERN et al. 1999; Bertrand & Muntslag 1993; Wortmann 1992). Moreover, the occurrence in later order fulfilment process is another reason for rework and scrap (Clarkson et al. 2004; Terwiesch & Loch 1999; Sudin et al. 2009).

Another impact incurred by ECs in product level is change propagation, This is also an important one in ETO context due to the couplings between the modified component and interfacing components (Terwiesch & Loch 1999). It was found that around 32% of the total ECs were incurred by change propagation in terms of inventory, manufacturing, and design error (Shankar et al. 2012).

Change propagation becomes apparent when change happen in the product with a complex structure. This is another impact incurred by ECs in ETO context. “The stronger these couplings, the more likely is a change in one part of the system requiring change in another part” (Terwiesch & Loch 1999, p.167). Rouibah et al. (2003) classified the relationship of couplings into three types, all of which exist in ETO product. Firstly, coupling between part of product and production process. Secondly, coupling between part of product and other internal parts. Thirdly, coupling between part of product and other external parts, mostly refer to parts of suppliers.

The impacts of change propagation were differentiated by Eckert et al. (2004). In their work, these impacts were classified in terms of the absorbing degree of a product and its ability to transfer to other dimensions. There are four types of change propagation impact, namely constants, absorbers, carriers, and multipliers. Constants are those cannot be affected by EC. In other words, they absorb no EC and result no change propagation. Absorbers are those can absorb ECs more than themselves incur. Hence absorbers can reduce the complexity of EC. Carriers are those can absorb a similar number of ECs with the number they incur. So carriers remain the complexity of ECs in an existing level. Multipliers are those can incur more ECs than they can absorb, which means they increase the complexity of ECs. Due to the close coupling relationship between components in ETO, despite current ECs may have little influence on target parts, huge impact on other parts or systems can still be incurred because of change propagation (Eckert et al. 2006; Rouibah et al. 2003), which in the words of Eckert et al. (2004) are multipliers. Therefore, it is necessary for ECM process to predict change propagation. This can not only improve the efficiency of EC evaluation but also benefit activities such as new product tendering, project planning, and redesign (Clarkson et al. 2004).

It worth mentioning that ECs can also bring benefits to the companies if they were managed in an appropriate and coordinated way (Wright 1997). Quality improvement in product, cost-saving are both the benefits that ECs bring in ETO companies. ECs can also enable the plan to follow the schedule (Fricke et al. 2000; Ibbs et al. 2001; Eckert et al. 2004). However, In most cases, ECs predicted to be beneficial initially sometimes proved not to be as cost-saving as predication (Terwiesch & Loch 1999), this may due to various factors in ECs implementation phase. Therefore, it is important to better manage EC and to have mechanism to evaluate and review the implementation of ECs (Fricke et al. 2000).

**ECM process**

Engineering Change Management (ECM) is the process of controlling and making ECs to product in a systematic way (Rouibah et al. 2003). It regulates the way of managing the change related data and information through the entire life cycle of ECs in an pre-defined way (Chen et al. 2002; Reddi & Moon 2011). ECM is a sub-process in ETO order fulfillment process, it covers the entire order fulfillment process in ETO since ECs can occur throughout the order fulfillment process (Hamraz et al. 2013; Sudin et al. 2009). The objectives of ECM process is to improve the performance in cost, time spent during order fulfilment process as well as make sure the quality of product to the customer (Fricke et al. 2000).

In the survey conducted by Huang & Mak (1999) among 100 manufacturing companies in UK, it revealed that there is a majority number of companies (95%) follow a formal ECM process, and most of them agreed that it is essential and necessary to have a well-structured ECM process. While there is still a small number of companies do not have a former ECM process to handle the ECs, however, these companies realized that a more formal ECM process should be followed. The result agreed with the findings from literature review among case study regarding ECM.

ECM process has been mentioned by various scholars. Table 5-3 presents a comparison of different processes applied in the research on ECM. It can be concluded from the comparison that most frameworks proposed by scholars (Loch & Terwiesch 1999; Kidd & Thompson 2000; Chen et al. 2002; Eckert et al. 2004; Jarratt et al. 2004; Tavčar & Duhovnik 2005; Lee et al. 2006) fail to cover the entire life cycle of ECs. One of expectation is a comprehensive framework proposed by Dale (1982) who separated the entire ECM process with two sub-process, namely, the procedure to approve and on approve. However, since the framework was based on a paper-based ECM process, the flow of proposed framework can only handle EC by a single discipline each time, which reduces the efficiency of managing EC. The framework developed by Reddi & Moon (2011) is the most comprehensive one that covers the entire life cycle of ECM process (Figure 5-3). There are four phases in ECM process: propose, approve, plan and implement, and document. With three decisions gate embedded between every two phases, the process allows the iterations within the process of ECM.

Table 5-3: Comparison of ECM process.

| Steps | Proposed ECM Processes | (Dale 1982) | (Kidd & Thompson 2000) | (Chen et al. 2002) | (Eckert et al. 2004) | (Jarratt et al. 2004) | (Lee et al. 2006) | (Loch & Terwiesch 1999) | (Reddi & Moon 2011) | (Tavčar & Duhovnik 2005) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ECs receive | + | | + | | | | | + | |
| 2 | ECs request raised | + | + | + | + | + | + | + | + | + |
| 3 | Approval | | | | | | | | + | |
| 4 | Possible solution identification | + | + | | | + | + | + | + | + |
| 5 | Tendering | | | | + | | | | + | |
| 6 | Notification | + | | + | | | | | + | |
| 7 | Affected system assessment | + | | | + | | | + | + | |
| 8 | Risk/Impact assessment | + | | | | + | | + | + | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 9 | Decision and approve on solution | + | | | | + | + | + | + | |
| 10 | Planning and review | | + | | + | | | | + | + |
| 11 | Change of documentation | + | + | | | | | | + | + |
| 12 | Implementation | + | + | + | + | + | | + | + | + |
| 13 | Solution evaluation | + | | | + | | | | | |
| 14 | Approval or postpone | + | + | | + | | | | + | |
| 15 | Review | | | | | + | + | | + | |
| 16 | Documentation | + | | + | | | + | | + | |

Note: “+” means the step is applied in the proposed ECM process.

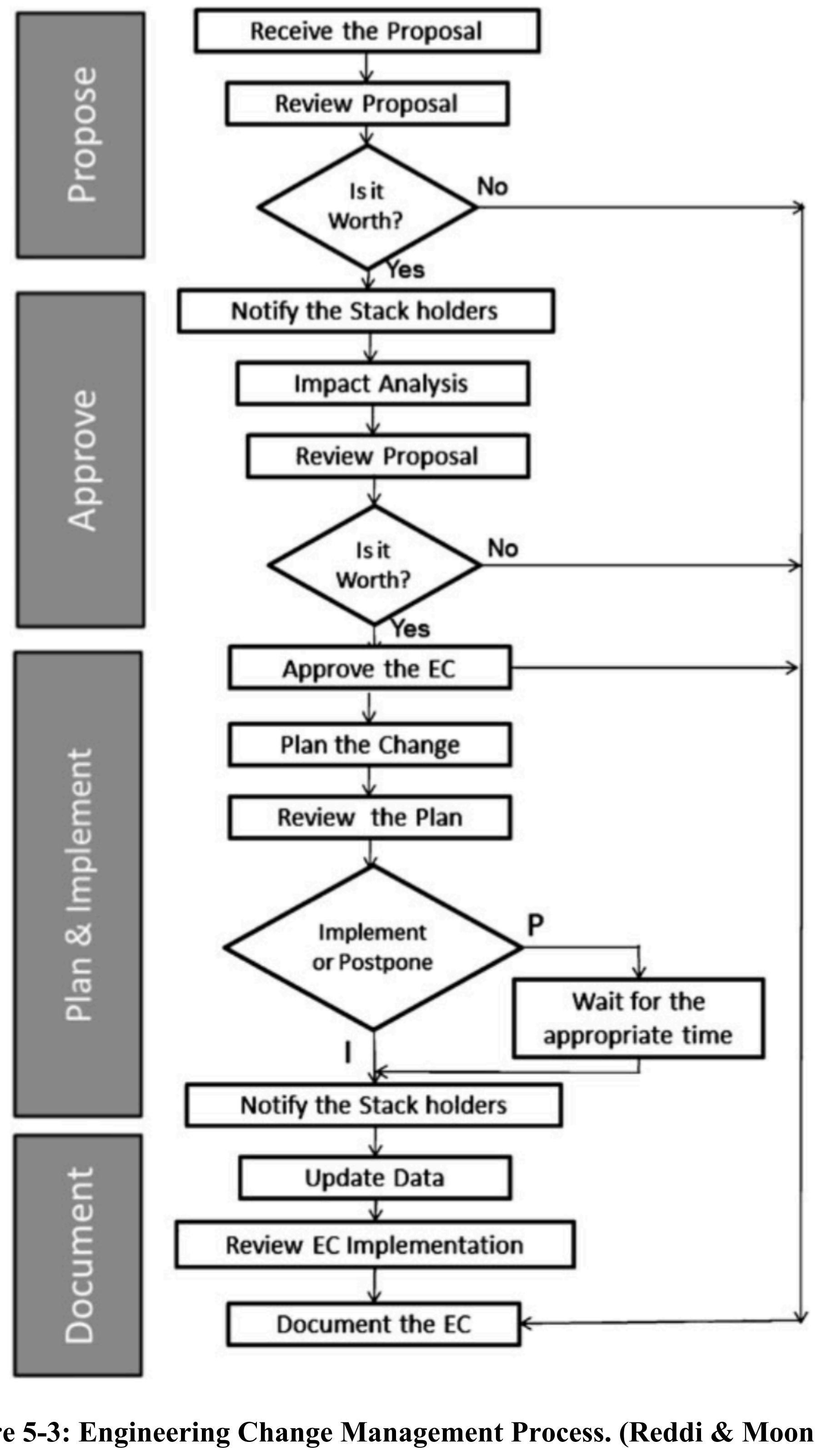


**Figure 5-3: Engineering Change Management Process. (Reddi & Moon 2011)**

The ECM process start with the propose of ECs. In the first step, the initiator of EC specifies the change objective, change reasons, priority, change type. Part, component or system that is affected by the change objective should also be evaluated and listed in this step. After receiving EC propose, EC committee are used to evaluate EC and make decision on whether it should be accepted or not.

In propose phase, short response time to customer proposed ECs is important. It was pointed out by Pikosz and Malmqvist (1998) in their studies among three Swedish ETO companies that it is necessary for design department to have a fast response to the changing customer requirements. A fast and reliable process for EC can improve the relationship between customers and companies (Pikosz & Malmqvist 1998). Their points of view are supported further by Rouibah et al.(2003) and Tavcar & Duhovnik(2005).

After EC being accepted for further processing, stakeholders affected by ECs are notified and asked to identify the potential solutions and analyze the corresponding impact.

During solution identification, engineers usually refer to their past experience and tacit knowledge. They also refer to EC documentation system that stores the previous ECs for the similar situations(Lee et al. 2006). By doing so, the processing time can be shortened while the capacity can be saved for other tasks.

Impact caused by change propagation is also evaluated in this step. In this phase, the time that engineer spent on processing the specific EC depends on the complexity of this change (Terwiesch & Loch 1999). Due to the snowball effect, change in one part will affect other parts or components (Terwiesch & Loch 1999; Eckert et al. 2006; Jarratt et al. 2004). The more complex the change product is, the more processing time engineer will spend on the EC (Eckert et al. 2006). Hence, a system storing with the coupling relationship that can have an overview about the additional ECs required to make for applying the current change is necessary (Do 2015; Pikosz & Malmqvist 1998). This kind of system can help to improve the efficiency of this process, which can eventually improve the efficiency of ECM process(Rouibah et al. 2003).

Impacts in terms of cost and schedule plan are analyzed as well. As elaborated in the previous section that ECs predicted to be beneficial initially sometimes proved not to be as cost-saving as predication in most situation (Terwiesch & Loch 1999). Hence, the cost impact evaluation is necessary for the review of EC implementation. Furthermore, the lead time of parts, components and final products in ETO environment are longer and more uncertain than other production environment, which makes controlling over project schedule important(Bertrand & Muntslag 1993). Besides, in ETO companies, project management is one of the key capability that was required from customer(Hicks et al. 2000). Thus, it is necessary to have impact analysis on schedule. All the reasons above make impact analysis among cost and schedule plan essential in ETO companies.

The outcomes of solution identification and impact analysis will then be discussed in the approving phase. Usually, there are several alternative solutions offered during discussion and people from different disciplines have to evaluate the alterations and corresponding impacts then make decision on which solution should be applied or considerate into one feasible solution. Negotiation and making trade-off are unavoidable during the approving.(Eckert et al. 2004). In some cases, communication and information sharing with external organizations are essential as well. At the end of this phase, approvers or the team should achieve an agreement on the solution to apply and the estimation on time and costs related to the particular solution.

After being approved, EC is processed to planning and implementation, which is based on the priority of EC (Tavčar & Duhovnik 2005; Veldman & Alblas 2007; Balcerak & Dale 1992). The study among ETO company conducted by Veldman & Alblas (2012) revealed that different strategies are applied in EC implementation according to the priorities of EC. For example, regarding with those ECs to improve product function, the implementation is executed with a better plan in the design phase of next product's generation. While for those ECs to correct a problem, their implementation is faster than others. Vianello & Saeema (2012) further revealed in the study among two ETO companies that trade-off has to make between time and cost when implementing ECs. ECs due to failure correction should be implemented immediately despite of the high cost of implementation while the implementation of ECs due to product improvement should focus more on cost efficiency. Therefore, batch implementation is necessary to distinguish between ECs with high priority (quality failure, safety reasons, error correction) and ECs with low priority (product improvement, moderate problem-solving).

Except planning, monitoring on implementation is also important (Ibbs et al. 2001). Detailed implementation planning and metrics for measuring the implementation should be developed and discussed with all the related stakeholders. This is important not only for the purposes of process performance measurement but also for review and learning, which can be helpful if there were the similar ECs occur (Ibbs et al. 2001). Before implementation, change-related documents must be updated (Wright 1997). Communication and information sharing are happening between all the stakeholders before and during implementation. If the change concerning on customers or suppliers, timely information and document should also be shared with them.

ECM process end with documentation. It worth mentioning that the review of implemented ECs is important (Huang et al. 2003; Lee et al. 2006; Fricke et al. 2000). The design, the process of design together with the ECM process can be improved from reviewing and learning of history ECs (Fricke et al. 2000).

Data such as findings, experiences, lessons-learned, and tacit knowledge during the entire ECM process should be collected and documented during the process of review (Lee et al. 2006). According to Huang et al.(2003), these data can be classified into three categories in terms of their functions in ECM process, they claimed that all of those categories are important for companies. First category is documents with reasons of initiation. Second category is documents with the assessments of impacts in different aspects caused by ECs among the lifecycle of ECM. Third category is documents with the implementations of approved ECs, it is about what and when the changes have been applied.

Lee et al.(2006) also pointed out that intensive collaboration on knowledge and communication for “problem-solving” and “decision-making” between different departments and teams during EC process are the sources of valuable knowledge and information, which can help to reduce the development time and cost for a new product. However, It is different to capture and take advantage of these “informal” and “unstructured” knowledge and information without the supporting function(Lee et al. 2006). Therefore, it is essential to achieve the efficient knowledge management with the appropriate knowledge management in ECM process.

Despite the objectives of ECM process are to lower the effects of ECs while maximize their benefits (Fricke et al. 2000), the complex ECM process especially in ETO companies fails to treat ECs according to their own characteristics, which makes ECM process contrasts with the objectives of ECM process. Therefore, flexibility is essential for ECM process (Balcerak & Dale 1992; Terwiesch & Loch 1999; Pikosz & Malmqvist 1998; Huang et al. 2003; Tavčar & Duhovnik 2005; Do 2015). The flexibility in ECM process refers to the ability of the ECM process to cope with different ECs. Huang et al. (2003) point out that there are different types, reasons, and urgency of ECs. However, the complex ECM process fails to treat them according to their characteristics, which results the long lead time for all types of ECs. It was further argued that in order to cope with this challenge, it is essential to enable the flexibility of ECM process. Scholars such as Balcerak and Dale (1992) together with Tavcar & Duhovnik (2005) also stated that in order to reduce waiting time and lead time in ECM process, it is necessary to treat ECs with different processes by their importance. Balcerak and Dale (1992) claimed that ECs have no impact or minor impact on material planning and sales should be approved by relevant engineering department. The implemented of those ECs should be executed by engineering without discussion in EC committee. Pikosz and Malmqvist (1998) claimed that for the purposes of reducing the amount and work load of ECs as well as improving the efficiency of ECM process, ECs with larger impacts should be treated by meetings with all affected persons from different departments. Companies should also treat ECs without impact and non-technical changes with a simplified EC process such as performing ECs within the design department. They concluded that there would be large effect on the progress of product development if all the ECs are applied to the same formal process. The similar argument was supported by various scholars (Huang et al. 2003; Eckert et al. 2004; Storbjerg et al. 2016) who stated that it is unnecessary to process every EC with all the activities in ECM process. They argued that since the complexity of ECs are different from each other, therefore, not every activity included in the formal process is useful. For example, when the ECs are not technical related, which means that they are initiated just for error correction, only few related activities should be included. When the ECs are complicated, which contain functional or technical changes, all the formal activities should be included. In some case, even more procedures can be added to the processes according to specific requirements. Tavcar & Duhovnik (2005) draw a conclusion which can be applied here that because of a high degree of unpredictability, process in ECM should be flexible enough hence they can be adopted according to the different requirements.

**Organizational Structure**

As stated in Section 5.2.1 that the involvement of different disciplines can be various ranging from design and engineering department to other departments such as marketing, production and manufacturing, quality management, prototyping, project management, and after-sales (Huang et al. 2003; Terwiesch & Loch 1999) The involvement of multiple disciplines during ECM process highly depends on different influence factors such as complexity of EC, phase of ECM process, effects of ECs etc. (Subrahmanian et al. 2015; Huang et al. 2003; Veldman & Alblas 2007). In ETO companies, external disciplines such as customers, suppliers, and auditors can also be required to participate in the process because of the high degree of customization, increasing level of outsourcing, and the audition requirement in certain ETO companies (Hicks et al. 2000; Elfring & Baven 1994; Eckert et al. 2004).

As the person who is responsible for collecting information for evaluation as well as collaborating the activities (Dale 1982; Joshi et al. 2005), EC Coordinator is mentioned by various scholars (Balcerak & Dale 1992; Chen et al. 2002; Dale 1982; Hamraz et al. 2013; Huang & Mak 1999; Joshi et al. 2005; Kocar & Akgunduz 2010; Pikosz & Malmqvist 1998; Reddi & Moon 2011; Veldman & Alblas 2007; 2003). Balcerak and Dale (1992) stated that a full-time EC coordinator should be hired and report to the chairman of EC committee. In a study conducted by Pikosz & Malmqvist (1998), they revealed that EC coordinator is essential for the companies without an user-friendly ECM tools and distributed organization structure where the later one fit the characteristic of ETO companies. EC coordinator in this case can help to answer the question about the application of the system during ECM process but also to coordinate the ECM activities among distributed organization structure. In most cases, EC coordinators "were employed under the engineering discipline" due to the content of ECM is highly relevant to engineering (Huang et al. 2003).

ECM Board or EC committee is also commonly mentioned in literature (Huang & Mak 1999;

Huang et al. 2003; Alblas & Wortmann 2012; Fricke et al. 2000; Huang & Mak 1998; Kidd & Thompson 2000; Kocar & Akgunduz 2010; Lee et al. 2006; Pikosz & Malmqvist 1998; Veldman & Alblas 2012; Veldman & Alblas 2007; Joshi et al. 2005). However, according to the survey conducted by Huang (Huang & Mak 1999) among 100 manufacturing companies in UK revealed that the number of companies that have EC Board or committee is less than 60%. A well-managed ECM process should be "followed by a well-organized group of people often called the EC Board/Committee (Huang & Mak 1998, p.187). The responsibilities of ECM Boards are to evaluate EC proposals, approve or reject ECs, and make decisions on the implementation of ECs. ECM Board realize its function by holding ECM meeting regularly or when necessary. Participants in ECM Boards are those who are relevant for the activities of ECM (Huang & Mak 1999; Huang et al. 2003; Kocar & Akgunduz 2010; Lee et al. 2006). Design and engineering, workshop, purchasing, marketing, quality control are the main participants, customers, suppliers, and external auditors can also be involved if necessary (Huang et al. 2003). Balcerak & Dale (1992) proposed four different EC committee for managing different types of ECs in order to increase the effectiveness and efficiency of ECM process. The four different EC committees are minor, emergency, full, and sales enquiry notification while different departments and people are involved in the corresponding EC committee.

**Tools used to support ECM**

Tools used to support ECM can be classified into two types. One is for improving ECM process, the other is for supporting decision making.

<u>Tools for improving ECM process</u>

Tool of this type is used to improve the overall ECM processes and documentation ECs. ECM activities, namely, identify EC requests, input EC proposals, receive EC application, accept EC application, filter ECs, submit EC requests, documentation and update ECs, prioritize ECs, approve ECs, notify all related stakeholders, and review documented ECs should be included as the functions of this type of tool (Huang & Mak 1999).

The essentiality of computer-based ECM system are widely recognized by scholars (Huang et al. 2001; Kidd & Thompson 2000; Huang & Mak 1998; Pikosz & Malmqvist 1998). Comparing with the inefficient paper-based ECM system, computer-based ECM system can execute ECM activities mentioned above electronically, which helps to capture, track, and handle EC efficiently and simultaneously (Huang & Mak 1998). This is especially important in ETO context due to the complex company structure, distributed environment, various EC volume and reasons. Despite of the advantages, the application of computer-aided ECM system is relatively low, most ECM activities are still executed manually or by merely using word and spreadsheets (Huang & Mak 1998; Huang & Mak 1999; Huang et al. 2003). According to Huang & Mak (Huang & Mak 1998), the reasons for the low application of computer-aided ECM system can be engineer lacking of awareness and understanding, existing ECM system fails to reflect ECM practice, lacking of customization, requiring massive data. In a study conducted among three project-based companies, Pikosz & Malmqvist (1998) revealed that all the case companies fail to take advantage of their computer-aided ECM system. Not user-friendly is the main reason in one of the case companies. However, since all the companies were trying to apply new computer-aided ECM system, their challenge shift to whether to get a customized package with high cost or to get a cheaper standard package but not totally fitting into the context.

Tools used for managing ECM process can be classified into three categories (Huang & Mak 1998). Firstly, system dedicated for ECM with a database storing data and electronic forms of EC. The system supports the function to maintain, capture and retrieve ECs, as well as provide ECM report. However, since the narrow focus, these systems are mostly developed in-house and not widely developed by commercial software vendor. Secondly, systems for configuration management. This type of system has more functions than ECM with controlling and identifying product structure, controlling and managing revision and history information associated with ECs. Thirdly, product data management (PDM) system with sophisticated ECM function and configuration management. In these system, order fulfilment process is taken into consideration as the structure of work center. This type of system can be most beneficial to company by improving the profit and gaining competitive advantage.

Tools for supporting decision making

Tools for supporting decision making deal with activities such as solution identification, change propagation, and impact analysis. Hard techniques and soft techniques are two types of tools supporting decision making (Huang & Mak 1999).

The examples of hard techniques are Computer Aided Design (CAD), Computer Aided Process Planning (CAPP) and Material Requirement Planning (MRP), these techniques are used not designed for ECM but can be extended to simple ECM. For example, CAD software such as CATIA can be used to evaluate the impact of EC in terms of geometry and coupling components. But it fails to predict change propagation.

Soft techniques are applied for identifying potential EC and try to avoid them. Examples for soft techniques are Quality Function Deployment (QFD), Failure Mode and Effect Analysis (FMEA), Design for Manufacture and Assembly (DFMA), and Value Analysis (VA). Eckert et al. (2009) found in their study among twelve manufacturing companies that customers are involved early in the design phase and QFD systems are used to avoid potential change in customer requirement.

### 5.2.2 Existing Research on Engineering Change Management

A systematic literature search is required in order to investigate the previous research on ECM. The search ended up with 45 articles on the topic. The results of this search are structured into three categories adapted from Huang and Mak (1999). Table XX shows an overview of some existing research on ECM while Table XX shows the categorization of these research.

The distribution of the research numbers in Figure 5-4 shows majority of scholars focus on developing frameworks for managing EC directly. Meanwhile, around 22% scholars discussed guidelines and strategies to manage EC. Further insight shows that there are 22% of methodologies and 16% of guidelines and strategies are developed on industrial case studies.

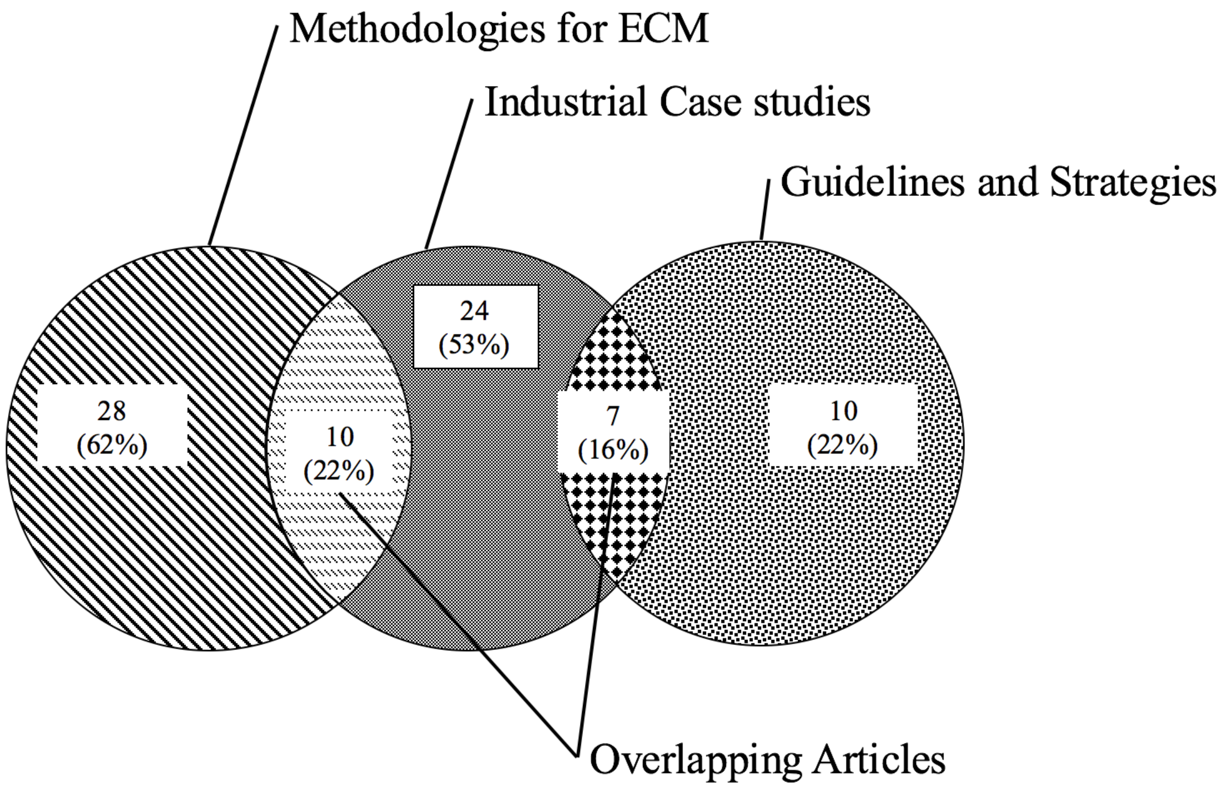


**Figure 5-4: Distribution of Research for ECM**

Moreover, investigation into literature on ECM was extended to check whether these methods have been validated in reality as well as whether performance measurement have been used. As Figure 5-5 shows that among all these proposed frameworks, guidelines, and strategies, only 57% of these proposal has been validated in real situation. This can be explained with the low percentage in the use of performance measurement since it is impossible to evaluate and improve without the measuring of performance (Fortuin 1988).

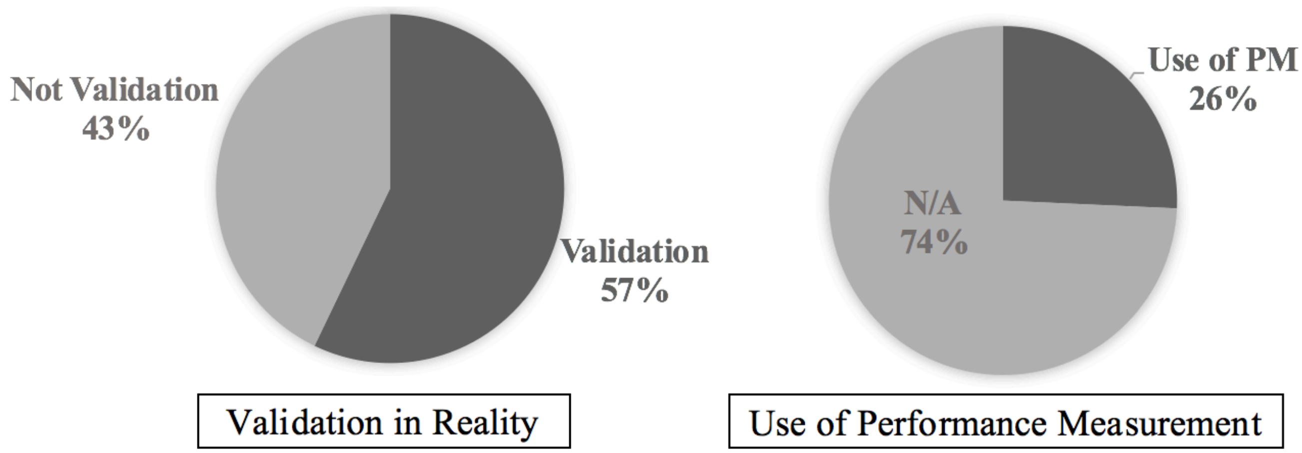


**Figure 5-5: Distribution of Research with Validation and Use of Performance Measurement**

28 kinds of methodologies and 10 kinds of guidelines and strategies were identified in various literature for managing EC. Table 5-4 gives an overview in order of year of publication. These methods cover 18 types of industries while most of which follow Engineer-to-Order strategies.

Table 5-4: Case Studies on ECM from literature

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Dale | 1982 | Not Specify | A framework for managing EC with activities, procedures, and roles of responsibilities. | No | No |
| Reidelbach | 1991 | Make-to-order | Guidelines for management of EC | No | No |
| Stevens and Wright | 1991 | Not Specify | A configuration management system to minimize the negative impacts incurred by EC. | No | No |
| BALCERAK & DALE | 1992 | Engineer-to-order | A specified pattern for defining the reasons for EC is determined. Two classification systems were developed to improve the classification scheme of ECs. Different committees are formed to handle different levels of ECs. Six determinants for EC effectivity date were identified. The effectivity date for all ECs except for simplest ECs are required to be considered with more than one determinants. Feedbacks are required to the success of ECM process. | Yes | No |
| Hegde et al. | 1992 | Mass Production | Metrics are used to measure the impact of ECs, raw material discrepancies, and overloaded machines on response time. Findings gave an concrete and quantified evidence and revealed that ECs have an negative impact on productivity, which results the delay on response time. Metrics also provide management a tool to measure the performance of improvement actions. | Yes | Yes |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Pikosz & Malmqvist | 1998 | Engineer-to-Order | Different strategies were developed for improving the ECM process as well as of the product data management systems in order to achieve an optimal process. | No | No |
| Mokhtar et al. | 1998 | Engineer-to-Order | Information model based on a central database to propagate design changes in order to improve the coordination of design information | Yes | No |
| Huang & Mak | 1998 | Not Specify | The necessary of computer-aided ECM system is identified. Reasons for low application rate are also identified. | No | No |
| Terwiesch & Loch | 1999 | Make-to-Order | Identify five contributors for long lead time in ECM process: a complex ECM process, change propagation, lack of capacity and congestion, setup time and processing in batch, and organizational problems. | No | No |
| Loch & Terwiesch | 1999 | Make-to-Order | To reduce EC lead time, five improvement strategies were developed: flexible capacity, merging tasks, balancing workloads, sharing workloads to reduce specialization, and reduced setup time and batch size. | No | No |
| Huang & Mak | 1999 | Engineer-to-Order/ Make-to-Order | Industrial practices in ECM were investigated. It highlights the importance of ECM in reality. Guidelines for good ECM practices are developed. | No | No |
| Hanna et al. | 1999 | Engineer-to-Order | ECs can lower the labor efficiency in certain way | Yes | Yes |
| Lin et al. 1999 | 1999 | Make-to-Order | A model combine multiple-error diagnosis and logic minimization techniques. | Yes | No |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Cohen et al. | 2000 | Make-to-Order | A method called Change Favorable Representation is proposed by using matrix calculation to improve change and change evaluation at the attribute level. | Yes | No |
| Huang et al. | 2001 | Not Specify | A web-based system to improve the effectiveness and the efficiency of ECM | No | No |
| Barzizza et al. | 2001 | Make-to-order Industry | A method was proposed for managing ECM process effectively with a EC classification scheme. | Yes | Yes |
| Ibbs et al. | 2001 | Not specify | A project change management system was proposed with five key principles. | No | No |
| Chen et al. | 2002 | Not Specify | Allied concurrent engineering based ECM system is developed. | No | No |
| Huang et al. | 2003 | Not Specify | state of EC and industrial practice in ECM were investigated. It revealed that ECs were still problematic in manufacturing industries that required efforts to manage in an effective and efficient way. It is essential to have guidelines, methodologies, perhaps techniques in ECM for better managing ECs in the product life cycle. | No | No |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Rouibah et al. | 2003 | Engineer-to-Order; Make-to-Oder | An framework uses parameter basis to track design change in the cross-company environment | Yes | No |
| Clarkson et al. | 2004 | Engineer-to-Order; | A model was developed to predict change propagation. | Yes | No |
| Eckert et al. | 2004 | Engineer-to-Order; | Key to the success of ECM require the well information on the following elements: source and causes of ECs, interdependencies between parts and systems, change propagation and the tolerant margins of dependence, impacts of ECs in terms of quality, cost, and time, and tolerant margins on important parameters. It is also important to have a good understanding on the situation in design and the connection between parts of a design. | No | No |
| Jarratt et al. | 2004 | Engineer-to-Order; | A model to rate the like hood and impact of changes propagating. | Yes | No |
| Tavčar & Duhovnik | 2005 | Engineer-to-Order; Make-to-Order; Mass Production | Establish a general model for ECM to identify weak points and improve it. | No | No |
| Joshi et al. | 2005 | Not Specify | A method was proposed to improve the efficiency of decision supporting process on the effects of EC by the use of industrial specified knowledge as well as previous knowledge. | No | No |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Lee et al. | 2006 | Make-to-Order; | A knowledge management model with case-based reasoning mechanism was developed. The model integrated collaboration and knowledge management while managed ECs in a life cycle perspective, which provided a tool for companies to effectively capture and retrieve valuable knowledge during collaboration in ECM process. | No | No |
| Wänström & Jonsson | 2006 | Make-to-Order; | Due to the characteristics of ECs in the certain industry, they have both positive and negative together with direct and indirect impacts on material planning. It was also found that different strategies should be applied in material planning in order to cope with different ECs situation in one company. | Yes | No |
| Eckert et al. | 2006 | Engineer-to-Order; Make-to-Order; | Tool for change prediction management by using probabilistic prediction change effects and using product couplings to visualize change propagation. | Yes | No |
| Nadia et al. | 2006 | Not Specify | A method that processing EC in batch was proposed, which helps to improve the productivity of ECM. However, in some situations, ECs are required immediate attention. A mechanism will always be needed to deal with situations directly. | No | No |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Ahmed & Kanike | 2007 | Engineer-to-Order; | ECs occur throughout the product life cycle and majority ECs happen in manufacturing and production phase. Main reasons for ECs were highly relevant to the phase in product life cycle. | Yes | No |
| Veldman & Alblas | 2007 | Engineer-to-Order; | Local decision authority can make decision on ECs with more variable processes and products while central decision authority can work on ECs with standard processes and products. | No | No |
| Ouertani | 2008 | Engineer-to-Order; | A method was proposed to evaluate the effect of EC in terms of technical data on the basis of data dependencies network. It was also proposed to re-organizing design activities in ECM process according to product dependencies. | Yes | Yes |
| Sudin et al. | 2009 | Engineer-to-Order; | Most of ECs to specification occurred in manufacturing, production and testing phase while internal employees were the main initiators in all the phase of product life cycle. Error correction was the main reasons for ECs to specification. | Yes | No |
| Kocar and Akgunduz | 2010 | No Specify | Active Distributed Virtual Change Environment (ADVICE) was proposed to give priorities to ECs and predict change propagation during processing. It improve the efficiency of review and authorization process by involving both parametric and graphical information. | Yes | No |

| Author | Year | Industry | Short Description | Validation | Performance Measurement |
|---|---|---|---|---|---|
| Reddi & Moon | 2011 | Not Specify | A system for analyzing the relationship between members among supply chain. | Yes | Yes |
| Wasmer et al. | 2011 | Make-to-Order; | Standards for handling ECs in a cross-organizational environment have been proposed, which helps to reduce the lead time of ECM process meanwhile improve the quality of the process. | Yes | Yes |
| Habhouba et al. | 2011 | Engineer-to-Order; | A collaborative tool was proposed to help decision-making in ECM process by keeping data consistency between different disciplines. It also provide potential solutions when agreement were not achieved. | Yes | No |
| Vianello & Ahmed | 2012 | Engineer-to-Order; | The distribution of ECs were similar in both companies that most of ECs occur during production phase. The main reasons for ECs were dependent on types of production process in the companies and the phase that ECs occur. | Yes | No |
| Shankar et al. | 2012 | Make-to-Order; | 32% of the total ECs were incurred by change propagation. Reasons for these propagation were due to document error and design error corrections. Appropriate controls should be taken by improving the existing tools in the product development phase in order to reduce the quantity of ECs due to change propagation. | Yes | No |

| **Author** | **Year** | **Industry** | **Short Description** | **Validation** | **Performance Measurement** |
|---|---|---|---|---|---|
| Alblas & Wortmann | 2012 | Engineer-to-Order; | The difficulty in managing EC was found in cast study, which reduce the feasibility of managing different ECs efficiently. A number of guidelines have been proposed to cope with these challenges including alignment goals and impacts of ECs with all levels as well as planning, monitoring and controlling ECs as individual projects. | Yes | Yes |
| Ahmad et al. | 2013 | Not Specify | A cross-domain solution was proposed to restructure a design, which helps to identify the linkages between potential change propagation. This tool can improve the capability of knowledge capture and reuse. | Yes | Yes |
| Do | 2015 | Not Specify | A product data management database that can support engineering change analysis. | Yes | No |
| Hamraz & Clarkson | 2015 | Engineer-to-Order; | A function-behavior-structure linkage method improve change prediction method. | Yes | No |
| Subrahmanian et al. | 2015 | Engineer-to-Order; | A supporting system was developed based on the characteristics of ECM. It helps to reduce the cognition of ECM process in terms of design process. | No | Yes |
| Storbjerg | 2016 | Engineer-to-Order; | A maturity grid was developed to help improve the efficiency of ECM process on the basis of maturity framework. | Yes | No |

Proposal for managing EC can be categorized into two types, one is guidelines and strategies for overall ECM process, the other is methodology for ECM. Within the latter category, four sub-types can be categorized further, namely, frameworks for overall ECM process, change propagations and impact evaluation, and collaborations between disciplines. A categorization for current research on ECM is shown in Table 5-5.

Table 5-5 Categorization for 45 publications on ECM

| **Categories** | | **Reference** | **Total Articles** | **Percentage** |
|---|---|---|---|---|
| Industrial Case Studies | | (Balcerak & Dale 1992); (Hegde et al. 1992); (Pikosz & Malmqvist 1998); (Huang and Mak 1998); (Terwiesch & Loch 1999); (Loch & Terwiesch 1999); (Huang & Mak 1999); (Hanna et al. 1999); (Barzizza et al. 2001); (Rouibah et al. 2003); (Huang et al. 2003); (Lee et al. 2006); (Clarkson et al. 2004); (Eckert et al. 2004); (Wänström & Jonsson 2006); (Ahmed & Kanike 2007); (Veldman & Alblas 2007); (Ouertani 2008); (Sudin et al. 2009); (Vianello & Saeema 2012); (Shankar et al. 2012); (Alblas & Wortmann 2012); (Storbjerg et al. 2016); (Subrahmanian et al. 2015); | *24* | *53%* |
| Guidelines and Strategies for Overall ECM Process | | (Pikosz and Malmqvist 1998); (Loch and Terwiesch 1999); (Huang and Mak 1999); (Eckert et al. 2004); (Tavčar and Duhovnik 2005); (Wänström and Jonsson 2006); (Nadia et al. 2006); (Wasmer et al. 2011); (Shankar et al. 2012); (Alblas and Wortmann 2012); | 10 | 22% |
| Methodologies for ECM | Frameworks for Overall ECM Process | (Dale 1982); (Reidelbach 1991); (Stevens and Wright 1991); (Balcerak and Dale 1992); (Hegde et al. 1992); (Huang et al. 2001); (Barzizza et al. 2001); (Ibbs et al. 2001); (Veldman | 11 | 24% |

| | | | |
|---|---|---|---|
| | and Alblas 2007); (Storbjerg et al. 2016); (Subrahmanian et al. 2015); | | |
| Change Propagations and Impacts evaluation | (Mokhtar et al. 1998); (Lin et al. 1999); (Cohen et al. 2000); (Clarkson et al. 2004); (Jarratt et al. 2004); (Joshi et al. 2005); (Eckert et al. 2006); (Ouertani 2008); (Kocar and Akgunduz 2010); (Ahmad et al. 2013); (Do 2015); (Hamraz and Clarkson 2015) | 12 | 27% |
| Collaborations between disciplines | (Chen et al. 2002); (Rouibah et al. 2003); (Lee et al. 2006); (Reddi and Moon 2011); (Habhouba et al. 2011); | 5 | 11% |

Methods supporting change propagations and impacts evaluation are most developed methods in literature as shown in Table XX. Around 27% of methods belongs to this category. This type of methods focuses on propose phase in ECM process, where impacts of EC are evaluated. In these methods, linkages between each parts and components are predefined or mapped in order to capture and predict the change propagation during evaluation (Mokhtar et al. 1998; Cohen et al. 2000; Clarkson et al. 2004; Jarratt et al. 2004; Eckert et al. 2006; Ouertani 2008; Kocar and Akgunduz 2010; Shankar et al. 2012; Ahmad et al. 2013; Do 2015; Hamraz and Clarkson 2015), which helps to improve the efficiency and effectiveness of propose phase.

Similar to these methods, a system based on product lifecycle management (PLM) system proposed by Joshi et al. (2005) also take advantages of the linkages between parts and components for improving change evaluation. However, different from other methods, the idea dynamic workflow of evaluation was introduced, which is suitable for the complex characteristics of EC in reality. In the system, EC evaluation workflow starts with the evaluation of change target mentioned in the initial EC, then the workflow develops to the evaluation of affected components according to the linkages between change target and parts, assemblies, BOMs. workflows, etc. that are predefined in the PLM system. However, it worth mentioning that EC coordinator can edit evaluation workflow according to real situation and assign related engineer to the corresponding evaluation, which enable the dynamic development of comprehensive EC evaluation.

Nevertheless, despite these methods can speed up ECM procedure by improving the evaluation of EC, they still focus on propose phase only. According to scholars (Subrahmanian et al. 2015; Pikosz & Malmqvist 1998; Terwiesch & Loch 1999), approving process in ECM procedure is also time-consuming, which affect the efficiency of ECM process as well. Therefore, the method that can help to improve not only part of ECM process but also the overall performance is necessary.

Collaborations between different disciplines is another focus that scholars have for developing method to improve (Chen et al. 2002; Rouibah et al. 2003; Lee et al. 2006; Reddi and Moon 2011; Habhouba et al. 2011). These type of method, in most case, use certain mechanism to get the related disciplines involved in either evaluation or approving phase, which eventually improve the communication and information sharing within ECM process. However, drawback of these methods still exist. These methods handle EC in general manner, which fails to cope with the complex characteristics of ECs such as urgency and impact etc. Hence, it is essential for ECM method to consider and deal with the different characteristics of EC as well.

Two major categories of ECM method are both focus on the improvement of overall ECM process, which are more suitable for the scope of this thesis.

A systematic framework proposed by Dale (1982) is the earliest one among other methods. In his work, activities, procedures, and role of responsibilities were developed and defined. Due to the early time of his work, the framework is still based on paper. However, most of the framework he developed is still applicable. For example, EC coordinator can still be identified in many other literature (Huang et al. 2003; Dale 1982; Joshi et al. 2005).

A configuration management system was proposed by Stevens & Wright (1991) to eliminate the negative consequences of introduction ECs. Within the system, a classification method was proposed to enable different levels review on different classes of ECs. The three classes, namely Class 1, 2, and 3, were classified by the impacts of ECs. ECs belong to Class 1 have most impacts on cost and downtime. While ECs belong to Class 3 have the least impacts. ECs belongs to Class 2 have the impacts that are in between Class 1 and 3. For the purpose of fast reviewing

ECs, only ECs belong to Class 1 and 2 should be reviewed by a control board. Those ECs in Class 3 are reviewed by facility/process supervisors and technical engineers only.

A similar classification of ECs by the criteria of their impacts was introduced by Barzizza et al. (2001) in the new methodology proposed by them for managing EC process in an effective way. In the methodology, the main idea is to implement ECs differently by the classification of their impacts on products. These impacts are categorized as “scrap”, “rework”, and “use-as-is”. If a product is classified as “scrap” or “rework”, ECs are required to be implemented as fast as possible. If a product is classified as “use-as-is”, then the implementation of ECs is not urgent, it can be decided on the basis of economic efficiency.

Both classifications proposed by Stevens & Wright (1991) as well as Barzizza et al. (2001) use the impact of ECs as classification criteria. The former one focus on process of review while the later one focus on process of implementation. However, both of the schemes ignore the fact that the impact of EC on products does not necessarily stand for the implementation urgency. For example, the EC from customer feedback during commission phase can result “rework” of product. According to the classification, this certain EC requires implementation immediately. But, in some cases, customer allow that their change request happen in the next generation of product. Hence, the implementation of the certain EC does not require immediate implementation. In this case, these ECs belongs to none of the category.

A research conducted by Veldman & Alblas (2007) found that one of the case company had a rigid decision making process with centralized decision making authorities while the other company had too much decentralized decision making authorities. By trying to find the appropriate degree of standardization in ECM process especially in decision making process, a matrix was developed with the dimensions of processes and products standardization together with decision making authority (Figure 5-6). It is suggested that local decision authority can make decision on ECs with more variable processes and products while central decision authority can work on ECs with standard processes and products. The matrix offers a very good strategy for company to handle different types of ECs according to their own characteristics. Still, this matrix treat EC in a too general way with only two criteria: variable and standard. Also the matrix leaves some many openings in the application on ECM process.

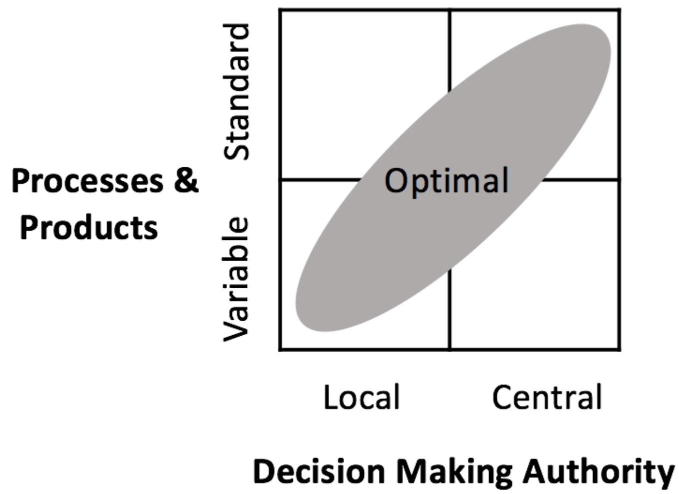


**Figure 5-6: Standardization-decision making matrix.**
**(Adapted from Veldman & Alblas 2007)**

Framework proposed by Balcerak and Dale (1992) was the most sophisticated one that treats EC with their own characteristics. With a EC classification scheme and different types of EC committees, the purpose of this framework is to enable the flexibility in ECM process. The purpose of classification scheme was to indicate the effects of ECs on the various departments and classify ECs in different levels. In classification scheme, two separate criteria, namely type and grade, were developed to classify ECs in different level. “Type” was used to describe the nature of ECs regarding with affected parts or systems. Type 1 refers to ECs that affect components including ECs to components drawings, raw material and manufacturing standards that have no impact on finished product. Type 2 refers to ECs that affect assemblies and new components. This type of change affect assemblies with one or more components. Type 3 refers to ECs to assemblies. These ECs affect the content and/or the configuration of an assembly including changes in bill of material, assembly drawings. “Grade” was used to describe the urgency that ECs require to be implemented. In grade criteria, four grade was used. Grade E refers to ECs due to errors, therefore, the reason of Grade E is to correct error. Grade M is applied to ECs that are mandatory, which due to safety, workability, functionality reasons and failure to meet the requirements of customers. Grade S refers to ECs from sales enquiry. Grade P refers to ECs require minimal cost, which need to be implemented "in the most economical and least disruptive fashion". Along with classification scheme, four EC committees were proposed, the function of EC committees were to minimize costs of EC while determine when ECs should be applied. Four EC committees are: Minor EC committee, emergency EC committee, full EC committee, and sales enquiry notification. Different EC committees are used to deal with different levels of ECs. For example, for the easiest EC level-1E, Minor EC committee should be the one who evaluate these ECs and approve them. For two most complex EC levels-2P and 3P, full committee should take the responsibility. The framework provides a well-structured classification scheme for managing ECs, it is more sophisticated and suitable for complex situations in ECM. However, drawbacks of this model still exist. Firstly, the classification scheme does not take impact into consideration, which might result the misleading in reviewing and implementation process. A good example can be an EC to a single component for error correction after the component has been progressed in manufacturing process. According to the the scheme proposed by Balcerak and Dale (1992), this EC belongs to 1E category and should be evaluated and approved by Minor EC committee. However, since the component has been produced, the change can have huge impact on cost and schedule. Apparently, evaluation and approve from Minor EC committee is not enough. Therefore, it is better to have more complicated evaluation and planning for this EC. Secondly, some of the EC committee can be replaced with other mechanism. For example, since the purpose of minor EC committee is to simplify ECM process and increase the efficiency, it would be easier and more efficient to have related engineers evaluate and approve these ECs.

It can be seen that the proposed methodologies in the existing research on ECM focus on various aspects. However, none of them can be applied for handling the complex ECs in ETO companies and provide improvement on the overall performance of ECM process. This finding direct the remainder of this research towards the development of such a methodology that, firstly, can help to improve both overall ECM process as well as sub-phase of the process. Secondly, the methodology should be flexible enough to deal with the complex characteristics of EC especially in terms of impacts and priorities. Thirdly, for the purpose of applicability, the method should be sophisticated enough not only in the core concept but also in the details.

## 5.3 Performance Measurement for ECM

In this chapter, a review among the literature on performance measurement was conducted in order to investigate the performance measurement and existing measures for ECM. Three sections are presented to show the findings among this theme. In Section 5.3.1, performance measurement is defined and the purposes for performance measurement is described. In Section 5.3.2, performance indicators are defined followed by the method and principles of developing performance indicators. In Section 5.3.3, existing research on performance measurement for ECM is elaborated. The findings from the three sections can answer the third research: "What performance indicators can be applied for improving ECM in ETO companies?"

### 5.3.1 Performance measurement

Performance measurement refers to "the process of quantifying the efficiency and effectiveness of action" (Neely et al. 2005, p.1229) while the metrics used to quantify the efficiency and/or effectiveness of an action are called performance indicators (Fortuin 1988; Neely et al. 2005; Ahmad & Dhafr 2002). It is necessary for companies to measure the performance of a certain process by using performance indicators in order to learn whether their processes are healthy and beneficial enough as well as to implement continuous improvement (Kloss-Grote & Moss 2008; Neely et al. 2005; Behn 2003). According to the definition, efficiency refers to the economical extent that a firm's resources are used to reach a certain objective level while effectiveness refers to the extent that the certain objective levels are met (Neely et al. 2005).

Behn (2003) defined eight purposes for performance measurement with characteristics of performance indicators suitable for the corresponding purposes (Table 5-6). In this paper, the purposes of developing performance indicators are to evaluate, learn, and improve the performance of ECM process, therefore, the corresponding characteristics of performance indicators are described further.

Table 5-6: Purposes and Characteristics of Performance Measurement. (Behn 2003)

| **Purposes** | **The characteristic of performance Indicators** |
|---|---|
| Evaluate | Outcomes, integrated with inputs and with the effects of exogenous factors |
| Control | Inputs that can be regulated |
| Budget | Efficiency measures (Specifically outcomes or outputs divided by inputs) |
| Motivate | Almost-real-time outputs compared with production targets |
| Promote | Easily understood aspects of performance about which citizens really care |
| Celebrate | Periodic and significant performance targets that, when achieved, provide people with a real sense of personal and collective accomplishment |
| Learn | Disaggregated data that can reveal deviates from the expected |
| Improve | Inside-the-black-box relationships that connect changes in operations to changes in outputs and outcomes |

Firstly, one of the common purposes for performance measurement is evaluation. For this purpose, outcome of a system or a process need to be measured. The objectives or the standard are supposed to know and be clearly formulated (Neely et al. 2005). In here, standard refer to previous performance or those from similar system or process, it also can be the standard from the same industry. By comparing the objectives or the standards with results, the current performance can be evaluated. However, it is important that other factors which have influence on the result of those performance indicators should be taken into consideration. (Behn 2003)

Information provided by performance indicators can be applied not only in evaluation but also in learning. In other words, they can be used for identifying the reason of inadequacy. However, learning from performance measurement requires performance indicators provide information in disaggregated level so that it can be used for benchmarking. Nonetheless, the results of performance indicators do not reveal the reason toward the good, fair, or bad performance (Zairi 1994). Data processing and extraction are required. Moreover, when evaluating performance, those indicators that reveal failure need special attention. By comparing the present performance with the best practices (benchmarking), knowledge is transferred to the organization. (Behn 2003)

Thirdly, which is also the eventual aim for performance measurement, performance indicators offer the basis for improvement (Behn 2003). As Fortuin (1988) argued that the implementation of performance indicator make sense only if the organization has decided to take advantage of the result and to use for continuous improvement. His point of view is furthered supported by Neely et al. (2000). But it is important to know that the performance measurement itself does not provide improvement (Behn 2003; Leyer et al. 2015). Users need to figure out which factor such as the knowledge, the logic, the principle, the cause, the effect, and interdependency behind the certain performance and how it contributes to the specific performance. Furthermore, the way of reuse of the success factor is a challenge for improving the performance as well. (Behn 2003)

### 5.3.2 Performance indicators

As the approaches to quantify the efficiency and/or effectiveness of the measured process or system, performance indicators provide user with a tool to make comparison with actual performance and predefined objectives, which leads to the necessary improvement in the certain performance area (Garengo et al. 2005; Fortuin 1988).

Performance Indicators that can show critical aspects which focus on the critical performance of systems or processes are called Key Performance Indicators (KPIs) (Parmenter 2007; Gries et al. 2011; Cao et al. 2015; Collin 2002). The differences between KPIs and performance indicators are: firstly, KPIs reflect the performance in an overall level (Gries et al. 2011; Cao et al. 2015), it focus on the critical success factors (Parmenter 2007; Collin 2002), while performance indicator, on the other hand, reflecting the performance in a basic level (Cao et al. 2015; Parmenter 2007). Moreover, compared to performance indicators, the number of KPIs should be limited to a small volume since having too much KPIs can be time consuming(Chae 2009; Collin 2002) and it is difficult to use(Parmenter 2007).

The Balanced Scorecard is the mostly used model to develop Performance Indicators(Gomes et al. 2004). According to a literature research on performance measures by Gomes et al.(2004), there is a high number of literature citation on the balanced scorecard, which indicates its acceptability and popularity among managers and scholars. Proposed by Kaplan and Norton in 1992, the balanced scorecard creates performance Indicators in a multi-dimensional way which allows managers to review the performance of the company in four perspectives, namely customer, internal, innovation and learning, and financial perspective. The balanced scorecard addresses both financial and non-financial performance Indicators, which can be used to evaluates the taken actions and provides drivers for future performance(Tangen 2004). However, Ghalayini et al.(1997), pointed out that the weakness is that the model is not applicable for operations level. The argument was supported later by Neely et al.(2000).

Method more suitable for this paper is an integrated performance indicators method proposed by Cao et al.(2015). It is used to develop performance indicators for manufacturing companies. In the method, performance indicators are divided into three levels: company, departmental and post. In company level, Performance Indicators are derived from the strategic objectives (key success factors) which are initially generated from mapping "*the mission, values, vision and long-term and short-term development goals of the company*"(Cao et al. 2015, p.4107). The success in company-level depends on the success in departmental-level. So, performance Indicators in company level are further broken down into department level. It is important that the scope of performance Indicators in departmental level should be appropriate enough, either too wide or too narrow will disable the functions of these performance Indicators. On one hand, it is impossible for department to operate the performance Indicators if they are too wide; one the other hand, it is hard for these performance Indicators to accurately show the performance of the department if they are too narrow. The development of performance Indicators in post level is similar to the process in departmental level(Cao et al. 2015). Different from the balanced scorecard, this method not only provides an overall view of the performance with performance Indicators in company level, but also includes performance Indicators in the department and post level. In general, performance Indicators in both aggregated and disaggregated levels are included in this method, which provides the basis not only for evaluating the overall performance but also for identifying the inadequacy and their reasons, which can be applied further for improving.

Besides the characteristics proposed by Behn (2003), there are certain principles that should be followed for performance indicators.

Firstly and most basically, performance indicators together with their purposes should be clearly defined, they should be easy to use, and understandable(Fortuin 1988; Neely, Mills, et al. 2000; Santori & Anderson 1987). They should have consistency, which means that they should still be significant after time(Fortuin 1988).

Globerson(1985) suggested that performance indicators are preferred to be measured in an objective way rather than in a subjective way, he further argued that they can be relative instead of absolute since that relative measures are easier to read and understand. These points are supported later by Neely et al.(2000).

It is important that performance indicators should be developed on the basis of organization's strategy(Santori & Anderson 1987; Fortuin 1988; Kaplan & Norton 1996; Ahmad & Dhafr 2002), objectives, key success factors, customer need, and customer satisfaction (Manoochehri 1999; Neely et al. 2005; Globerson 1985). However, besides developing the performance measures based on the organization and the customer perspectives, Neely et al.(2000) included investors, intermediaries, suppliers and regulators into the scope by using stakeholders perspectives to develop performance measures. They argued that all the stakeholders will have different importance to the organization.

Santori & Anderson(1987) claimed that in order to cope with the change of different environment, flexibility is one of the rule that should be followed when developing performance indicators.

It is significant that balanced performance indicators should be developed(Ahmad & Dhafr 2002). They should be multidimensional, which means they need to cover both financial and non-financial aspects of the measuring object(Fortuin 1988; Manoochehri 1999; Neely et al. 2005;

Santori & Anderson 1987; Neely, Mills, et al. 2000). This is due to the fact that the improvement in one aspect of the performance cannot at the expense of the others(Kaplan & Norton 1996; Kaplan & Norton 1993; Ahmad & Dhafr 2002).

A summary of rules for developing performance indicators is shown in Table 5-7. These rules provide a framework that can be applied not only to appraise identified performance indicators, but also to develop performance indicators.

Table 5-7: Principles for Performance Indicators.

| **Principles for developing Performance Indicators** | **Reference** |
|---|---|
| Performance indicators together with their purposes should be clearly defined, they should be easy to use, and understandable | (Fortuin 1988); (Neely, Mills, et al. 2000); (Santori & Anderson 1987) |
| Performance indicators should be developed based on the perspective of stakeholders, organization's strategy, objectives, key success factors, customer need, and customer satisfaction should take into consideration. | (Santori & Anderson 1987); (Fortuin 1988); (Kaplan & Norton 1996); (Ahmad & Dhafr 2002); (Manoochehri 1999); (Neely et al. 2005); (Globerson 1985); (Neely, Adams, et al. 2000) |
| Performance indicators should be flexible enough to cope with the changing environment. | (Santori & Anderson 1987) |
| Balanced Performance indicators should be developed, they should cover both financial and non-financial aspects | (Ahmad & Dhafr 2002); (Fortuin 1988); (Manoochehri 1999); (Neely et al. 2005); (Santori & Anderson 1987); (Neely, Mills, et al. 2000); (Kaplan & Norton 1996); (Kaplan & Norton 1993) |
| It is better that Performance indicators are in an objective way, they can be relative instead of absolute | (Globerson 1985); (Neely, Mills, et al. 2000) |
| Performance indicators should measure the performance in both aggregated and disaggregated level. The purpose of performance indicators should be considered when developing performance indicators | (Behn 2003) |

### 5.3.3 Existing Research on Performance Measurement for Engineering Change Management.

In ECM context, performance measurement for ECM is the process of quantifying the efficiency and effectiveness of ECM process. The efficiency of ECM process means that how economically the resources in terms of time, effort, cost etc. are used to handle ECs, while effectiveness of ECM process means the extent that the correctness of EC is achieved comparing with the expectations.

A success ECM cannot be realized without the performance measurement for ECM process (Balcerak & Dale 1992; Hegde et al. 1992; Storbjerg et al. 2016; Fricke et al. 2000). The success in ECM can can eventually improve the engineering capability and project management (Alblas & Wortmann 2012; Fricke et al. 2000), it can improve product quality, reduce the product developing time, as well as keep the plan on schedule (Fricke et al. 2000; Eckert et al. 2004; Barzizza et al. 2001; Wright 1997; Ibbs et al. 2001). By using performance indicators regarding efficiency and effectiveness of ECM process, performance measurement evaluates and improves over ECM process, which provides the basis for continuous improvement of ECM process (Balcerak & Dale 1992; Alblas & Wortmann 2012; Subrahmanian et al. 2015; Fricke et al. 2000).

Despite performance measurement is evaluated as an important issue in both business and operational management, little attention has been paid on measuring the performance of ECM process.

In order to evaluate the impact of EC in term of time aspect, a performance indicator called "idle time-in-processes (ITIP)" was developed (Hegde et al. 1992). The indicator equal to "total time-in-process" minus "actual manufacturing time". Through regressing the formula, it reveals the importance of ECM with quantification of impact of EC on time. The conclusion was achieved that the overall performance of workshop highly depends on engineering activities and shop floor activities.

Several performance indicators, namely, "total actual labor hours", "estimated change order hours", "actual base labor hours", "estimated base labor hours", and "actual labor efficiency", are developed by Hanna et al. (1999) to evaluate the impact of EC on labor efficiency. The difference between "actual base labor hours" and "estimated base labor hours" reveals the negative impact of EC on labor efficiency.

In order to study the relationship of performance between project and ECM, the situation of ECs was investigated by Alblas & Wortmann (2012). Metrics for EC have been developed to show the characteristics of EC in the case company. These metrics are: "number of changed initiated", "average estimated impact on development employee-hours", "percentage increase in development work-hours", "average throughput time in days", "standard deviation throughput time in days", and "total employee-year impact". It is obvious that these metrics focus on measuring the effect of ECs.

Instead of measuring the performance of ECM process, the indicators developed by Hegde et al. (1992), Hanna et al. (1999), and Alblas & Wortmann (2012) all targeting on the impact of EC in terms of time and labor efficiency, which provide an indirect measurement on the performance of ECM process.

In the study conducted by Loch & Terwiesch (1999), three performance indicators were developed: "processing time", "waiting in the batch", and "waiting time" to identify the congestion of EC process in an automobile company. Five contributors for long EC lead time were identified, namely, complex approval process, congestion and lack of capacity, setups and batching, the snowball effect, and organizational cost management culture. Based on these findings, they suggested five improvement strategies for companies to speed up the process, which are flexible capacity, balanced workloads, merged tasks, pooling, and reduced setups and batching.

Nadia et al.(2006) used "development time" (time spent on processing ECs) and "effort" (day per person spent on processing ECs) as performance indicators to test if processing ECs in batch can reduce the time and effort spent on ECM. Their conclusion is that it is better to process ECs in batch rather than individually, however, urgent ECs still need immediate attention.

Another performance indicator named “EC capacity” was proposed to identify the productivity of ECM process in a study for analyzing the relationship between members among supply chain. According to the definition, it refers to “the number of ECs an organization can process per unit time” (Reddi & Moon 2011, p.1235). Their finding revealed that EC capacity can have impact on the lead time of product. However, the EC capabilities of suppliers do not have huge impact on the performance of supply chain as well as on OEM.

An ECM reference process was proposed by Wasmer et al.(2011) in order to improve the ECM across the companies. Through comparing their internal ECM process with the reference process, company can have a clear view on when and what can be shared with their ECM partners. In the validation, the impact of the proposed model was evaluated by using two performance indicators dedicating for overall performance of ECM process, namely, “lead-time” and “quality of process”. Eventually, a 20% to 40% reduction in lead time and the improvement in quality of process are identified, which validate the benefits of the model.

Ahmad et al. (2013) proposed a cross-domain solution to restructure a design in order to help for identifying the linkages between potential change propagation. To assess the usability and utility of the model, certain metrics are used to reveal the performance of ECM process. One of the metrics is “EC evaluation time”. It refers to time spent to evaluate EC cases”. The conclusion of their assessment is that this tool can improve the capability of knowledge capture and reuse, which eventually improve the efficiency of ECM process.

It seems that all the above performance indicators focus on measuring the efficiency of ECM process, which is only part of the scope of performance measurement on ECM process. According to the definition, the performance indicators for ECM process should take both efficiency and effectiveness into consideration.

A methodology to manage EC process in an effective way was developed by Barzizza et al. (2001). In the methodology, a five-steps framework has been suggested. The core concept behind this framework is to implement EC according to their impacts on products. These impacts are categorized as “scrap”, “rework”, and “use-as-is”. If a product is classified as “scrap” or “rework”, ECs are required to be implemented as fast as possible. If a product is classified as “use-as-is”, then the implementation of ECs is not urgent, it can be decided on the basis of economic efficiency. To control ECM process dynamically, two performance indicators were proposed as the control points, which are “costs control point (CP)” identifies the error in average percentage of estimating EC costs for all processed ECs; and “time control point (TP)” shows the average delay of EC implementation comparing with expected due date. The two performance indicators can identify the overall performance of ECM process. However, factors not belonging to ECM can also have impacts on the results of those performance indicators, which should be taken into consideration when evaluating the performance of ECM.

Performance indicators were developed in a survey aiming at exploring the present state of ECs and ECM among Hong Kong manufacturing companies (Huang et al. 2003). There are three quantitative performance indicators for measuring the volume of ECs and few qualitative performance indicators for measuring the effects of ECs. The three quantitative performance indicators are: “the number of active ECs” that are under consideration or implementation (except those that have already been implemented and rejected); “the calendar time” from the initiation to implementation of ECs; “men-effort-days” that actual time spent per person on processing ECs. For effect evaluation, since it is different to assess the impact of ECs by using quantitative assessment, qualitative indicators are used to evaluate the effects of ECs by collecting interviewee’s opinions in the following perspectives: product quality, organizational efficiency, delivery time, job disruption, cost increase. Conclusion was draw that EC should be managed in a way that balance the effectiveness and efficiency of a system in order to minimize the time, cost and effort. All of these performance indicators focus on revealing current practices of ECM, however, they are dedicated for the particular aspects of ECM, which can only work in the disaggregated level of ECM. For the purpose of overall improvement, both aggregated and disaggregated performance indicators should be used (Behn 2003; Neely et al. 1997).

One of the most relevant method on performance measurement for ECM is the conceptual models proposed by Tavcar and Duhovnik (2005). The model was designed for the reference to identify the weakness of ECM within three production strategies. A questionnaire with a list of important factors as performance indicators for efficient ECM is proposed (Figure 5-7). By comparing these factors with the current ECM practices, the efficient of ECM process can be assessed by interviewee. However, it is important to mention that these performance indicators in the questionnaire are subjective, which means the result of assessment can be easily affected by the personal feelings. Performance indicators should be preferred to be objective rather than subjective (Globerson 1985; Neely, Mills, et al. 2000). Therefore, it is important to have indicators that reveal the performance of ECM process more objectively.

Performance indicators proposed by Subrahmanian et al. (2015) are the most sophisticated among other proposals. These performance indicators cover the time spent for ECs, and volume of ECs in terms of reason and type. However, all these performance indicators are presented in an absolute way. Since the performance indicators imply a point of reference such as an objective, as assessment, and are therefore should be relative rather than absolute (Neely, Mills, et al. 2000; Neely et al. 2005).

Table 5-8 summaries the existing performance indicators for ECM from previous research. The results of literature review show that the existing performance indicators have the contributions in their own value. They either focus on part of the scope of ECM performance which might result the sub-optimization or being subjective and absolute which might be affected by other factors and cannot reflect the performance. All the existing performance indicators are not suitable for improving the overall performance of ECM process in ETO companies. To fill this gap, new performance indicators were developed on the basis of a new reference framework for ECM. These new performance indicators are able to help for decision-making on where to improve to achieve overall the performance of ECM process in ETO companies.

| | Question | Criterion and assessment | | | | |
|---|---|---|---|---|---|---|
| **0** | **Criteria for assessing the ECM system as a whole** | **1** | **2** | **3** | **4** | **5** |
| 0.1 | The EC process is clearly defined and well understood in the company. | | | | x | |
| 0.2 | The time from proposal to implementation of the change is short. | | x | x | x | x |
| 0.3 | Active work accounts for a large proportion of the total time from suggestion to change implementation. | | | x | x | |
| 0.4 | The total costs of the procedure and change implementation are low. | x | | | x | |
| 0.5 | Changes increase the competitive advantage of products and lower the costs. | | x | | x | |
| 0.6 | Few changes are required immediately after start-up of production of new products. | x | | | | |
| 0.8 | The company has a good product concept, in which upgrading and derived products are already envisaged. | x | | | | |
| 0.9 | The entire EC process is computer-aided. | | | | | x |
| **1** | **Idea – change request** | | | | | |
| 1.1 | The employees are aware of the importance of improvements and motivated to collect useful proposals. | | x | | x | |
| 1.2 | The system for collecting proposals is simple and clear. | | x | | | x |
| 1.3 | Quick responses to proposals are ensured. | | x | x | x | |
| 1.4 | Tracking of changes is enabled. | | | | | x |
| **2** | **Preparing a change** | | | | | |
| 2.1 | Technical assessment is performed of a change's feasibility and advantages. | | x | | x | |
| 2.2 | Only a short time is required for preparing a change, including all data for its approval. | | | x | | x |
| 2.2 | All data for preparing a change are clear and readily accessible (material stocks, accessibility of relevant drawings, 3D models). | | | | | x |
| 2.3 | Additional research can be done quickly and is of high quality. | | x | x | | |
| 2.4 | The prototype production and testing are quick. | | | x | | |
| 2.5 | The costs of change implementation and any savings are assessed. | | x | | x | x |
| **3** | **Change approval** | | | | | |
| 3.1 | Change approval is performed frequently enough. | | | x | x | |
| 3.2 | Data on the change are prepared well enough to enable good decision-making. | | x | | | x |
| 3.3 | Correctness of the adopted decisions is ensured from all viewpoints. | | x | | | |
| 3.4 | The adopted decisions are final and there is adequate support for their implementation. | | x | x | | |
| **4** | **Change of documentation** | | | | | |
| 4.1 | Quick changes in the documentation are ensured. | | | x | | x |
| 4.2 | Correct implementation of changes in the entire documentation is ensured: 3D model, drawings, ERP system (bill of materials, material data). | | | | x | x |
| 4.3 | Changes in the documentation are in accordance with the approval. | | x | | x | x |
| 4.4 | Changes in the documentation do not disturb the current production process. | | | | x | x |
| **5** | **Distribution of documentation and implementation in the production process** | | | | | |
| 5.1 | Mix-ups between old and new versions of documents are prevented. | | | | x | x |
| 5.2 | The costs of document distribution and replacement are low. | | | | x | x |
| 5.3 | Simultaneous replacement of documents is ensured. | | | | x | x |
| 5.4 | Professional implementation of changes in the production process is ensured. | | | x | | |
| 5.5 | Implementation of changes is always harmonized with the documentation. | | x | | | |

**Figure 5-7: Questionnaire for ECM. Source: Tavcar and Duhovnik (2005)**

Table 5-8: Proposed Performance Indicators for ECM from previous research.

| Proposed Performance Indicators | Reference |
|---|---|
| Idle time-in-process | (Hegde et al. 1992) |
| Total actual labor hours, estimated change order hours, actual base labor hours, estimated base labor hours, and actual labor efficiency. | (Hanna et al. 1999) |
| Processing time, Waiting in the batch, Waiting time | (Loch & Terwiesch 1999) |
| Costs control point, Time control point | (Barzizza et al. 2001) |
| Number of active ECs (exclude those have been implemented and rejected), Calendar data for ECs, Men-effort-days | (Huang et al. 2003) |
| Subjective performance indicators such as: clear definition of EC process; time for processing ECs; total costs of procedure and change implementation are low; quick responses to proposal are ensured, etc. | (Tavčar & Duhovnik 2005) |
| Development time; EC Effort | (Nadia et al. 2006) |
| Qualitivity Performance indicators: Product Quality, Organizational Efficiency, Delivery Time, Job Disruption, Cost Increase. | |
| EC Capacity | (Reddi & Moon 2011) |
| EC lead time; Quality of process | (Wasmer et al. 2011) |
| Number of changed initiated, Average estimated impact on development employee-hours, Percentage increase in development work-hours, Average throughput time in days, Standard deviation throughput time in days, and Total employee-year impact. | (Alblas & Wortmann 2012) |
| EC evaluation time | (Ahmad et al. 2013) |
| Time spent for ECs, volume of ECs in terms of reason and type. | (Subrahmanian et al. 2015) |

# 6 A new methodology for ECM in ETO Companies

Through the literature study, the proposals in the existing research for ECM are not suitable to deal with complex situation of ECs in ETO companies according to their own features. Moreover, they fall to provide a methodology to improve the overall ECM process by identifying the area of improvement. Therefore, a new methodology for ECM with a reference framework and a set of performance indicators, which meets the above requirements was proposed. The purposes and advantages of this new methodology are stated as follow:

Firstly, the reference framework within the new methodology visualize the ECM process, which provides the basis for monitoring and controlling over EC and ECM activities.

Secondly, the reference framework allows the flexibility in ECM process, which enables the process to handle different types of ECs in ETO companies according to their own characteristics. Hence, it reduces the process lead time of EC as well as improve the quality of decision.

Thirdly, the reference framework rationalizes ECM process. By comparing the existing ECM process with the reference framework in the new methodology, user can adjust the process and the function of their ECM process to improve their own ECM process. It helps to Improve the quality of ECM process as well as increase transparency of ECM process.

Fourthly, with the evaluation of performance indicators dedicated for both overall ECM process and each phase within the process, current performance of ECM process can be assessed while the strengths, the weaknesses, and area need to be improved within ECM process can be identified. Decision of where to improve can be made based on the results of the evaluation. With the application of further improvement action, the performance of ECM process in terms of efficiency and effectiveness can be improved as well.

All in all, the new methodology can reduce the time and cost spend on ECM, maximize the benefits of ECs. Furthermore, it helps to Increase engineering quality and capability, reduce the product development cost and time. Eventually, the new methodology can ensure the quality of product, reduce the time-to-market, as well as keep customer satisfaction in a high level.

The remaining of this chapter is structured as follow. In Section 6.1, reference framework for ECM is explained with a classification mechanism and matrix for ECM. In Section 6.2, a set of KPIs was developed together with a set of performance indicators for separated ECM process.

# 6.1 Reference framework for engineering Change Management Process

The reference framework for ECM process proposed in this paper consists of a classification mechanism, which work as the core mechanism for the framework. Therefore, the new EC classification scheme will be introduced first in Section 6.1.1, this is followed by Section 6.1.2 with the new proposals for reference framework for ECM process.

The purpose of this reference framework is to rationalize ECM process, it provides a decision supporting tool for evaluating and implementing ECs by their own characteristics. Furthermore, the framework is the basis for the decision making on the performance improvement in ECM process by using performance indicators.

## 6.1.1 EC Classification

The aim of classification is to help in decision making and implementation for different types of ECs within ECM process. The classification schemes used in this framework are adapted from the works by Balcerak and Dale (1992), Barzizza et al. (2001), together with Eckert et al. (2004) Similar with Balcerak and Dale (1992), two dimensions are used in the framework. However, instead of differentiating ECs in terms of type and impact on department, the new classification scheme includes two dimensions, namely impact and priority. For impact dimension, it is used to describe the nature of EC regarding the impacts on product and change propagation incurred by ECs while priority dimension is used to describe the timing of EC that should be implemented. Two classification dimensions are now described.

### 6.1.1.1 Impact Dimension

Impact dimension is used to differentiate the impact incurred by EC in terms of design, change propagation, product, and production. It identifies to which extent the decision-making mechanism should be involved. In this framework, the dimension was adapted from the scheme developed by Barzizza et al. (2001) and Eckert et al. (2004).

Type 1- “Multipliers”. In the order of impact severity, multipliers have the most impact on component and/or product. As the name shown, this type of ECs cause change propagations more than they can absorb, which increase complexity of EC. As a result, multipliers causing scrap or rework in a serious degree. Cease of procurement, production, or other order fulfilment process are required if multipliers occur. Generally speaking, this type of ECs should be avoided as much as possible. However, this is not the case in ETO companies. For example, although the change request from customer may cause scrap and reengineering for the majority part of existing design, some of the customer will still afford the cost incurred by those ECs, which would probably bring cost benefits eventually.

Type 2- “Carriers” are those ECs with modest impact on component and/or product. They can have impact either on cost or time. ECs belongs to “carriers” require modification or rework on the affected components and/or product in a fair degree. In change propagation perspective, carriers incur the similar number of ECs to the number they can absorb, which remains the complexity of ECs in an existing level. However, carriers still interrupt engineering, procurement, production, or other order fulfilment process in a modest and controllable degree.

Type 3- “Absorbers” are those ECs with no or minor impact on component and/or product. In other words, it means that these ECs cause no or minor impact on cost and time. In change propagation perspective, the absorbers can absorb more ECs than incur change propagation to other components, which reduce the complexity of EC. Therefore, engineering procurement, production, and other order fulfilment processes are not disrupted by this type of ECs.

It is important to mention that the categories have no direct relationship with the reason of ECs. For instance, a simple drawing error in the key component can be type 3- “Multipliers” if it was discovered at the end of the production phase, which will eventually cause scrap of produced product and reengineering on the existing design. Another example could be a change request from customer seems to be with greater impact on product, it can be just a simple modification on the drawing, which modification on paperwork only.

#### 6.1.1.2 Priority Dimension

Priority dimension is used to describe how urgent EC should be handled. They reflect the nature of ECs in terms of the urgency. The dimension was proposed based on the work by Balcerak and

Dale (1992). However, two priorities were removed and two were added, namely convenience and urgent. Priority dimension is now described.

Grade U- “Urgent” ECs are the most urgent among others and should be implemented immediately. These ECs can be initiated due to safety reasons that are expected “to kill, injure, damage property or cause commercial damage” (T. Jarratt et al. 2011, p.109) or due to quality problems found during manufacturing, assembling, and commissioning. Therefore, the evaluation and implementation of those ECs should focus on time efficiency rather than cost. Because of the fact that the later implementation of these ECs could cost even huger impact not only on the final product but also on the company, it is highly suggested that those ECs should be implemented immediately.

Grade E- “Error” are those ECs due to errors correction. The objective of these ECs is to correct mistakes on drawings such as dimension, part number, note etc. or on bills of material (BOM) such as part number, quantity etc. The impact of this type of ECs could range from nothing to the scrap of produced product, which highly depends on the timing that those ECs are initiated. However, since the late processing of these ECs can eventually result huge impact such as scrap or quality failure, ECs belongs to Grade E should also be processed immediately but not as urgent as Grade U.

Grade M- “Mandatory” are those ECs that should be processed but have less priority than Grand U and Grade E. The implementation of ECs in Grade M requires careful planning in order to minimize the impact on cost and time. In most cases, those ECs are initiated by customers or suppliers whose change request cannot be refused. ECs result from the change in certification requirements also belongs to Grade M.

Grade C- “Convenient” ECs have least priority among others. The purpose of those changes can be cost reduction, technical innovations, customers feedbacks etc. This type of ECs need careful evaluation and planning for implementation in order to keep efficient in cost. Therefore, the management of Grade C ECs requires skills and reflects the capability of the company in ECM.

Similar with impact dimension, it merely reflects the priority of ECs in an objective way. In other words, reasons of EC have no direct impact on which category it belongs to.

Table 6-1 gives a summary of the characteristics in each category of dimension.

Table 6-1: Characteristics of EC categories in the dimension of impact and priority.

| **Dimensions** | **Categories** | **Characteristics** |
|---|---|---|
| Impact | Type 1: "Multipliers" | • Severe in impact in terms of cost and/or time etc.<br>• Change propagate to other components in a serious level.<br>• Increase the complexity of EC.<br>• Cease of order fulfilment process Cause scrap of produced product and reengineering on existing design. |
| | Type 2: "Carriers" | • Modest impact in terms of cost and/or time etc.<br>• Change propagate to other components in a controllable level.<br>• Remain the complexity of EC in the existing level.<br>• Interrupt order fulfilment process.<br>• Require rework of produced product and modification on existing design. |
| | Type 3 "Absorbers" | • Minor or no impact in terms of cost and/or time etc.<br>• Change propagate to other components in a minimal level.<br>• Reduce the complexity of EC.<br>• Require minor rework and modification on existing design. |
| Priority | Grade U: "Urgent" | • Most urgent in evaluation and implementation.<br>• Require implementation immediately.<br>• Focus on time efficiency despite of high cost. |
| | Grade E: "Error" | • Error in existing design and document.<br>• Require implementation as soon as possible but with flexibility in time.<br>• Focus on time efficiency and cost efficiency if possible. |

| | | |
|---|---|---|
| Grade M: "Mandatory" | • EC request cannot be refused.<br>• Implementation with a modest degree of flexibility in time.<br>• Focus on both time and cost efficiency. |
| Grade C: "Convenient" | • EC for product improvement mostly.<br>• Implementation can be hold to wait for best timing.<br>• Evaluation and implementation focus on cost efficiency. |

### 6.1.2 Matrix for ECM

Two EC dimensions are combined together as shown in Figure 6-1. It shows all 12 possible types of EC with different of impact and priority. The matrix identify four kinds of strategy, namely "Full Track", "Board Track", "Simplified Track" and "Fast Track" to handle different types of ECs especially in approving and implementation phase, which are the challenges for ECM process in ETO companies (Balcerak & Dale, 1992; Eckert et al., 2004; Huang, Yee, & Mak, 2003; Pikosz & Malmqvist, 1998; Storbjerg, Brunoe, & Nielsen, 2016). In approving phase, four strategies reflect different involvement degree of decision making mechanism. While in implementation phase, three levels represent different timing and focus for EC implementation. These strategies are presented in the following paragraph in the order of complexity of ECM process.

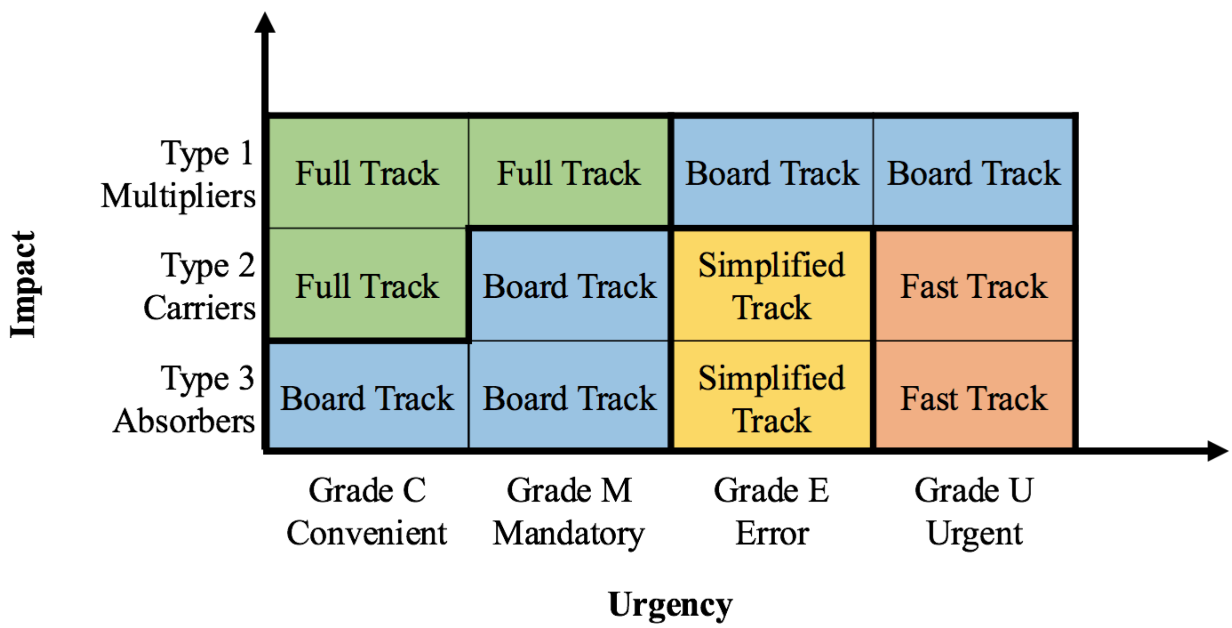


**Figure 6-1: Matrix for ECM**

**Full Track**

Full Track refers to ECM process with completed approving function and full focus on implementation regarding time and cost. The strategy of "full track" can be applied for ECs belongs to type "1C", "2C", and "1M". To approve these ECs, they require the decision making from both disaggregated and aggregated level. In other words, evaluation go firstly by related engineers from different departments, then by ECM board. People from different disciplines and different management level are involved in the approving process in Full Track. So the time spend on approving those ECs is longer in Full Track than other strategies. For the implementation, since those ECs mostly have huge impact and more flexibility in time, therefore, the implementation of those ECs is hold for the best timing. Batch-processing can be applied for those ECs with the similar objectives. During implementation, cost efficiency should be valued far more than time efficiency in order to minimize the negative impacts of ECs and maximize the benefits.

**Board Track**

ECs belongs to "3C", "2M", "3M", "1E", and "1U" can follow the strategy of "Board Track". In this strategy, only ECM Board is involved in the approving step. ECM Board takes the responsibilities of evaluation, approving or rejecting ECs, and making decisions on the implementation of ECs. However, the member of ECM Board is dynamic according to the content of the meeting and its necessity. In most cases, people from engineering, manufacturing, procurement, and project management should be the regularly participants. Customers and suppliers can also be invited to attend the meeting if it is necessary for the evaluation and approving. It worth mentioning that since the higher degree of involvement in different disciplines, the frequency of ECM Board meeting can be weekly or monthly, which highly depends on the requirements of certain companies. Due to the characteristics of ECs belongs to this strategy, the implementation of these ECs have more priority than those ECs follow "Full Track", which means that cost efficiency is important than time efficiency to some extent.

**Simplified Track**

Different scholars hold the similar views on simplifying ECM process for those simple ECs and urgent ECs as stated previously (Eckert et al., 2004; Huang et al., 2003; Storbjerg et al., 2016). Therefore, "Simplified Track" and "Fast Track" are developed to cope with this gap. ECs belongs to “2E” and “3E” should follow the strategy of “Simplified Track”. Due to the content of these ECs, the approving process should be as simple as possible, which means the involvement of initiator and related engineers from affected department such as engineering, procurement, and manufacturing departments is necessary only. For example, if there was an error correction EC found by sales department about error on drawing with no or minor impact, this EC should belong to type “3E”. Therefore, “Simplified Track” should be followed, in the approving step, there should be only the engineers from initiated department, in this case, sales department and engineering department involved in approving process. Since the late correction of error could lead to huge impact, the implementation of should be as fast as possible but still with certain flexibility in time.

**Fast Track**

“Fast Track” is applied to ECs within type “2U” and “3U”. These types of ECs are mostly due to safety reasons or quality failures with greater impact on change propagation, components and products, as well as order fulfilment process. Therefore, the approving step should be as simple as possible meanwhile with a higher degree of authority. In this case, managers from related departments should be involved in the approving step. The implementation of those ECs in “Fast Track” strategy should focus on time efficiency despite the high cost in implementation.

### 6.1.3 Reference Framework for ECM Process

Reference framework for ECM process gives definition on the functions and the flow of process for ECM. Combining with the classification mechanism and the matrix, the framework is able to handle ECs with different levels of process according to their own characteristics. This kind of flexibility can improve both efficiency and effectiveness of ECM process. Moreover, the framework also provides a basis for the performance indicators developed in the later section.

Reference framework for ECM process, as shown in Figure 6-2, was adapted based on the model proposed by Reddi & Moon (2011). There are four phases in ECM process: propose, approve, implement, and document. Different functions are carried out within each phase. Decision gates exist between each phase, which provides function for calling off the rest of ECM process if necessary. If an EC fail to pass any decision gate, the flow goes direct to the documentation of EC. This can be used to help engineer for the future reference if the similar situation occurs.

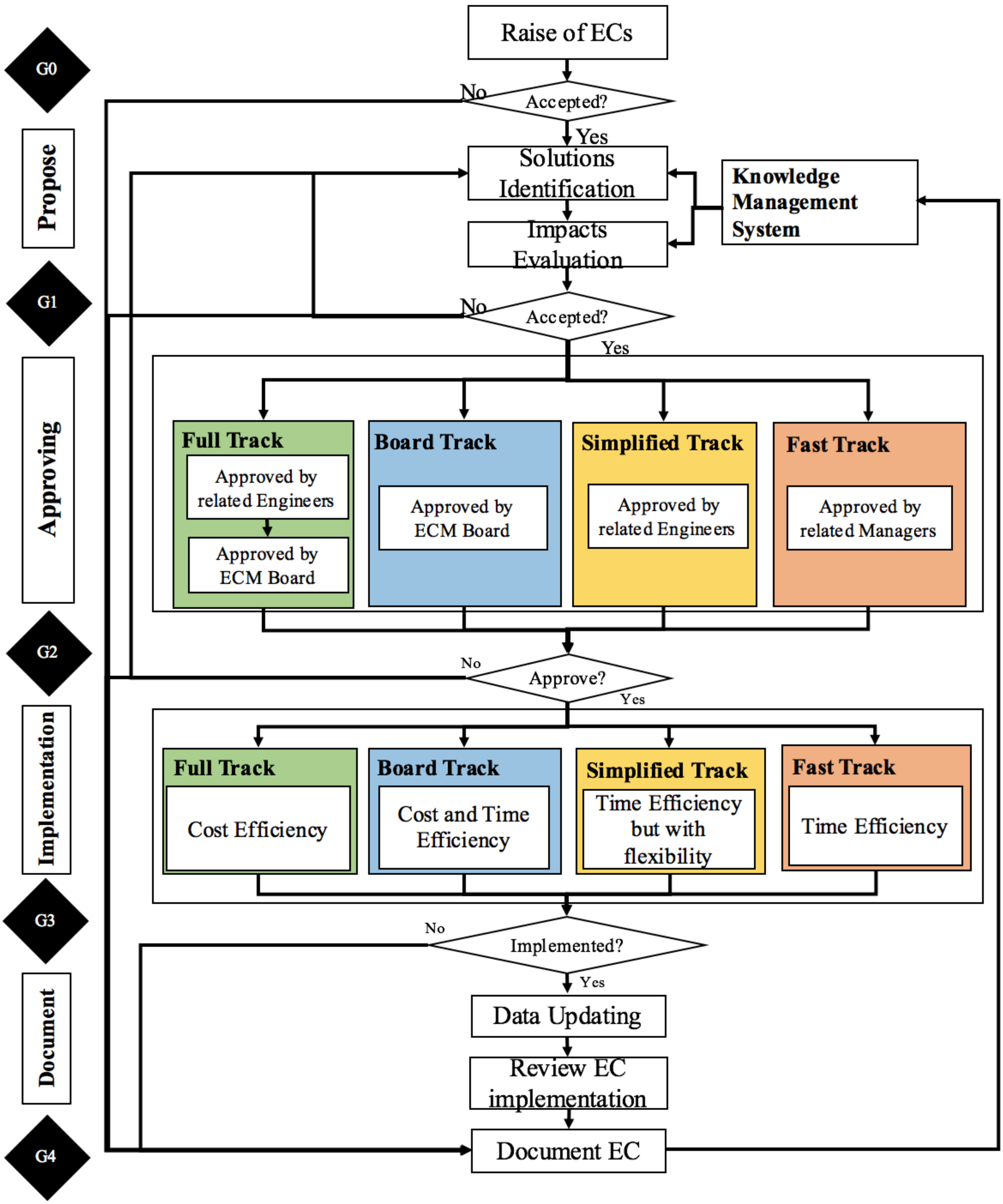


**Figure 6-2: Reference Framework for ECM**

The entire ECM process starts with the raise of ECs, which is the most basic and important step. The initiator from either internal or external departments should specific the related information on EC such as change objective, change reason, possible solution. The initial version of dimension of priority and impact is also assigned in this step. These dimension will be used later to involve corresponding people in the solution identification and impact evaluation. Meanwhile revaluation of the two dimensions will be carried out and final version of two dimensions will be confirmed in the step of impact evaluation in order to make these dimension more objective. First decision gate (G0) appears after the raise of EC. It should be decided by the supervisor or the manager of the initiator whether to accept this EC for further handling or not.

Solution identification and impact evaluation are carried out after the approval of Gate 0. Although they are two separated function in the figure of framework, the solution identification and impact evaluation happen synchronously in most situation. People from different disciplines should be involved in the two steps based on the first version of two dimensions assigned in the raise of ECs. More disciplines should be involved if the impacts of EC are higher. For ECs belong to Type “3” since those ECs cause minor impact, only initiator and engineer from engineering department are involved in solution identification and impact evaluation. For ECs belong to Type “2”, initiator, and more engineers from related department such as engineering, purchasing, manufacturing, production, and quality control should be involved. For solution identification and impact evaluation of Type “1”, except the people included in Type “2”, people with a high authority level should be involved as well.

In solution identification step, the solutions to solve this EC are figured out. They can be modification or reengineering of the existing design. They can also be the replacement of a new component or a new configuration. Usually, more than one solution is identified, people from different disciplines should evaluate these alternations and their corresponding impacts then make decision on which solution should be applied. In impact evaluation, the impacts on cost, time and schedule etc. caused by the solution within different stakeholders are evaluated and attached to the particular EC. Dimensions of impact and priority are re-evaluated and assigned according to the results of evaluation, which provides the instruction for handling EC with different strategy in the following process. It is important to notice that there is an iteration within the propose phase, which is normal in reality because sometimes it is hard to achieve the agreement on the solution between each discipline with discussion for a single time.

Different types of ECs follow the corresponding strategies, namely “Full Track”, “Board Track”, “Simplified Track”, and “Fast Track” in approving and implementation. Since details have been plotted in the section “matrix for ECM”, they are not discussed in here. In approving phase, decision on whether to approve the identified solution and corresponding impacts are made. There is an iterated process back to solution identification if EC was rejected. After ECs have been approved, implementation should be executed according to the priority of EC. Before implementation, plan and Metric used to monitor the EC implementation are discussed with different disciplines and developed, which is used not only for the purposes of performance measurement but also for review and learning in the later phase. Change-affected documents are updated before implementation as well. Communication and information sharing are happening between all the stakeholders before and during implementation. If the change concerning on customers or suppliers, timely information and document should also be shared with them.

After approval and implementation of EC, ECM process end with documentation. It worth mentioning that data updating and review of EC implementation is important in this phase, which provide the basis for learning and further improvement. Moreover, findings, experiences, lessons-learned, and tacit knowledge during the handling of EC can be collected during the process of review. These data together with the information and data documented during the entire ECM process formed a great knowledge management system that engineer can refer to during propose phase if the similar EC occur.

## 6.2 Performance Indicators for Improvement the Performance of ECM in ETO companies.

As discussed in Section 5.3.1 that it is necessary for ETO companies to learn the health of their ECM process and the ability of ECM process to handle EC in a beneficial way. Therefore, as the performance measures for evaluating the efficiency and/or effectiveness of ECM process, performance indicators provide a system that is easy to use for measuring and evaluating the performance of ECM process as well as monitoring and managing ECM activities within the process. By benchmarking the performance with internal and external objectives, best practices and areas of improvement can be identified. All of these can be applied to improve the performance of ECM process eventually. Thus, Lower the cost and time for engineering, ensure a high product quality and maintain a high customer satisfaction level.

To prevent misunderstandings, it is essential to emphasize that performance indicators are not for evaluating EC, but for evaluating ECM process. They offer methods for determining the performance of ECM process and detective the strengths and weaknesses, which eventually help to improve ECM process. According to the principles, learning and improving from performance measurement requires both aggregated and disaggregated level. Therefore, performance indicators for both overall process and separated phases were developed.

The development of performance indicators in this thesis is based on the findings and conclusions from the specialization project carried out in Autumn 2015. One of the conclusions of the specialization project is a list of performance indicators for ECM process (Appendix A). However, by reviewing the result, it was found that these performance indicators are not well structured enough and not able to support each other for evaluating the complex situation in reality. Therefore, in this thesis, a new set of performance indicators was developed on the basis of the reference framework proposed in the previous section. These performance indicators are able to fit the flexibility of ECM process as well provide a aggregated and disaggregated level of view on the performance of ECM process.

There are two sections in this part. In section 6.2.1, key performance indicators for overall ECM process are presented. This is followed by performance indicators for separated phase within ECM process in section 6.2.2.

### 6.2.1 Key Performance Indicators for overall ECM Process

It is essential to have key performance indicators (KPIs) to reveal the overall performance of ECM process. These KPIs enable the comparison of performance with internal and external objectives. They can also help to ensure the improvement in a balanced way instead of sub-optimization within a particular phase of ECM process. Six KPIs were proposed as the KPIs for overall performance of ECM process, which will be explained in the following paragraph.

**Overall Process Efficiency Index (OPEI)**

OPEI identify the efficiency of overall ECM process to handle EC with the ratio between finished ECs with all ECs in the system within a certain period of time that is decided by the requirement for individual company. It can be a week, two weeks, or a month.

$$\mathrm{OPEI} = \frac{\mathrm{N_{Finished}}}{\mathrm{N_{All}}} \times 100\%$$

$$\mathrm{N_{All}} = \mathrm{N_{Finished}} + \mathrm{N_{Unfinished}} - \mathrm{N_{Rejected}};$$

$$\mathrm{N_{Finished}} = \text{Number of Finsihed EC};$$

$$\mathrm{N_{Unfinished}} = \text{Number of Unfinished EC};$$

$$\mathbf{N_{Rejected}} = \textbf{Number of Rejected EC};$$

**Equation 1: Overall Process Efficiency Index (OPEI)**

Despite that it reveals the percentage of finished EC in a certain period of time, the result of OPEI does not necessarily identify the efficiency of overall ECM process. In other words, it just reveals part of the efficiency of overall ECM process. For example, assumed that the result of OPEI is 80% among one week, it means that there are 80% ECs finished among all the received ECs except those rejected within one week. If the average time spent for processing these EC is one month and most of the ECs within the 80% was late for implementation, the seemingly high percentage does not necessarily mean the high efficiency of overall ECM process. Therefore, KPI that help to provide an objective reference are required as well. This directs the propose of next two KPIs.

**Average EC Lead Time (AELT)**

Average EC lead time measures the average time spent for ECs to go through the entire ECM process. The definition of ALT is shown in Equation 2. It is a quantitative indicator to help to reveal the efficiency of overall ECM process.

$$\mathrm{ALT} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} \left(\mathrm{D_i^{G4}} - \mathrm{D_i^{G0}}\right)$$

$$\mathrm{D^{G4}} = \text{Actual Date when EC finish entire process (Reach Gate "4")};$$

$$\mathrm{D^{G0}} = \text{Actual Date when EC start entire process (Start from Gate "0")};$$

**Equation 2: Average EC Lead Time (ALT)**

As discussed previously that the individually utilization of this KPI failure to assess the efficiency of overall ECM process, therefore, the evaluation of efficiency for overall ECM process requires the supporting of OPEI and AEID that will be explained follow.

**EC Implementation Delay Rate (EIDR)**

EC implementation delay rate is used to quantify the number of late implemented EC among total implemented EC. EIDR together with the "Average EC Implementation Delay" proposed next are two supplementary KPIs used to assess the efficiency of ECM process. This is based on the fact that the low efficiency in overall ECM process can eventually results the late implementation of EC. Moreover, it is hard to evaluate the efficiency of ECM process only with "OPEI" and "AELT" proposed previously because the result from these KPIs are merely reflect the quantity of finished EC and the time they spent in average. It could be the situation that all the finished ECs were delayed despite there is a high percentage in "Overall Process Efficiency Index" and relatively low number in "Average EC Lead Time". Therefore, "EIDR" and the upcoming KPI- "Average EC Implementation Delay" are also essential to evaluate the efficiency of overall performance in ETO companies. The two KPIs are also applied for the measurement and evaluation of implementation phase within ECM process. The definition of EIDR is shown in Equation 3.

$$\mathrm{EIDR} = \frac{\mathrm{N_{late\ implemented}}}{\mathrm{N_{implemented}}} \times 100\%$$

$$\mathrm{N_{late\ implemented}} = \text{Number of Late Implemented EC;}$$
$$\mathrm{N_{implemented}} = \text{Number of Implemented EC}$$

**Equation 3: EC Implementation Delay Rate (EIDR)**

**Average EC Implementation Delay (AEID)**

Average EC implementation delay is used to assess the average extent that the implementation is later than due date. It compares the actual implementation date with the due date in average level. This KPI is also used to evaluate the efficiency of overall ECM process. Equation 4 gives the definition of this KPIs. This definition has also been proposed by Barzizza et al. (2001).

$$\mathrm{AEID} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} (\mathrm{ID}_{\mathrm{i}}^{\mathrm{Actual}} - \mathrm{ID}_{\mathrm{i}}^{\mathrm{Expected}})$$

$$\mathrm{ID}^{\mathrm{Actual}} = \text{Actual EC Implemented Date;}$$

$$\mathbf{ID}^{\mathbf{Expected}} = \textbf{Expected EC Implemented Date (Due date);}$$

**Equation 4: Average EC Implementation Delay (AEID)**

If the number of AEID is minor, it means that, averagely speaking, the EC implementation is faster than expected. If the number if plus, it means that the EC implementation is slower than expected.

It should be noticed that other influential factors such as stroke, or power failure in the work floor should be taken into consideration during the evaluation of this KPI.

**Average EC Implementation Cost (AEIC)**

Average EC implementation cost was firstly proposed by Barzizza et al. (2001). It refers to difference between actual cost with expected cost. The KPI quantifies the effectiveness of overall ECM process in terms of cost. Equation 5 gives the detailed definition.

$$\mathrm{AEIC} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} (\mathrm{IC}_{\mathrm{i}}^{\mathrm{Actual}} - \mathrm{IC}_{\mathrm{i}}^{\mathrm{Expected}})$$

$$\mathrm{IC}^{\mathrm{Actual}} = \text{Actual EC Implemented Cost;}$$

$$\mathrm{IC}^{\mathrm{Expected}} = \text{Expected EC Implemented Cost (Planned Budget);}$$

**Equation 5: Average EC Implementation Cost (AEIC)**

Similar to AEID, if the number of AEIC is minor, it means that actual EC implementation cost is lower than expected in average, which reflects the high effectiveness in overall ECM process. On the contrary, if the number if plus, it means the actual EC implementation cost is higher than expected in average, which reflects the low effectiveness in overall ECM process. During the evaluation of this KPI, influential factors that leads to the good or poor performance (e.g. exchange rate) should also be taken into consideration.

**Average Changed Component Quality (ACCQ)**

Average changed component quality is a qualitative KPI to describe that to which extent the changed components agree with the specifications or expectations, which reveals the effectiveness of overall ECM process.

$$\mathrm{ACCQ} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} \mathrm{Q}_{\mathrm{i}}^{\mathrm{C}}$$

$$\mathrm{Q}^{\mathrm{C}} = \text{Quality Degree of Changed Component}$$

(1 to 5, 1 being worst, 5 being best)

**Equation 6: Average Changed Component Quality (ACCQ)**

Definition of ACCQ is shown in Equation 6. It is calculated by averaging the quality degree of changed component, which is in a range between 1 to 5, where 1 represents the worst quality while 5 represents the best.

Since the quality degree of changed component requires the evaluation by individual, the result of this KPI can be affected by factors such as personal experience. Hence, the evaluation of this KPI should take this point into consideration.

**EC Related Customer Satisfaction Level (ECSL)**

EC related customer satisfaction level is another qualitative KPI used to measure the effectiveness of overall ECM process in terms of the customer satisfaction. It describes to which extent the customers are satisfied with ECM in the company. Equation 7 gives out the definition.

$$\mathrm{ECSL} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} \mathrm{CSL}_{\mathrm{i}}$$

(CSL= Customer Satisfaction Level on ECM)

**Equation 7: EC Related Customer Satisfaction Level (ECSL)**

Since this is also a subjective KPI, the result of this KPI can be affected by personal experience as well, which should be considered during the evaluation.

### 6.2.2 Performance Indicators for separated phase within ECM Process

KPIs proposed in the last section can assess the overall performance of ECM process. However, drawback still exists. KPIs for overall performance of ECM process are not able to provide information that can help to identify strengths and weakness. In order to identify area of improvement, performance indicators for each phase are required.

**Efficiency Indexes for Each Phase**

Based on the reference framework proposed in Section 6.1.3, there are four phases within the entire ECM process. Hence, there are four performance indicators dedicating for measuring the efficiency of each phase, namely, Efficiency Index for Propose (EIP), Efficiency Index for Approve (EIA), Efficiency Index for Implementation(EII), EC Archive Index (EAI). The definitions of these performance indicators can be summarized into one equation, which is shown in Equation 8. They are the ratios of processed ECs to received ECs in the particular phase within ECM process.

$$\frac{N_{Processed}^{Phase}}{N_{Received}^{Phase}} \times 100\%$$

$$N_{Processed}^{Phase} = \text{Number of Processed EC in the phase;}$$

$$N_{Received}^{Phase} = \text{Number of Received EC in the phase.}$$

**Equation 8: Efficiency Index for Each Phase**

These PIs are used to assess the efficiency in each phase, which aid the decision-making on where to improve in terms of efficiency. For example, if the result of evaluation on KPIs shows that the efficiency of overall ECM process is low, evaluator can investigate further into these efficiency index for each phase to check which phase lead to the low efficiency of overall ECM process. Therefore, action can be taken to improve the insufficiency. These PIs can also be applied for monitoring the effect of the improvement action.

**Processing Time for Each Phase**

Similar to OPEI, the efficiency indexes for each phase are not also to provide the objective and complete idea about the efficiency for each phase without the reference of time spent. Therefore, performance indicators of processing time for each phase were proposed, which are: Average EC

Responding Time (AERT), Average EC Approving Time (AEAT), Average EC Implementation Time (AEIT). These performance indicators measure the time spent on corresponding activities in each phase, namely, responding to change request with proper solution, approving EC, implementing EC. The definition of these performance indicators can be summarized in Equation 9.

$$\frac{1}{N} \times \sum_{i=1,2,3\ldots}^{N} (D_i^{G(x+1)} - D_i^{G(x)})$$

$$D^{G(X+1)} = \text{Actual Date when EC finish phase (Reach Gate "X + 1");}$$

$$D^{G(X)} = \text{Actual Date when EC start the phase (Start from Gate "X");}$$

**Equation 9: Processing Time for Each Phase**

The processing time for each phase is calculated by averaging the difference between the actual date when EC finish the process in the phase and actual date when EC start the process in the phase. In other words, if using the reference framework, it is the time spent for EC to go from the previous decision gate to the next decision gate.

**EC Rework Index (ERI) and EC Rejected Index (ERJ)**

According to the framework, there are two iterations in the propose and approve phase. In the propose phase, the iteration is due to the failure in achieving the agreement on the proposed solutions, therefore, rework is required. In approving phase, the iteration is triggered because of the rejection to the particular EC, then the flow directs to the solution identification again to reevaluate the particular EC. The rates of these iterations can reveal the effectiveness within propose and approving phase. Therefore, EC rework index (ERI) and EC rejected index (ERJ) were proposed. Definition is presented in Equation 10.

$$\frac{N_{\text{Reworked/Rejected}}^{\text{Phase}}}{N_{\text{Received}}^{\text{Phase}}} \times 100\%$$

$$N_{\text{Reworked}}^{\text{Phase}} = \text{Number of Reworked or Rejected EC in the phase;}$$

$$N_{\text{Received}}^{\text{Phase}} = \text{Number of EC received in the phase.}$$

**Equation 10: EC Rework Index and EC Rejected Index**

When evaluating the two performance indicators, it is important to take other influential effects (e.g. change of EC itself) into consideration.

**Knowledge Management Index (KMI)**

Knowledge management index is a supporting indicator to identify the effectiveness and utilization of knowledge management system in ECM process by measuring the ratio of ECs that have been improved by referring to the system (Equation 11). With this system, the efficiency and effectiveness of propose phase can be improved. This performance indicator is applied for those ECM process equipped with a knowledge management system. If the result of this performance indicator is high, which means that the system is effectiveness and useful enough for the reference by engineers.

$$\frac{\mathrm{N_{Improved}}}{\mathrm{N^{Phase}_{Received}}} \times 100\%$$

$\mathrm{N_{Improved}}$ =Number of EC that has been improved with the reference to Knowledge Management;

$\mathrm{N^{Phase}_{Received}}$ = Number of Received EC in the phase.

**Equation 11: Knowledge Management Index**

**Average Degree of Interaction Difficulty (ADI)**

Average degree of interaction difficulty is a qualitative performance indicator used to describe the difficulty of interaction between different disciplines within propose phase. As discussed in previously that the communication and information sharing is vital for ECM process. This is especially important for propose phase because all the following ECM process are based on it. Nevertheless, the interaction difficulty can also reflect on the final quality of changed component and efficiency of overall ECM process. Therefore, if the quality of changed component is not good enough or the efficiency of overall ECM process is low, evaluator can use this performance indicator "ADI" as a reference to identify the area of improvement, in this case, is the interaction within propose phase.

$$ADI = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} \mathrm{DI_i}$$

DI=Degree of Interaction Difficulty with engineers

(1 to 5, 1 being easiest, 5 being most difficult)

**Equation 12: Average Degree of Interaction Difficulty (ADI)**

Definition of ADI is shown in Equation 12. It is calculated by averaging the degree of interaction difficulty, which is in a range between 1 to 5, where 1 represents the easiest to interaction while 5 represents hardest. Since this is also the subjective performance indicator, the result of ADI can be affected by factors such as personal feeling, etc.

**Information Sharing Efficiency Index (ISE)**

Communication and information sharing is essential for the implementation of EC. This is especially important for those ETO companies outsourcing most of their order fulfilment activities. The quality and efficiency of information sharing with supplier can directly affect the quality of supplied component, which eventually affect the quality of final product and customer satisfaction level. Therefore, two performance indicators were developed to measure the efficiency and effectiveness of information sharing within ECM process between suppliers and the companies. One is Information sharing efficiency index (ISE) and the other one is Average supplied component quality (ASCQ) that will be explained later.

Information sharing efficiency index is used to identify the efficiency of information sharing with supplier during EC implementation. It is a ratio of ECs that has been informed with supplier to ECs that should be informed (Equation 13).

$$\frac{N_{\text{Informed}}^{\text{Phase}}}{N_{\text{Supplier}}^{\text{Phase}}} \times 100\%$$

$N_{\text{Informed}}^{\text{Phase}}$=Number of EC that has been informed to supplier

$N_{\text{Supplier}}^{\text{Phase}}$ = Number of EC that suppler should be informed.

**Equation 13: Information Sharing Efficiency Index (ISE)**

The utilization of ISE should be combined with ASCQ that will be explained further.

**Average Supplied Component Quality (ASCQ)**

Average supplied component quality is an indicator to describe the quality of procured component from supplier. It reveals the extent that the quality of supplied components is agreed with specification.

$$\mathrm{ASCQ} = \frac{1}{\mathrm{N}} \times \sum_{\mathrm{i}=1,2,3\ldots}^{\mathrm{N}} \mathrm{Q}_{\mathrm{i}}^{\mathrm{S}}$$

$$\mathrm{Q}^{\mathrm{S}} = \text{Quality Degree of Supplied Component}$$

(1 to 5, 1 being worst, 5 being best)

**Equation 14: Average Supplied Component Quality (ASCQ)**

Definition of ASCQ is shown in Equation 14. It is calculated by averaging the quality degree of supplied component, which is in a range between 1 to 5, where 1 represents the worst quality while 5 represents the best. Since the quality degree of supplied component requires the evaluation by individual, the result of this performance indicator can be affected by factors such as personal feeling, etc. Hence, the evaluation of this PI should take this point into consideration.

The proposed two performance indicators: "ISE" and "ASCQ" are able to help to analyze the effectiveness and the efficiency of overall ECM process in terms of supplier related aspect. For example, supposed that there is an ETO company that outsources all their order fulfilment activities from manufacturing to assembling, and installation. If the KPIs "OPEI", "ALT", and "AQC" is low in performance, which means that the efficiency of ECM process is not good enough while the ECM process is not able to meet the requirement of product specification. In this case, evaluator can not only refer to the efficiency indexes for each ECM phase, but also refers to the two performance indicators: "ISE" and "ASCQ" that related to suppliers for the reference. If the performance of "ISE" and "ASCQ" is poor, then improvement should be executed in this area.

**EC Review Index (ERWI)**

Review of EC implementation is important. This is due to that review process provides the basis for learning and further improvement. Moreover, findings, experiences, lessons-learned, and tacit knowledge during the handling of EC can be collected during the process of review. For the purpose of encouraging company to review EC, EC review Index was proposed to describe the situation of EC review function within ECM process. With a ratio of reviewed ECs to archived ECs, the frequency of EC review can be identified (Equation 15).

$$\frac{N^{Phase}_{Reviewed}}{N^{Phase}_{Archived}} \times 100\%$$

$$N^{Phase}_{Reviewed} = \text{Number of Reviewed EC in the phase;}$$

$$N^{Phase}_{Received} = \text{Number of Archived EC in the phase.}$$

**Equation 15: EC Review Index (ERWI)**

It is important that high EC review rate does not necessarily means the high efficiency and effectiveness of ECM process, while the low efficiency and effectiveness of overall ECM process could probably result by the low EC review. Therefore, this performance indicator can just be used as the reference to identify the area of improvement. But still, ERWI can be used to improve the frequency of EC review activities.

Table 6-2 gives a summary of abbreviation, definition, unit, and attribute of each KPI and performance indicator for both overall ECM process and each phase within the process.
It is important to mention that these proposed indicators can measure EC according to their types, which makes the performance measurement and further improvement more specified. For example, all the data can be collected based on Grade-U ECs, which means that the performance of ECM process to handle "urgent" ECs is assessed and evaluated. In this case, the improvement can focus more on how to improve ability of ECM process to handle the urgent ECs and to make ECM process efficiency enough to handle this type of ECs. Another example can be the performance measurement on the process to handle Grade C ECs. Then the objective of improvement shifts from efficiency to effectiveness. In other words, the performance measurement on that type of ECs can answer the question such as "What is the ability of ECM process to handle product improvement and how can the process to maximize the benefits of this type of ECs".

It is important to keep in mind that proposed KPIs are used to measure and evaluate the overall performance of ECM, while performance indicators are dedicated for supporting decision making on where to improve among the entire ECM process, thus they focus on the performance of detail ECM activities. All KPIs and performance indicators are able to use separately but the value of these indicators can only be shown by using them together.

However, it worth mentioning that the results of performance indicators do not provide any suggestion on whether the current performance has been improved or not. It can only be figured out by comparing them with their corresponding targets or objectives. These targets or objectives can be the performance result collected in the last time or the best practice in the similar industry.

Despite that performance indicators were developed with their own measure objectives, their results do not necessarily mean the actual performance. A good example for this is "Average EC Implementation Delay". The poor result of this KPI does not necessarily means that the implementation of ECM process is inefficient. The bad performance can result from other influential factors such as late delivery of supplier's components, facilities break down, or strike of labor union. Therefore, the evaluation of the performance on certain indicators require further analyzing. Otherwise, wrong decision would be made.

The frequency and way of collecting and presenting the data is also important for the correct understanding of the performance of ECM process. Inaccurate or not-update-to-date results can lead to wrong decision which eventually reduce the performance of ECM process.

Last but not least, as mentioned early, the results of PIs themselves do not provide information about the performance of ECM process or solution to improve the performance. Further analysis or decision making are required for the purpose of improvement. However, since this is not the scope of this project, the way of data analyzing or solutions identification will not be discussed hereby.

Table 6-2 Summary of Performance Indicators

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| **Key Performance Indicators for overall ECM Process** | | | | | | | | |
| EKP1 | OPEI | Overall Process Efficiency Index | $\frac{N_{Finished}}{N_{All}} \times 100\%$<br>$N_{All} = N_{Finished} + N_{Unfinished} - N_{Rejected}$;<br>$N_{Finished} = Number\ of\ Finsihed\ EC$;<br>$N_{Unfinished} = Number\ of\ Unfinished\ EC$;<br>$N_{Rejected} = Number\ of\ Rejected\ EC$; | % | √ | | √ | |
| EKP2 | AELT | Average EC lead time | $\frac{1}{N} \times \sum_{i=1,2,3\dots}^{N} (D_i^{G4} - D_i^{G0})$<br>$D^{G4}$ = Actual Date when EC finish entire process (Reach Gate "4");<br>$D^{G0}$ = Actual Date when EC start entire process (Start from Gate "0"); | Day | √ | | √ | |
| EKP3 | EIDR | EC Implementation Delay Rate | $EIDR = \frac{N_{late\ implemented}}{N_{implemented}} \times 100\%$<br>$N_{late\ implemented}$ = Number of Late Implemented EC;<br>$N_{implemented}$ = Number of Implemented EC | % | √ | | √ | |
| EKP4 | AEID | Average Implementation Delay | $\frac{1}{N} \times \sum_{i=1,2,3\dots}^{N} (ID_i^{Actual} - ID_i^{Expected})$<br>$ID^{Actual}$ = Actual EC Implemented Date;<br>$ID^{Expected}$ = Expected EC Implemented Date | Day | √ | | √ | |

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| EKP5 | AEIC | Average EC Implementation Cost | $\frac{1}{N} \times \sum_{i=1,2,3\ldots}^{N} (IC_i^{Actual} - IC_i^{Expected})$<br>$IC^{Actual}$ = Actual EC Implemented Cost;<br>$IC^{Expected}$ = Expected EC Implemented Cost (Planned Budget); | Currency | √ | | √ | |
| EKP6 | ACCQ | Average Changed Component Quality | $\frac{1}{N} \times \sum_{i=1,2,3\ldots}^{N} Q_i^C$<br>$Q^C = Quality\ Degree\ of\ Changed\ Component$<br>(1 to 5, 1 being worst, 5 being best) | None | | √ | | √ |
| EKP7 | ECSI | EC related Customer Satisfaction Index | $\frac{1}{N} \times \sum_{i=1,2,3\ldots}^{N} CSL_i$<br>(CSL=Customer Satisfaction Level on ECM) | None | | √ | | √ |
| **Performance Indicators for Propose Phase** | | | | | | | | |
| P1 | EIP | Propose Phase Efficiency Index | $\frac{N_{Processed}^{Phase}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Processed}^{Phase}$ = Number of Processed EC in the phase;<br>$N_{Received}^{Phase}$ = Number of Received EC in the phase. | % | √ | | √ | |

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| P2 | AERT | Average EC Responding Time | $\frac{1}{N} \times \sum_{i=1,2,3...}^{N} (D_i^{G1} - D_i^{G0})$<br>$D^{G1} =$ Actual Date when EC finish proposing (Reach Gat );<br>$D^{G0}$ = Actual Date when EC start proposing (Start fro | Day | √ | | √ | |
| P3 | KMI | Knowledge Management Index | $\frac{N_{Improved}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Improved}$ =Number of EC that has been improved with the reference to Knowledge Management;<br>$N_{Received}^{Phase}$ = Number of Received EC in the phase | % | √ | | √ | |
| P4 | ERI | EC Rework Index | $\frac{N_{Reworked}^{Phase}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Reworked}^{Phase}$ = Number of Reworked EC in the phase;<br>$N_{Received}^{Phase}$ = Number of EC received in the phase. | % | | √ | √ | |

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| P5 | ADI | Average Degree of Interaction Difficulty | $\frac{1}{N} \times \sum_{i=1,2,3...}^{N} DI_i$<br>DI=Degree of Interaction Difficulty with engineers (1 to 5, 1 being easiest, 5 being most difficult) | None | √ | √ | | √ |
| **Performance Indicators for Approve Phase** | | | | | | | | |
| A1 | EIA | Approve Phase Efficiency Index | $\frac{N^{Phase}_{Processed}}{N^{Phase}_{Received}} \times 100\%$<br>$N^{Phase}_{Processed}$ = Number of Processed EC in the phase;<br>$N^{Phase}_{Received}$ = Number of EC received in the phase. | % | √ | | √ | |
| A2 | AEAT | Average EC Approving Time | $\frac{1}{N} \times \sum_{i=1,2,3...}^{N} (D^{G2}_i - D^{G1}_i)$<br>$D^{G2}$ = Actual Date when EC finish approving (Reach G<br>$D^{G1}$ = Actual Date when EC start approving (Start from (<br>. | Day | √ | | √ | |

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| A3 | ERJ | EC Reject Index | $\frac{N_{Rejected}^{Phase}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Reworked}^{Phase}$ = Number of Rejected EC in the phase;<br>$N_{Received}^{Phase}$ = Number of Received EC in the phase. | % | | √ | √ | |
| **Performance Indicators for Implementation Phase** | | | | | | | | |
| I1 | EII | Implementation Phase Efficiency Index | $\frac{N_{Processed}^{Phase}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Processed}^{Phase}$ = Number of Implemented EC in the phase;<br>$N_{Received}^{Phase}$ = Number of Received EC in the phase. | % | √ | | √ | |
| I2 | AEIT | Average EC Implementation Time | $\frac{1}{N} \times \sum_{i=1,2,3...}^{N} (D_i^{G3} - D_i^{G2})$<br>$D^{G1}$ = Actual Date when EC finsih implementation (Reac<br>.<br>$D^{G2}$ = Actual Date when EC start implementation (Sta | Day | √ | | √ | |

| No. | Abbreviation | Name | Definition | Unit | Efficiency | Effectiveness | Objective | Subjective |
|---|---|---|---|---|---|---|---|---|
| I3 | ISE | Information Sharing Efficiency Index | $\frac{N_{Informed}^{Phase}}{N_{Supplier}^{Phase}} \times 100\%$<br>$N_{Informed}^{Phase}$=Number of EC that has been informed to supplier<br>$N_{Supplier}^{Phase}$ = Number of EC that suppler should be informed. | % | √ | | √ | |
| I4 | ASCQ | Average Supplied Component Quality | $\frac{1}{N} \times \sum_{i=1,2,3\ldots}^{N} Q_i^S$<br>$Q^S = Quality\ Degree\ of\ Supplied\ Component$ (1 to 5, 1 being worst, 5 being best) | None | | √ | | √ |
| **Performance Indicators for Documentation Phase** | | | | | | | | |
| D1 | EAI | EC Archive Index | $\frac{N_{Archived}^{Phase}}{N_{Received}^{Phase}} \times 100\%$<br>$N_{Documented}^{Phase}$ = Number of Archived EC in the phase;<br>$N_{Received}^{Phase}$ = Number of Received EC in the phase. | % | √ | | √ | |
| D2 | ERWI | EC Review Index | $\frac{N_{Reviewed}^{Phase}}{N_{Archived}^{Phase}} \times 100\%$<br>$N_{Reviewed}^{Phase}$ = Number of Reviewed EC in the phase;<br>$N_{Received}^{Phase}$ = Number of Archived EC in the phase. | % | √ | | √ | |

# 7 Case Study

The case study was carried out to examine the current practice of ECM as well as the performance measurement on ECM in an ETO company. The data was collected through the survey and the meeting and discussion during company visit. People from different disciplines of the company such as engineering, procurement, supply chain management, and project management were involved. The details of the participant are shown in Appendix B. The analysis of the data was conducted by considering the findings identified during the literature review.

The structure of the remaining in this chapter are as follows. In Section 8.1, basic information about case company-Hycast will be briefly introduced. This is followed by ECs and ECM in case company in Section 8.2 and 8.3. Then the performance measurement in the case company will be presented in Section 8.4. In Section 8.5, the current practice of ECM and performance measurement on ECM will be discussed and challenges for ECM in case company will also be discussed.

## 7.1 Overview of the case company

Hycast AS was originally founded in 1990 with the company located in Sunndal, Norway, and has built a strong reputation in the aluminum casthouse business. With 50 employees and its turnover around NOK 196 Millions (about US$ 24 million), Hycast AS provides aluminum casthouse technology, solution, and equipment to aluminum companies around the world (Ødegård 2014; Hycast 2016).

The order fulfilment activities in Hycast AS includes sales and marketing, engineering, procurement, assembling and testing, installation and commissioning. Hycast AS focuses their core competencies within engineering (mechanical and electrical/automation), project management, and process know-how. Therefore, activities, namely sales and marketing, engineering, assembling and testing together with installation and commissioning are conducted by the resources of Hycast AS while manufacturing are conducted by external disciplines.

According to the category in Hycast AS, both standard and customized products are provided. However, despite of the name, the standard products are still adapted to some extent according to the customer requirement.

Table 7-1. gives an overview of general information about Hycast AS.

Table 7-1: General Information in Hycast

| **Employees** | **Turnover (Million)** | **Product** | **Customers** | **Customization** | **Depth of product structure** |
|---|---|---|---|---|---|
| 50 | 196.729 | Aluminum Casting Equipment | Aluminum Companies | High | Medium |

## 7.2 EC in case company

In Hycast, EC is defined as the modification to the specification, component, layout, function after the existing design has been completed and ready to release to production phase.

Averagely speaking, lead time for handling ECs from creation to finish can range from as short as one week to as long as six weeks, which depends on the complexity of EC in terms of impact and efficiency of processing. Usually, the lead time for those ECs initiated from customers has longer lead time than those initiated by Hycast AS itself due to the iteration during evaluation and approving process within customers.

### 7.2.1 Reasons and Occurrence Phase of ECs

Several types of ECs have been identified in Hycast while the phase they occur depends on their reasons of initiation. Based on the order fulfilment process in Hycast, the reasons of ECs are elaborated as follow.

In initial phase, ECs are initiated from sales and marketing department due to the need to clarify or modify the product specifications and scope. Additional sales can also result the initiation of ECs. For example, the requirement for the quantity of particulars products. During this phase, the engineering is just start for conceptual design, therefore, iterations are not count for ECs in Hycast AS.

The finished conceptual design is forwarded to customers to apply for confirmation. Due to the early start of engineering, ECs becomes unavoidable in order to meet final requirements from customers. Therefore, during this phase, ECs are initiated due to customer requirements and function adjustments by engineering department of Hycast. Regarding customer requirements, ECs are initiated because of the adaption to the equipment from other vendors. They can also be initiated due to the changed interfaces to other equipment and change of layout from customer decision. During this phase, it is important to have quick and accurate responses to those ECs from customer requirement in order to have a high customer satisfaction level. Therefore, the ECM should focus on the efficiency in process and accuracy in data interpretation.

After finalization of final design, the process is then moved to the procurement of components from suppliers since Hycast does not execute the manufacturing within their companies. Suppliers become the main EC initiator during this phase while the reasons of EC are error correction and change of design. Errors in the released drawings and specifications can be detected by suppliers of Hycast, which incur ECs. Moreover, supplier may propose ECs to the existing design in order to comply to their own technical specification or material requirement. For example, in one project, EC was initiated by supplier due to the lack of a certain dimension of pipe from their stock, therefore, the dimension of pipe need to change in the existing design.

The assembling starts internally after the receiving of purchased components. ECs are initiated due to error correction and quality problem regarding manufacturability and function failure. Errors in assembling documents and problem for manufacturability can be found during assembling. Example can be that the component does not fit each other during assembling. Also, the function failure can also be identified during internal testing. These types of ECs require immediate attention since assembling and testing are ceased because of problem, which may cause delivery delay eventually. Different from findings through literature study among ECM, EC initiated by customer requirement is rare in Hycast. This is because of the confirmation process between customers and company during the engineering phase. Another reason is because that most of the customers have a high maturity level, hence, there is a rare number of EC initiated from customers during assembling and testing phase in Hycast AS.

Commissioning and installation phase in ETO companies make it different from the companies follow other strategy. In commissioning and installation, the equipment is installed and operated in customer sites while, in most of the case, Hycast take the responsibilities. ECs occur in this phase are due to quality problem found during installation and operation. These ECs have greater impact than those ECs occur in other phase. One example is the wrong application of terminates box in a batch of products in one project. This quality problem was found during the commissioning and installation in the customer. It was found that the root cause for this was the wrong definition in the specification released to the supplier by Hycast. Another reason for the occurrence of EC during this phase is the customer requirement for adapting the product to to those from other vendors. But this kind of EC occur more often in standard product than customized product because of the less degree of customization and customer involvement.

Generally speaking, there are around 25 ECs remain unfinished within the system, while the number of ECs for standard product is much less than those for customized products. The weights of ECs in different phases and reasons between standard and customized products are shown in Table 7-2.

Table 7-2: Initiators and reasons of EC in Hycast

| Phases EC occur | Weight | | Reasons |
|---|---|---|---|
| | Standard | Customized | |
| Sales and Marketing | 20% | 15% | Unclear specifications, undefined scope, and additional sales. |
| Engineering | 40% | 50% | Customer requirements, and function adjustments. |

| | | | |
|---|---|---|---|
| Purchasing | 15% | 15% | Error corrections, supplier suggestions, quality problems. |
| Production | 15% | 15% | Errors corrections, quality problems. |
| Commissioning and Installation | 10% | 5% | Quality problems, Customer requirements |

### 7.2.2 Impact of ECs

Both negative and positive impact of ECs were identified in Hycast (Figure 7-1 and Figure 7-2), which are elaborated as follows.

Firstly, ECs in Hycast have noticeable negative impacts on daily production schedule. They affect the efficiency of organization and increase the manufacturing cost in a considerate degree. Averagely speaking, more than 2,000 working hours have been spent on developing and handling ECs. However, ECs scarcely delay the delivery plan and disrupt the morals and workshop. However, ECs do increase scrap and rework to some certain extent. However, the quality of final product is always guaranteed even if ECs occur.

Instead of the negative impact, ECs can also result positive impact by saving total production cost, as well as improving product quality and existing design. ECs can also reduce time of product, which can make the delivery behind schedule. A good example of the beneficial EC is the standardization of surface treatment in one component, which results saving in both time and money. However, comparing with those ECs causing short-term negative impact, the impact of those beneficial EC can mostly be observed in the long run.

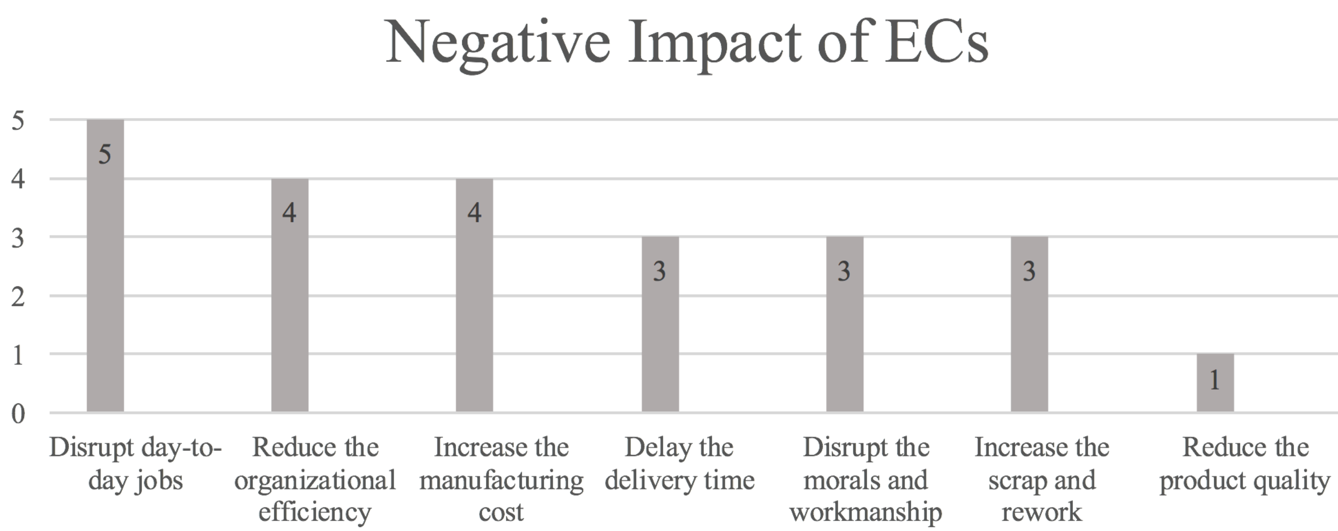


**Figure 7-1: Negative Impact incurred by ECs. (5 being major, 1 being minor)**

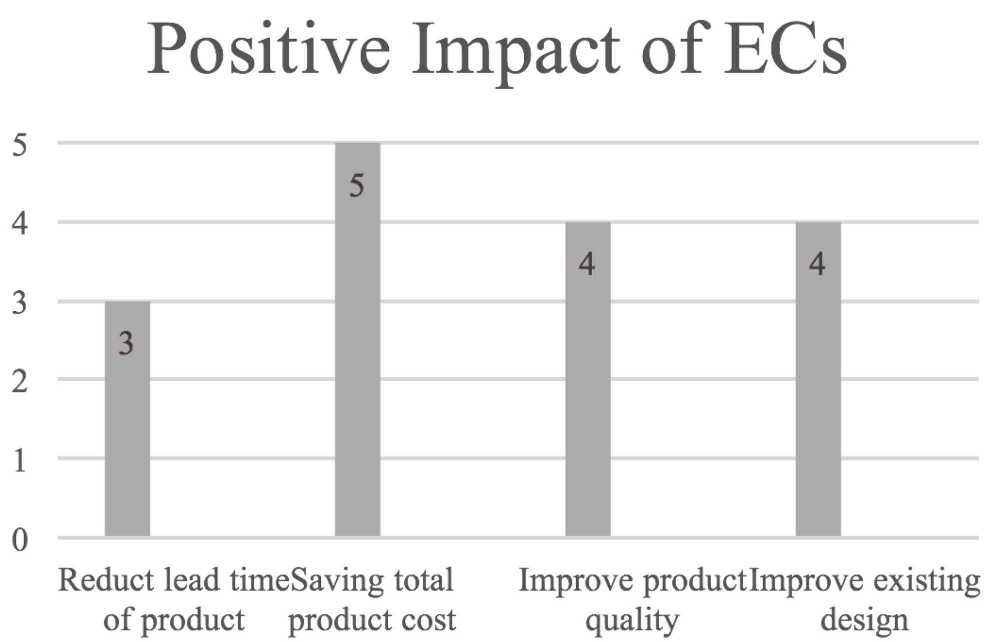


**Figure 7-2: Positive Impact incurred by ECs. (5 being major, 1 being minor)**

## 7.3 ECM in case company

During the interview, the attributes towards ECM in Hycast is divided. There is no unified conclusion on whether their current practice of ECM is good or not.

### 7.3.1 ECM Process

There are both formal and informal ECM process in Hycast so far. The formal ECM process deal with those ECs from customers, while the informal one deal with ECs from internal disciplines and suppliers. The formal ECM process in Hycast can be described by a four-steps flow chart, which is shown in Figure 7-3.

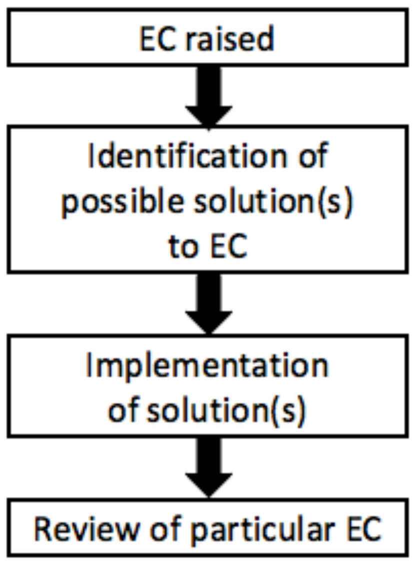


**Figure 7-3: Engineering Change Management Process in Hycast**

The formal ECM process starts with the raise of EC from customer, if it is approved by technical manager or technical engineer, then the potential solutions are identified by engineering department. Those potential solutions are forwarded to customer to get approval. If solutions are approved, then the EC will be implemented and related documents (e.g. drawings, cost and delivery plan) will be updated. The decision on when to implement EC is based on the question on whether the particular EC require reengineering on the product or apply the EC in as-built. The formal ECM process is ended with the review of particular EC to evaluate the implementation situation.

For the informal process, there is no pre-defined process within Hycast. It is based on informal communication such as email, phone call, meeting internally.

It worth mentioning that Hycast now is implementing a new product lifecycle management (PLM) system called Sovelia. By the time this thesis was completed, this system has only been implemented in mechanical engineering department. However, the ECM process embedded in the system has not been implemented in any of the discipline yet. Since Hycast AS planned to start using Sovelia system by the end of this year, therefore, it is also necessary to elaborate the ECM process embedded in the new PLM system as well. Figure 7-4 shows the flow of ECM process in the new system, which is summarized based on the technical specification from Sovelia system (Appendix D).

There are two sub-process within ECM process in Sovelia system, namely engineering change request (ECR), and engineering change order (ECO). A decision gate is located between the two processes to decide whether to continuous the flow in ECO process. States of ECR and ECO are developed as shown in the left column to identify where the particular EC is located within the ECM process.

ECR process is the pre-approving process before ECO process. Actually, there is no change implemented during this phase, only simple approving is executed. ECR process starts with the create of ECR where general information of EC regarding description, affected object, status, reasons, and potential solution is collected in ECR form. Then ECR is submitted to the review process and information is visible for the reviewer. A notification of the arrival of ECR will be sent to ECR approver. The ECR process is ended up when decision is make on whether ECR getting approved or rejected. A decision notification will be sent to ECR creator in either of the decision. If ECR is approved, it will be later implemented by creating a new ECO based on the information provided in the approved ECR. If it is rejected, it will be documented by the system for further reference.

ECO process is the main object in ECM process in Sovelia. ECO form carries the information about the change; reason, description, affected items and documentation and responsibilities. An important function of ECO process is to inform necessary disciplines about the EC and getting them involved in approving and implementation processes. ECO process start with the creation of ECO, information mentioned previously is inputted in the ECO form. Then ECO together with a notification are sent to controller who will then assign the designer to finish the potential solutions on existing design. The new design is linked to this ECO by designer and then submitted to controller again to execute data check. After the data check, ECO and a notification will be forwarded to approving. Designer will get an notification about the decision from approver and finalize the design and product definition and then release the ECO. Disciplines such as production, procurement, sales that are impacted by ECO will be informed by the system to implement ECO. ECO is closed after being implemented.

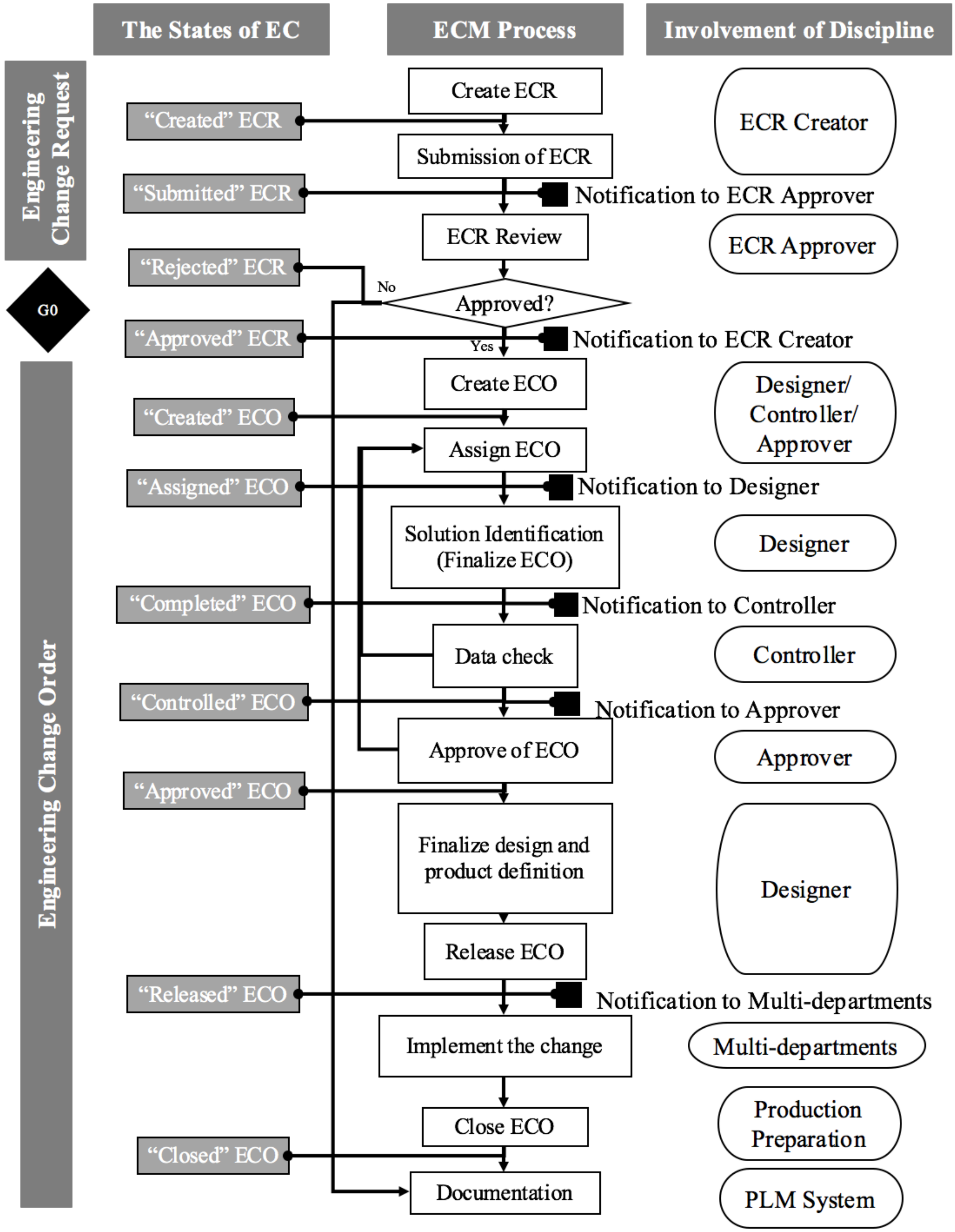


**Figure 7-4: Summary of New ECM Process in Sovelia**

### 7.3.2 Organizational Structure

In Hycast, there is no specified person takes the responsibility of EC coordinator. Instead, EC initiators are take charging of the ECs they initiated. Technical manager is responsible for approving ECs which has impact on functionality. Other ECs are approved by corresponding managers.

Meetings for EC are held when necessary in Hycast. They are used to make decision on those ECs with greater impact. During the meeting, alternative solutions will be discussed and a concrete solution will be identified and impact will be evaluated. As mentioned early, the decision on when to implement the EC depends on whether it can be applied on the as-built or reengineering. People from engineering, purchasing, production, supply chain management and project management are the main participants of this meeting. In some circumstance, customers will also be invited if EC has impact on them.

### 7.3.3 Tools Used to Support ECM

An enterprise resource planning (ERP) system is using currently in Hycast AS. However, this system is not applicable to manage EC. EC in Hycast is now handled manually. Spreadsheet is the tool used now to support and document EC. There are three types of spreadsheet: the first one is for change history, it documented change log with proposals for improvements, the second one is for quality problem detected during assembling and testing with suggestion, improvement and deviations for them. The last one is for project planning with particular EC impacted on it. There are no linkage between three document and they are updated manually. This way of ECM can result error and information deficiency, which reduce the efficiency and the effectiveness of ECM as well as engineering process.

In Hycast, communication and information sharing for ECM are via email, phone call, personal discussion and meeting. There is no tool to capture and document the experience, knowledge, and know-how during ECM process.

As mentioned in Section 7.3.1 that a new PLM system embedded with an ECM process will be implemented by the end of this year. According to categories proposed by Huang & Mak (1998) mentioned in Section 5.2.1, it belongs the third type of tools, which is the most beneficial one that can improve the profits and keep competitive advantages. Function within the system can highly support ECM. For example, the configuration management function can help to identify change propagation during evaluation. It can identify all the propagated product and component and their parent components and product. In ECM function, there is a clear ECM process, as mentioned in Section 5.2.1, to handle all ECs. Electronic form can be used during ECM process not only to document the EC information but also help to track EC for further reference. The form can also be applied to define the roles of people such as EC coordinator, designer, and approver; department in charge of EC; as well as disciplines that should be informed when implement EC. Additional data fields can also be attached automatically if there is any comment, data and useful information.

## 7.4 Performance Measurement in Case Company

Performance Measurement is applied in Hycast. However, instead of focusing on ECM process, the performance measurement used currently focus on overall performance of the company in terms of the output. Three KPIs are used now, which will be explained as follow.

**Number of engineering hours per million NOK.** This KPI is used to measure the engineering time spent per million NOK that Hycast sales. It reveals the cost in terms of time.

**Total cost of project including production and engineering.** This is a subjective KPIs based on project used to measure the cost spent on delivery a project.

**Number of deviation from plan.** The deviation in this KPI refers to the difference between real situation and expectation or plan in terms of time, cost, customer requirement and technical specification.

It is obvious that the current KPIs are used to measure the output the activities conducted in Hycast AS. And these KPIs are project based. Since the difference between project to project, it is really difficult to reveal the performance of the company by comparing between project. Hence, it is better to categorize project with similar characteristics and features and comparing the performance within the categorization.

## 7.5 Discussion of Case Company and Challenges

In this section, the current practice of case company regarding ECM will be discussed based on the findings from literature and case study. Then the challenges for ECM in case company will be summarized at the end of this section, which direct the work for the application of new methodology in the case company.

The definition of EC used in Hycast AS currently gives a clear scope, which is able to distinguish the EC from iterations especially during engineering phase. This distinguishment helps to reduce the workload of ECM and release more capacity to other engineering activities in the company.

In Hycast, the reasons of ECs are highly dependent on the phase they occur. ECs occur in the engineering phase were mostly for improving the existing design while those occur in the later phase were for correct the failure and error caused in the early phase. These features agree with the finding from literature review. However, difference is that, in Hycast, most ECs occur in the engineering phase. The difference is due to, firstly, early start of engineering. Since there is still information missing in the early stage of engineering, therefore, ECs are avoidable in order to meet the requirement from customers. Secondly, high degree of customer involvement during engineering phase, which are one of the major reason for EC occurring in the phase. Thirdly, the confirmation process between customer and Hycast AS, which work as the design freeze function. This process helps to clarify the design provided by Hycast and eliminate the occurrence of EC from customer requirement during manufacturing and assembling phase. Last but not least, a higher maturity level of customer who do not change their design very often, thus reducing the number of EC occur after the release of design.

Both positive and negative EC impact were identified in Hycast. In most case, ECs can disrupt plan and schedule, increase the cost while reduce the efficiency within the company. On the contrary, ECs can also result cost-saving, product quality and design improvement, and project lead time reduction. However, it takes time to see the benefits of EC while the negative impact caused by ECs is more obvious. Furthermore, since the various influential factors can eventually make those ECs not as beneficial as they were supposed to be. Therefore, it is the reason why most of the literature on ECM consider EC as the problem rather than the improvement. It is highly suggested that method for ECM should be able to maximize the benefits of ECs instead of only treating them as a problem.

Currently, there is no formal and well-structured ECM process and supportive system to handle EC, hence, the knowledge and experience learned from ECM process cannot be captured and stored. It is a challenge for Hycast since the company take the process know-how and the experience from other projects as their core competence. Moreover, without the formal and well-structured ECM process to evaluate and manage the impact caused by EC, the product quality, planned schedule and cost can be affected, which reduce the capability of project management that was considered as the core competence by Hycast AS as well.

The lack of formal and well-structured ECM process and system for handling ECs can be explained by the different opinion about the current practice of ECM in the company. During the interview, participants did not have the coincide opinion whether their current ECM and its process was in good practices or not. A few participants are not aware that ECM process is a problem for them. These divided opinions left the ECM process in an unstructured way for many years.

Second reason for this gap can be lack of resource and capacity. According to one of the interviewees, some of the management realized that the current ECM and its process is not good enough, however, the company do not really have time, resource, and effort to improve it in the past few years. It is true that the occurrence of EC in the company might consume majority of the capacity in the engineering and production. Therefore, the attention can be only focused in those most important ECs initiated from customers.

Another reason for this gap is that the benefits of a formal and well-structured ECM process have not been realized by the company. ECM can improve the performance in cost, time spent during order fulfilment process as well as make sure the quality of product to the customer. However, as mentioned early, it takes time to see the benefits of EC while the expected benefits can be reduced by various influential factor during implementation. Hence, the company does not truly realize the reason why they should implement a formal and well-structured ECM process.

Since the new PLM system is now implementing in the company, the ECM system embedded within the system can fill in this gap regarding the lack of a formal and well-structured ECM process for handling ECs. With a clear and predefined ECM process, it is possible for the company to evaluate the impact of EC and implement according to their own characteristics, which can maximize the benefits of ECs while minimize the negative impact. The new ECM process within the system can also allow user to monitor and control the progress of EC within the handling process by showing where they are. The computer-aided ECM also provide documentation and traceability of ECs, which helps to capture and store knowledge from ECM as well as provides the basis for the reference. The system can send the notification for the arrival of EC to the related person during ECM process, which reduces the chance of unawareness and waiting. It is hard to determine who should be involved within the ECM process. The new ECM system provides the function that user can predefined the roles of responsibilities so that right person can be involved in the ECM process in the right timing.

However, drawbacks of new ECM system still exist. Firstly, according the technical specification, the new ECM process is not flexible enough to handle different types of EC in terms of types, reasons, impact, priority according to their own characteristics. In other words, all ECs will still go through the same ECM process. Moreover, there is no classification for ECs in Hycast AS right now, which make it more difficult to handle and implement ECs according to their own characteristics.

Secondly, there is no step for impact analysis within the new ECM process, therefore, it is highly recommended that this step should be included in the new PLM system and integrated with the ERP system used in Hycast AS currently to ease the information exchange and reduce the error that could occur during data transfer.

Thirdly, since ECM is the cross-disciplines activities, there are different system and goal between different discipline. This is especially important between the company and their customers and suppliers. Therefore, new ECM process need to consider the integration between different disciplines both internally and externally.

Fourthly, there are ECs in commissioning and installation phase. Since the activities are executed in customer site, therefore, it is difficult for engineer to initiate EC within ECM process that just assess internally. Therefore, an interface that can be assessed from the field is essential.

There is no EC coordinator in Hycast AS currently. This is not a big problem so far since the EC initiator is acting as EC coordinator. However, it is necessary to have an EC coordinator after the implementation of new ECM system since the person can work as the consultants to answer the questions during the operation of the new system while coordinate the ECM activities among different disciplines internally and externally. EC coordinator should familiar with the product and the technical issues in Hycast but also has the knowledge of the project management. The person should also have the understanding of the new ECM system and process within it.

ECM meeting in Hycast now is held as necessary and the function of the meeting is to make decision on a particular EC. It is highly suggested that ECM meeting should hold regularly, and the function should not be limited in decision making but also include planning and review the EC implementation as well as evaluate the performance of ECM process.

When it comes to performance measurement, Hycast AS is not applying any measurement on the performance of ECM process currently. There are four reasons for this gap. Firstly, lack of unified opinion on the current practice of ECM. There are divided opinions on whether ECM in the company is a problem or not. Since the unified opinion has not been achieved, the performance measurement is not necessary to apply. Secondly, lack of the awareness on the benefits of performance measurement for ECM. Despite that a few participants of the interview considered that the ECM process was not good enough, they do not either realized the reason and benefit to apply performance measurement on ECM. Thirdly, difficulty in data collecting. Since the current ECM process was conducted manually and there is no clear and formal ECM process to handle ECs in Hycast AS, it is really hard for anyone to collect data from such deficient system. Fourthly, lack of enough power to make change on configuration of the organization, which was mentioned by one of our participants from the interview. The aim of performance measurement is to evaluate the current performance and detect where to improve. This kind of decision and improvement can only be possible for the authority that have power on changing the configuration.

Considering the application of new ECM process, it is essential for Hycast to have performance measurement on ECM process. It can be applied not only for measuring performance of ECM process and make-decision on where to improve but also helps to lower the cost and time for engineering, spare the engineering capacity, ensure a high product quality, and maintain a high customer satisfaction level. Nevertheless, the performance measurement on ECM process can also be applied to reveal the implementation state of new system.

Based on the discussion of the current practice of ECM, the challenges for ECM can be summarized as following.

1. There is a low awareness in the current practice of ECM as well as the benefits of improving ECM process.
2. There is also a low awareness in the performance measurement on ECM and the benefits of using it.
3. There is no formal, clear, and well-structured ECM process to handle ECs.
4. A classification mechanism for ECs and ECM process is missing for handling ECs according to their own characteristics.
5. Roles and responsibilities of the actors need to be defined in ECM process to ensure the right involvement of people in the right timing.
6. Impact analysis in terms of change propagation, product quality, cost, and plan schedule is missing in the new ECM process. The integration between new ECM system and existing ERP system is also missing.
7. There is no interface to handle EC from field (commissioning, installation etc.) is missing.
8. No EC coordinator to control and coordinate activities within ECM process.
9. ECM meeting is for decision making only, and it is held irregularly.
10. There is no performance measurement conducted for ECM, only project performance is measured.

# 8 Applying the New Methodology on Case Company

The current practice and challenges of ECM in case company motive the application of the new methodology on the case company. The new methodology was tailored according to the features and requirements from the case company. The solution is structured into two part. In Section 8.1, new ECM process was developed and elaborated. In Section 8.2, the corresponding performance indicators are tailored based on the new ECM process and the characteristics of the case company. The combination of two section form the new ECM method for the case company.

## 8.1 Proposing New ECM Process

The new ECM process was developed based on the new ECM process within PLM system in Hycast AS together with the reference framework proposed in Chapter 6.1. It is shown in Figure 8-2. As the core mechanism of the new ECM process, the new classification and its corresponding new matrix for ECM will be explained first.

### 8.1.1 New EC Classification.

The classification mechanism was tailored according to the characteristics of EC in the case company. The two dimensions: impact and priority are still applied in mechanism. However, different from the original one, categories in both impact and priority dimension was adapted according to the real situation. The details will be elaborated as follows.

**New Impact Dimension**

Impact dimension is used to differentiate the impact incurred by EC in terms of design, change propagation, product, and production. It identifies to which extent the decision-making mechanism should be involved. There are two categories in the impact dimension instead of three in the original proposals. The new categories are developed according the impact caused by EC in the case company. The criteria that whether the EC can be applied in the as-built or requires reengineering of product was taken into consideration. The new categories are more suitable for the characteristics of EC in the case company.

Type 1 - "High". This category is similar to "multipliers" in the original proposal. As the name described, this type of ECs has high impact on part, component, and final product. The impact can be both positive and negative. The initiation of this type of ECs can cause change propagation in a considerable level. In this case, the existing design require reengineering. And the produced parts, components, product need to scrap or rework in a serious degree. The assembling or manufacturing in the supplier site have to stop to wait the release of new design.

Type 2 - “Low”. This category is similar to “carriers” in the original proposal. These ECs cause modest degree of impact on part, component, and final product. Instead of reengineering, ECs belong to this type can be applied in the as-built, therefore, modification on the existing design is required. In production level, no scrap will be result only rework is required. Therefore, the order fulfilment activities are disturbed in a modest and controllable level.

**New Priority Dimension**

Priority dimension is used to describe how urgent EC should be handled. They reflect the nature of ECs in terms of the urgency. The original four categories are combined into two categories, namely convenient and urgent.

Grade U - “Urgent”. This new category is the combination between “Urgent” and “Error” in the original proposal. ECs belongs to “Urgent” are those most urgent in priority and should be implemented immediately. Safety reason, quality problem, error correction can be the reasons of this categories. The evaluation and implementation of those ECs should focus on time efficiency rather than cost, since the later implementation of these ECs could cost even huger impact not only on the final product but also on the company.

Grade C - “Convenient”. This new category is the combination between “Mandatory” and “Convenient” in the original proposal. ECs belongs to “Convenient” are those less urgent in priority and the evaluation and implementation of this types of EC can wait for a certain period of time or process in batch. Customer requirement, supplier suggestion, function adjustment, innovation and optimization can be the reasons of this type of ECs. The evaluation and implementation of Grade C ECs should focus on minimizing the negative impact on cost and time, while maximizing the positive impact on product, quality, cost and ECM.

It is important to mention that the all of the categories in both dimension have no direct relationship with the reason of ECs. Therefore, EC initiators should evaluate the dimension in an objective perspective instead of focus on their own goals.

Table 8-1 gives a summary of the characteristics in the new categories of both dimension.

Table 8-1: Characteristics of EC categories in impact and priority dimension.

| Dimensions | Categories | Characteristics |
|---|---|---|
| **Impact** | Type 1: "High" | • Severe in impact in terms of cost and/or time etc.<br>• Require reengineering on the existing design.<br>• Change propagate to other components in a serious level.<br>• Cease of order fulfilment activities.<br>• Cause scrap and rework of produced parts, components, and products. |
| | Type 2: "Low" | • Modest impact in terms of cost and/or time etc.<br>• Can be applied in the as-built with modification on the existing design.<br>• Change propagate to other components in a modest level.<br>• Interrupt order fulfilment process.<br>• Require rework of produced parts, components, and products. |
| **Priority** | Grade U: "Urgent" | • Most urgent in evaluation and implementation.<br>• Require implementation immediately.<br>• Focus on time efficiency despite of high cost. |
| | Grade C: "Convenient" | • EC has less urgency in the implementation.<br>• Implementation can be hold to wait for best timing.<br>• Evaluation and implementation focus on cost efficiency while maximize the benefits. |

### 8.1.2 New Matrix for ECM in Case Companies.

The new matrix for ECM in case companies is shown in Figure 8-1. Instead of 12 types of ECs, there is only 4 types of ECs in the new classification. Three strategies are applied to deal with corresponding type of EC. "Board Track" was removed to adapt the real situation in case company.

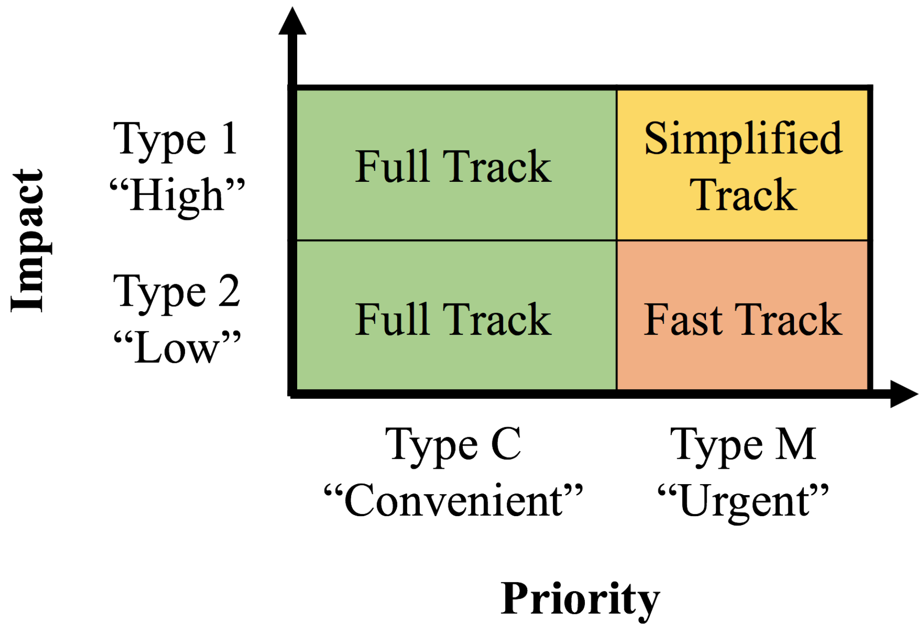


**Figure 8-1: Adapted Matrix for ECM in Hycast**

**Full Track**

Full Track refers to ECM process with the full approving process and cost efficiency. The strategy of "full track" can be applied for ECs belongs to type "1C" and "2C". To approve these ECs, they require the decision making from both disaggregated and aggregated level. In other words, evaluation go firstly by related engineers from different departments, then by ECM meeting. In the case company, engineer from engineering, procurement, production, supply chain management, and project management should be involved in the initial approving and then ECM meeting should be hold to make the final decision. For the implementation, since those ECs mostly have huge impact and more flexibility in time, therefore, the implementation of those ECs can be held for the best timing or process in batch. During implementation, cost efficiency should be valued far more than time efficiency in order to minimize the negative impacts of ECs and maximize the benefits.

**Simplified Track**

ECs belongs to type "1M" should follow the strategy of "Simplified Track". Due to the content of these ECs, the approving process should be as simple as possible. In this case, EC initiator, technical manager, procurement manager, project manager and supply chain manager should be involved in the approving process separately instead of holding meeting. Communication between each approver is also essential. The implementation of ECs should focus on time efficiency despite the high cost in implementation. In other words, the implementation should try to minimize the negative impact caused by those ECs as much and fast as possible.

**Fast Track**

"Fast Track" is applied to ECs belongs to type "2U". Since there is a modest level of impact caused by those ECs. Therefore, the people involved during approving process should with a lower level of authority than" Simplified Track". In this case, EC initiator, engineers from engineering and procurement, as well as project manager should be involved in the approving process. The EC implementation follow the same strategy as "simplified track" that the efficiency in time is more important than the cost.

Table 8-2 summarized the different characteristics in each strategy.

Table 8-2: Characteristics of Different Strategies in Adapted Methodology.

| **Attribute** | **Full Track** | **Simplified Track** | **Fast Track** |
|---|---|---|---|
| Involvement of people in approving process. | Disaggregated authorities: EC initiator, engineer from engineering, procurement, production, supply chain management, and project management.<br><br>Aggregated authorities: | EC initiator, technical manager, procurement manager, project manager and supply chain manager | EC initiator, engineers from engineering and procurement, as well as project manager |

| | | | |
|---|---|---|---|
| | ECM meeting by managers from different disciplines. | | |
| Implementation Focus | Focus more on cost efficiency than time efficiency.<br>Waiting for best timing or process in batch. | Focus more on time efficiency despite the high implementation cost.<br>Implemented immediately. | Focus more on time efficiency despite the high implementation cost.<br>Implemented immediately. |

### 8.1.3 Proposing ECM Process

New ECM process for the case company (Figure 8-2) is adapted on the ECM process embedded in the new PLM system by referring the reference framework developed in Section 6.1.3. The processes with improvement was highlighted with the stars.

Since the process in new PLM system has already been explained in Section 8.3.1, the unchanged process and function will not be presented again in this section. Only improvements will be explained further.

With the introduction of new classification mechanism, new ECM process is able to treat ECs according to their own characteristics. Therefore, impact and priority dimension should be assigned to the form of both ECR and ECO when they are created. Initiator should assign the dimension according the standard criteria listed in Table 8-2 instead of focus on their own goal and experience.

Roles and responsibilities of the actors in the each ECM process should be defined to get right people involved in the right process. In the "ECR review" step, manager of initiator should be the approver since ECR process is just a pre-approval process which used to evaluate the whether the certain EC should be implemented or not. Therefore, the decision from the initiator's manager is enough for this phase.

Instead of the involvement of designer only, more people should be involved during solution identification and impact analysis. Participants of the discussion in the case company can be engineers from engineering, purchaser, and production department in order to have a sophisticated solution and impact analysis. This involvement of people from different disciplines can also reduce the chance of iteration.

The approving process is most complex step among others. The roles of actors in approving process are different according to the strategy that EC belongs to. Details can be found in Table 8-2, therefore, it would not be explained further.

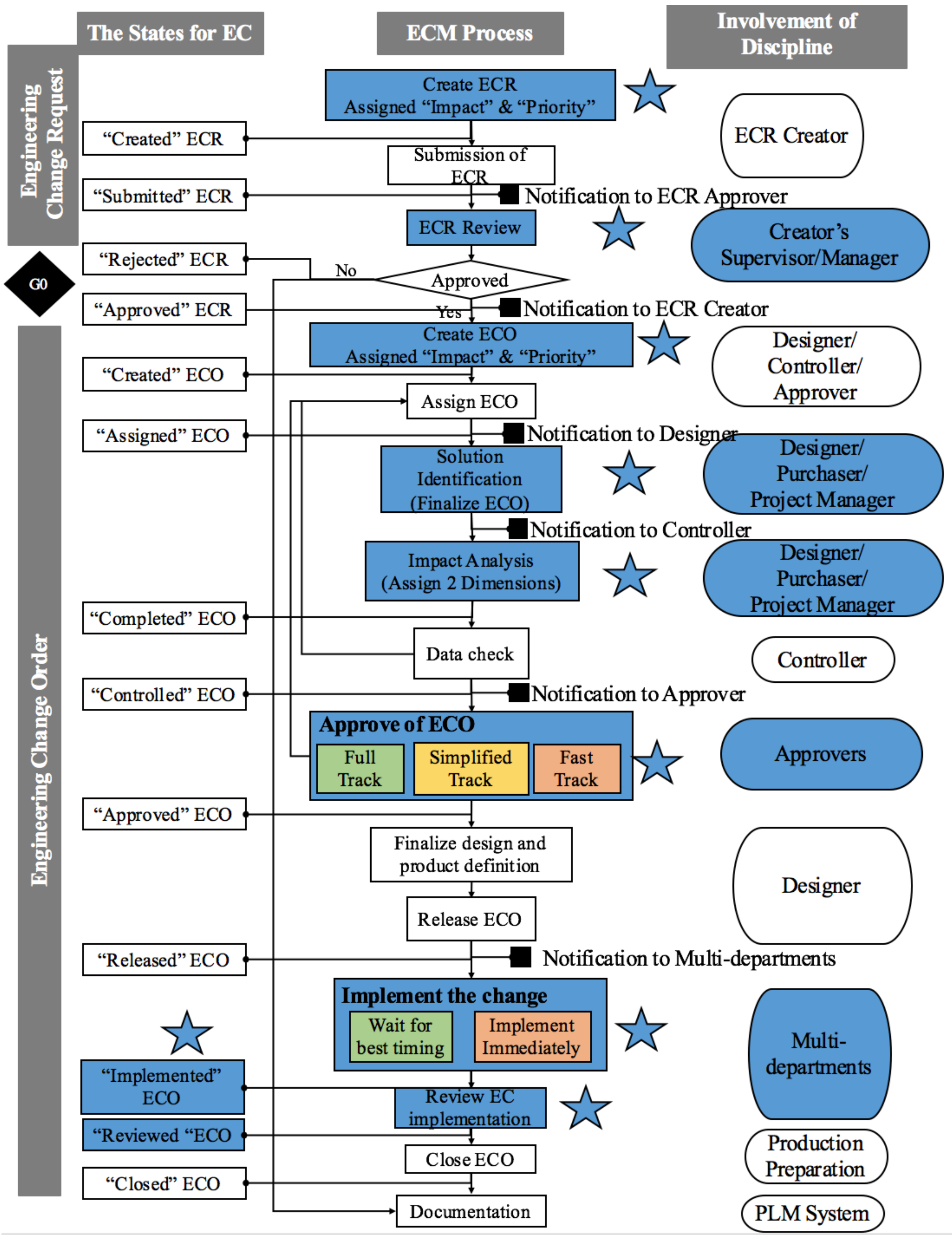


**Figure 8-2: Adapted ECM Process in Hycast**

The step “Impact Analysis” was proposed after the “solution identification”. Despite the position of this step, the two activities happen synchronously. The result of impact analysis should be attached in data field within the corresponding ECO form and ERP system, which provides the reference for approver to make decision in the approving process and implementation during production. During impact analysis, priority and impact dimensions are reevaluated, and change can be made if it is necessary. This reevaluation provides the accurate criteria in terms of priority for the implementation in the later step.

The implementation of ECO in the new proposal follows the strategy explained in Section 9.1.2, hence it would not be explained in here again. It is important to mention that a new ECO state is created named “Implemented ECO” to indicate that ECO has been implemented and ready to move to the next step.

The step “review EC implementation” is suggested for the company to review the implementation of EC, while knowledge and process know-how can be captured by doing so. This information can be used for the further reference if the similar EC occur again. They can also increase the competitive advantage of the company since the extensive experience and the process know-how are regarded as the core competence by Hycast AS.

## 8.2 Proposing Performance Indicators for ECM

In Hycast, no performance measurement for ECM is applied recently. Moreover, there is a low awareness in the performance measurement on ECM and the benefits of using it in Hycast. A set of performance indicators both in overall and local level is selected and adapted according to the findings from case company. Table 8-3 gives an overview of the descriptions and limitations of these performance indicators while Table 8-4 gives an overview of the definitions, units of these performance indicators.

The performance indicators proposed for case company focus mainly on measuring the efficiency of ECM process. The focus on efficiency is due to the easy accessibility of data, which would not complex the ECM process at all. If the data collection is too difficult, the company might be reluctant to apply. Therefore, the process of implementation performance measurement on the case company should start with those performance indicators that are easy to apply. Because of the application of new ECM system, the data required in these performance indicators is easy to collect by adding some formula in the system.

However, there is still a KPI named "Average EC Implementation Cost" was proposed, it is used to assess the effectiveness of ECM process in terms of cost. The KPI was proposed based on the attitude towards ECM and performance measurement in the company, which is the output is valued more than the process.

It is important to mention that the proposed performance indicators are based on the new classification mechanism proposed previously in this chapter. Therefore, the performance in both overall and separated ECM process can be categorized by impact and priority dimensions.

Table 8-3: Key Performance Measurement for EC Process

| No | Abbreviation | Name | Description | Limitation |
|---|---|---|---|---|
| **Key Performance Indicators for overall ECM Process** | | | | |
| EKP1 | OPEI | Overall Process Efficiency Index | Identify the efficiency of overall ECM process to handle EC with the ratio between closed ECOs with number of created ECRs in the system. | For overall performance, not very helpful for improvement in separate EC step. |
| EKP2 | AELT | Average EC lead time | Measure the average time spent for ECs to go through entire process. Quantitative metric to reveal the efficiency of overall ECM process. | It is an absolute metric, which requires further comparison. |
| EKP3 | AEID | Average EC Implementation Delay | By comparing the actual implementation date with the due date, it measures the efficiency of ECM process in terms of time. | Other influential factors (e.g. stroke, or power failure) should be considered. |
| EKP4 | AEIC | Average EC Implementation Cost | By comparing the actual cost with expected cost, it measures the effectiveness of overall ECM process in terms of cost. | Other cost factors within implementation (e.g. exchange rate) should be considered. |
| **Performance Indicators for ECR** | | | | |
| ERP1 | REI | ECR Phase Efficiency Index | Identify the efficiency of handling EC in ECR phase with the ratio of processed ECs to received ECs in this phase. | Disaggregated PI, sub-optimization should be avoided. |
| ERP2 | ART | Average Responding Time | Measure the time spent on responding to change request from created to approved. | An absolute metric requires measuring goal. |
| **Performance Indicators for ECO** | | | | |
| EOP1 | OEI | ECO Phase Efficiency Index | Identify the efficiency of ECO phase with the ratio of processed ECs to received ECs in this phase. It can be broke down by different urgency grade. | Disaggregated PI, sub-optimization should be avoided. |

| No | Abbreviation | Name | Description | Limitation |
|---|---|---|---|---|
| EOP2 | EEI | Evaluation Efficiency Index | Identify the efficiency of finish EC with the ratio of completed ECs to assigned ECs in this phase. It can be broke down by different priority | Disaggregated PI, sub-optimization should be avoided. |
| EOP3 | AET | Average Evaluation Time | Time spent for finish EC in average. It can be broke down by different priority grade. | An absolute metric requires measuring goal. |
| EOP4 | AEI | Approve Efficiency Index | Identify the efficiency of approving EC with the ratio of approved ECs to controlled ECs in this phase. It can be broke down by different priority | Disaggregated PI, sub-optimization should be avoided. |
| EOP5 | AAT | Average Approve Time | Time spent for approving EC in average. It can be broke down by different priority grade. | An absolute metric requires measuring goal. |
| EOP6 | IEI | Implementation Efficiency Index | Identify the efficiency of approving EC with the ratio of implemented ECs to released ECs in this phase. It can be broke down by different priority grade. | Disaggregated PI, sub-optimization should be avoided. |
| EOP7 | AIT | Average Implementation Time | Time spent for implementation EC in average. It can be broke down by different priority grade. | An absolute metric requires measuring goal. |
| EOP8 | ERI | EC Review Index | A quantitative metric measure used to reveal the situation of EC reviewing function. It is a ratio of reviewed ECs to closed ECs. | Difficult to have data collecting if ECM is paper based. |

To make these performance indicators easier to understand and use, the dashboard of performance measurement for ECM can be applied to give the management a simple and easy way of assess the performance of current ECM process. The dashboard can be developed based on the new ECM system that would be applied recently. Figure 8-3 to 8-6 shows the examples of the dashboard with different tabs to reveal both overall and local level of performance measurement in ECM process.

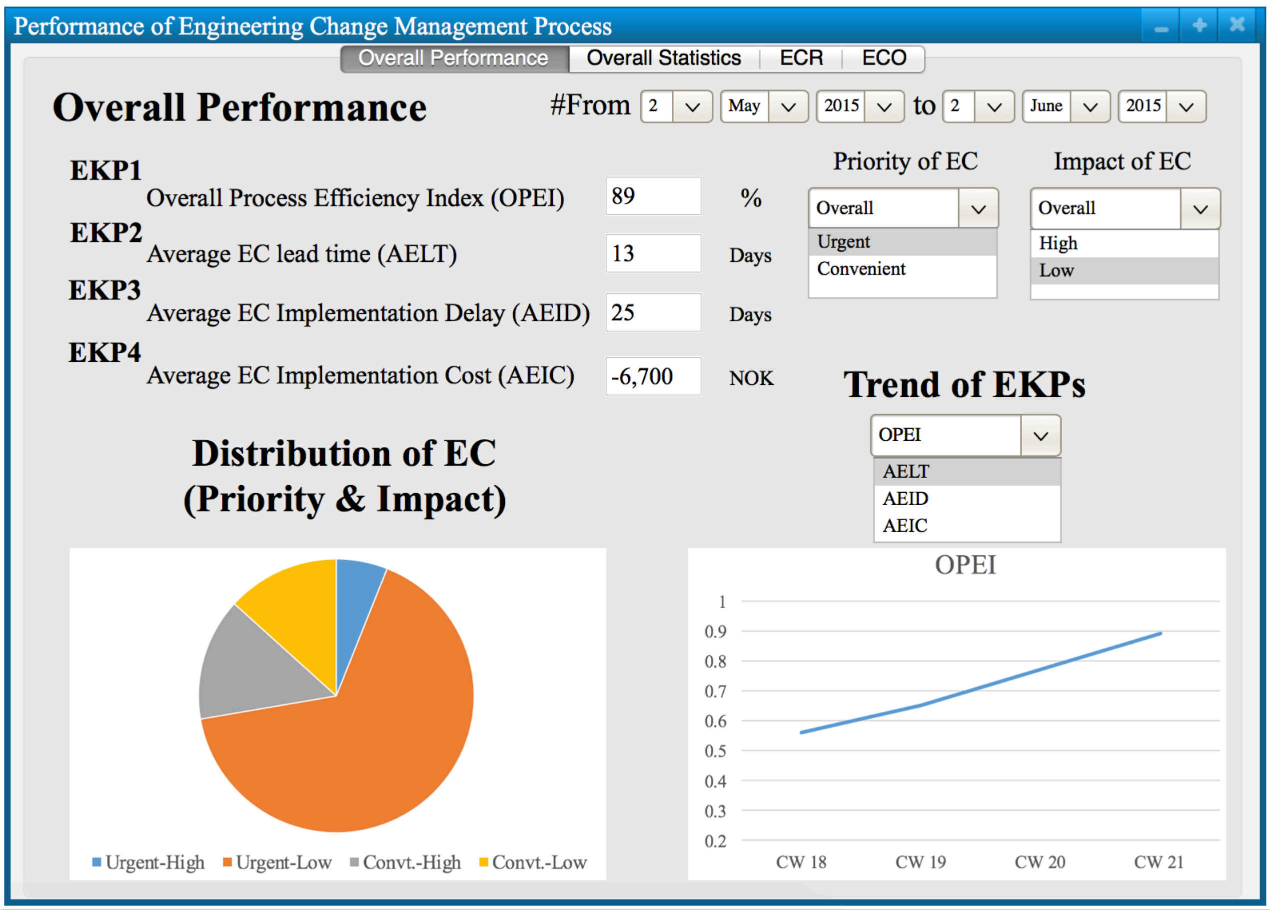


**Figure 8-3: Overall Performance Dashboard**

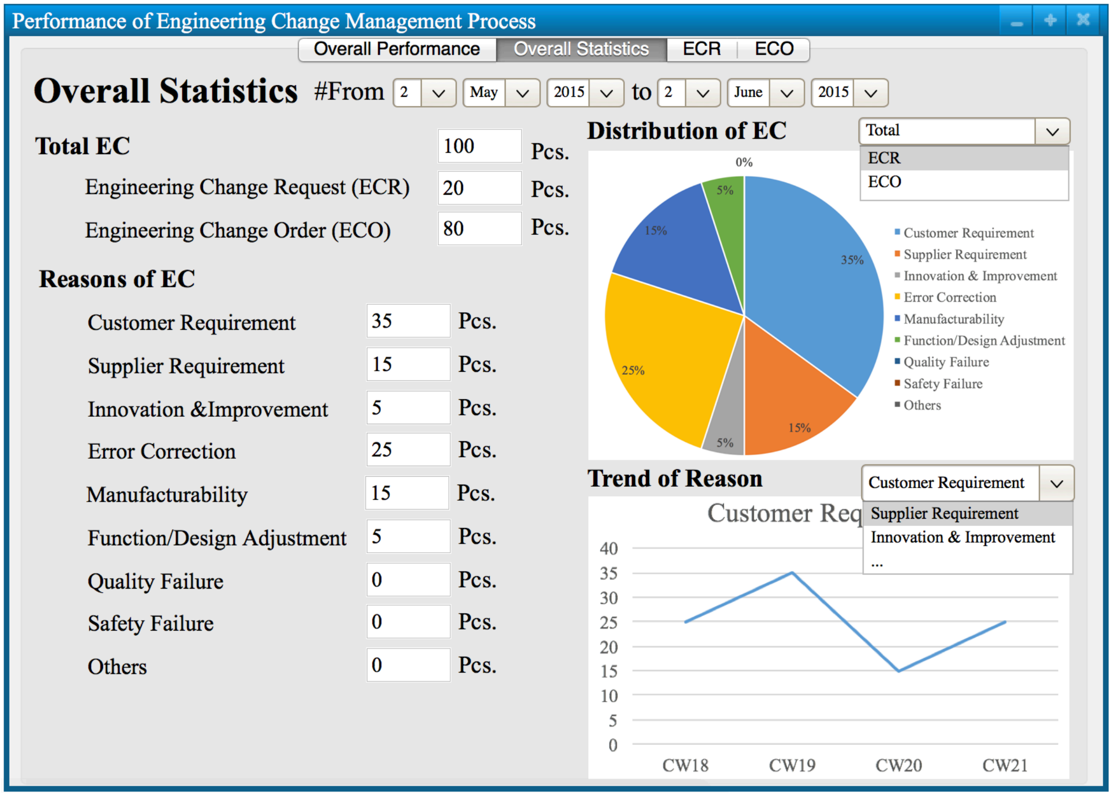


**Figure 8-4: Overall Statistics Dashboard**

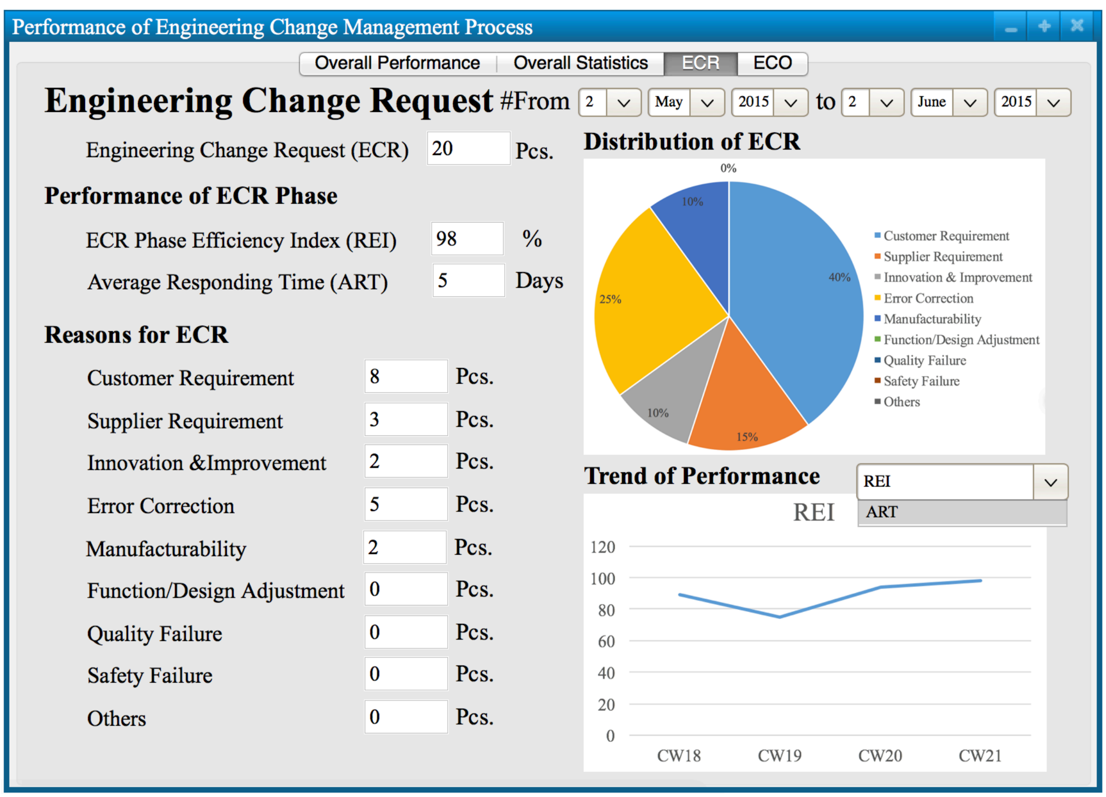


**Figure 8-5: Engineering Change Request Dashboard**

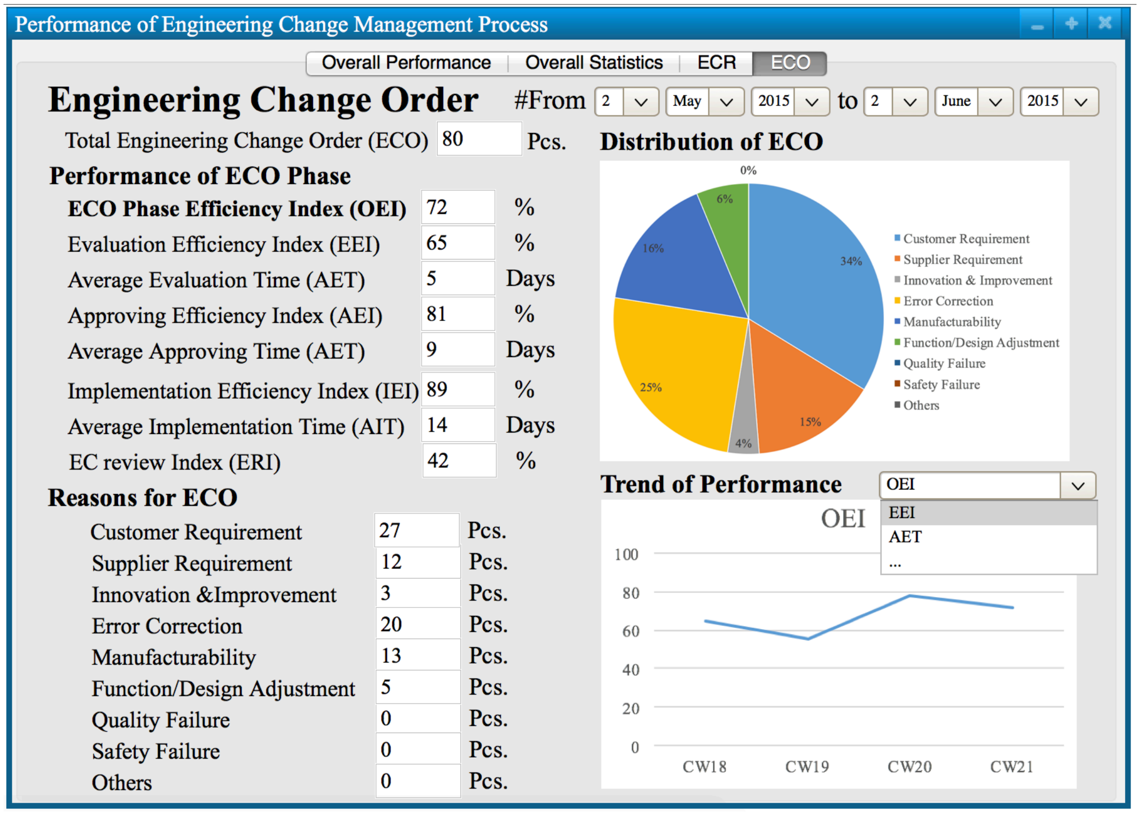


**Figure 8-6: Engineering Change Order Dashboard**

With the help of computer-aided system, the data for supporting these dashboards is very easy to collect. Development can just follow the formulas listed in Table 8-3.

For using the dashboard, Evaluator can review the performance of overall ECM process or the performance of separated ECM process to identify where to improve within the ECM process by choosing the corresponding tab. Evaluator can also filter the performance indicators by impact and priority dimensions, reasons of ECs, and specific data range. For example, evaluator can choose the priority into high so the performance of ECM process to handle urgent ECs is shown in the dashboard. The trend for each performance indicator can also be shown by the diagram within each tab, which provides the information about the development of particular performance indicators. This can be used to evaluate the improvement of ECM process after applying the certain action, which proved the basis for the continuously improvement.

## 8.3 Proposing Improvements for ECM

EC coordinator should be appointed to take the responsibility for managing and collaborating the ECM activities among different disciplines internally and externally. The person should familiar with the product and the technical issues in the company but also has the knowledge of the project management and the new ECM process. In order to actually improve the ECM process by using performance measurement, the person should have a higher authority level than engineer so that the essential change can be carried out in configuration. Furthermore, an ECM system that is not easy-to-use can also low its utilization as well as reduce the efficiency and effectiveness of ECM process. Since the new implementation of ECM system. Therefore, EC coordinator can act as a consultant to answer the questions during to ensure the functionality of the new system.

ECM meeting should be held regularly in the company. The function of ECM meeting is not limited to decision-making on the potential solutions, but also impact analysis, implementation planning and review, and ECM process review. The outcome of the meeting should be able to maximize the benefit and minimize the negative impact of EC as well as improve the performance of ECM process. The participants of ECM meeting should include but not be limited to engineers, managers from different disciplines.

Regarding the interface to handle ECs from field, accessibility through internet is highly suggested. The purpose of this interface is to document the ECs initiated during commission and installation, and then transfer the data to the company for further evaluation. Therefore, the ECR process within the ECM process embedded in the new PLM system is sufficient for this interface. Figure 8-7 illustrates the structure and flow of this web interface. Engineer can input related information of EC in the ECR form outside of the company through the web interface and then submit it to the manager of the corresponding department to get initial evaluation and approving. This ECR form work as the input for the initiation of ECO, which can be handled within the company in the later stage.

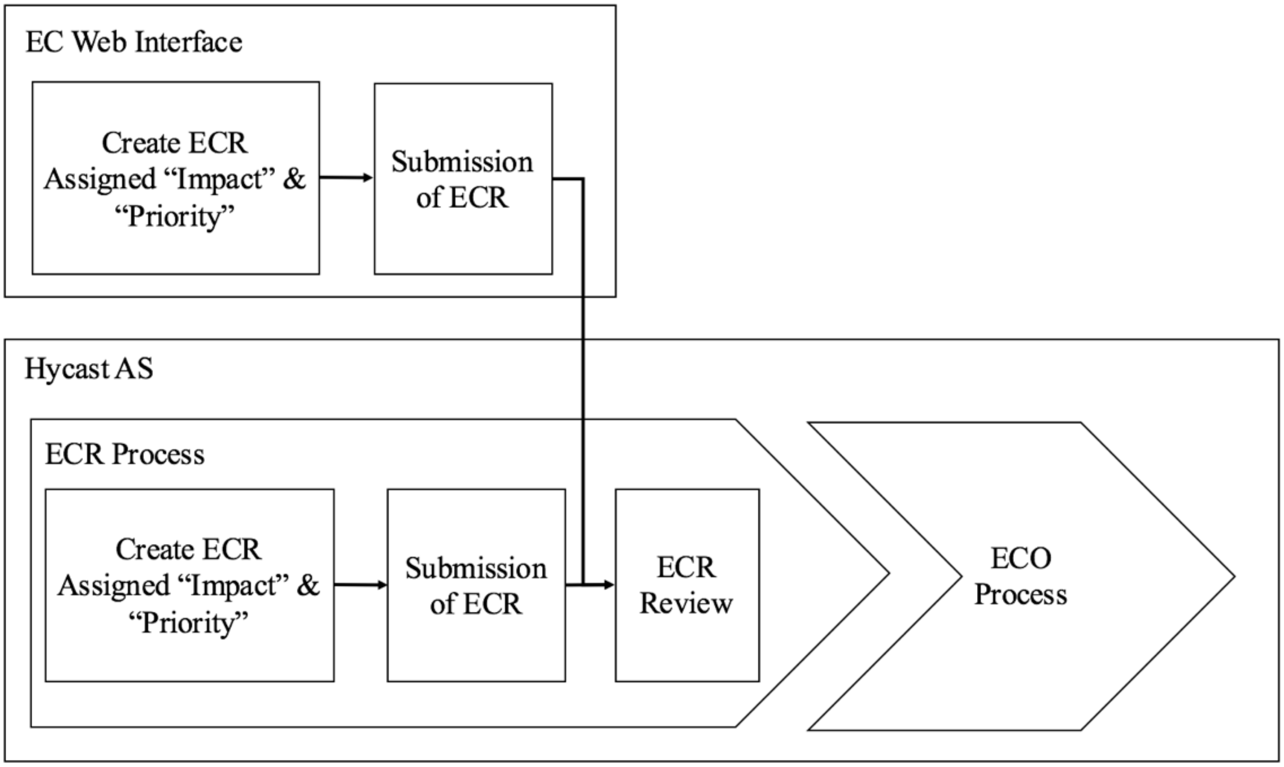


**Figure 8-7: Conceptual Map for Web Interface.**

Table 8-4 gives a summary of the solutions to the challenges for ECM in the case company.

Table 8-4: Summary of the solutions

| No. | Solutions to the challenges for ECM in case company |
|---|---|
| 1 | Set up a clear, well-structured ECM process for handling all type of ECs/ |
| 2 | Establish a classification mechanism to differentiate ECs in terms of impact and priority. Develop corresponding strategies to evaluate, approve, implement different types of EC. |
| 3 | Define the roles and responsibilities of actors in ECM process according to the impact and the priority of ECs to ensure the involvement of right person in the right step. |
| 4 | Propose impact analysis after the solution identification, and integrate ERP with impact analysis to increase the efficiency and effectiveness of information flow. |

| | |
|---|---|
| 5 | Propose a web interface to document and handle ECs initiated from field during commissioning and installation. |
| 6 | Develop performance indicators in both overall and local level according to the special features of the company to assess the current practice of ECM process and identify where to improve while increase the awareness of ECM and performance measurement. |
| 7 | EC coordinator should be appointed not only to manage and collaborate the ECM activities but also as a consultant to ensure the operation of new ECM system. |
| 8 | Have ECM meeting regularly to discuss, approve, plan, implement, and review EC and ECM process. |

# 9 Discussion

Despite that there is a variety of techniques and methodologies for ECM proposed in both practical and theoretical perspectives, the ECM is still a problem. This problem is especially apparently in ETO companies due to the high degree of customization and complexity in product, complicated structure in process, high quality and delivery requirement from customer, as well as distributed environment. The reasons for the problematic situation in ECM can be elaborated as follows.

Firstly, low awareness of current situation. This was found both in the literature on ECM and the study conducted in the case company. In most of the cases, there is some ECM process within companies but they are managed in either informal or mixed way. People within the companies just follow those process without realizing whether the current practice is good enough for the company. This indifference is commonly observed especially in management level due to their focus on the outcome instead of the process. Therefore, the current situation of ECM remain quite the same. Minor improvement will be carried out to establish a formal, pre-defined, and well-structured ECM process.

Secondly, lack of knowledge about the existence of better ECM techniques and methods. The study conducted by Huang & Mak (1998) also confirmed this point. People in the companies realized the insufficiency of current ECM practice, however, the way of better managing EC is not well known to them. Hence, the ECM in the company cannot be improved. In this case, the knowledge popularity of the state-of-the-art of techniques and methods in ECM is essential.

Thirdly, the benefit of better ECM has not been realized. A better ECM can reduce the time and cost spent on handling ECs so that the engineering capacity and the resources can be spared for other activities. With the better ECM, the efficiency and effectiveness within the process are improved, which can ensure a high product quality as well as the delivery performance. Hence, it is able to maintain a high customer satisfaction level. However, these benefits of improving ECM are not apparent to observe since there is no performance measurement applied for that purpose. Therefore, it was not truly realized the reason why it is important to improve ECM process.

Fourthly, lack of enough resource and capacity to improve. The company studies in this thesis is a good example. According to the interviews from the case companies, some of the management realized that the current ECM is not good enough, however, the company do not really have time, resource, and effort to improve it in the past few years. It is true that the occurrence of EC in the company might consume majority of the capacity in the engineering and production. Instead of improving ECM and its process, it becomes normal for them to be the "fire fighters" to deal with the impact caused by ECs. Therefore, the attention can be only focused in those most important ECs initiated from customers.

Fifthly, the existing ECM systems and proposals are too complex and rigid for managing different types of ECs. User just skip the existing ECM process in order to handle EC easier and faster (i.e. Eckert et al. 2004; Pikosz & Malmqvist 1998). But for certain type of EC (i.e. customer requirements), it is still necessary to have documentation and traceability. Therefore, this kind of situation results the mixed utilization of ECM system and remain ECM a problem. To cope with this challenge, it is suggested that ECM should have certain level of flexibility that can handle different types of ECs according to their own characteristics.

Last but not least, the different requirement on ECM between industry. It is true that certain type of industries has requirement for documentation and traceability of EC. For example, in aerospace and automobile industry, the design requires mandatory audit by external disciplines, which means that ECs applied in design require well-documented and managed. (i.e. Eckert et al. 2006; Pikosz & Malmqvist 1998). Therefore, the requirement for ECM in these types of industry is higher than others. In other words, the lower requirement for ECM in other types of industry gives the reason for those company to remain ECM process a problem.

As the core mechanism of the new methodology, the performance indicators with the basis of the reference framework for ECM process can largely fill the gap.

Function as the basis for the performance indicators, the reference framework visualizes the ECM process with a clear flow, which provides the basis for monitoring and controlling the process. It is difficult to monitor and control a process without a clear flow. Moreover, the visualization of the ECM process also helps to reveal the real states of ECs within the ECM process. It can help to control over the ECs in the existing process.

The reference framework proposed in the new methodology also gives a sophisticated but practical ECM process to follow. The development of the reference framework is based on a structured literature review in ETO and ECM. With the strong theory as background, the framework provides a good reference for the companies to evaluate their current practice of ECM, which can raise the awareness of the essential to improve ECM in the companies. Furthermore, the reference framework also provides a best practice for the company. By comparing their existing process with the reference framework, the weakness of the functionality within the ECM process can be identified. Improvement in the configuration or the process can be carried out. Therefore, the ECM process can be improved.

As mentioned early that there is a requirement for ECM to have certain level of flexibility that can handle different types of ECs according to their own characteristics. The classification mechanism and the matrix proposed in the new methodology can meet this requirement. Instead of other natures of EC, impact and priority are selected as the dimensions to classify various ECs. This is because the two dimensions related to two key ECM processes, namely approving and implementation process. The impact dimension is used to decide which level of authority should be involved during EC approving process according to the degree of impact caused by EC while the priority dimension is used to decide when EC should be implemented according to importance and urgency degree of EC. Moreover, the approving and implementation process, to a large extent, can decide the efficiency and effectiveness of ECM process. Therefore, the proposed classification mechanism and the matrix for ECM not able to handle ECs according to their own characteristics, but also help to improve the efficiency and effectiveness of ECM process.

It is important to mention that the performance indicators proposed in the new methodology can also help to raise the awareness of current performance of ECM process so that improve ECM eventually. However, different from the reference framework, they help to realize the current practices of ECM process by quantify the efficiency and effectiveness of the ECM process in both overall and local level while improve the ECM performance by learning continuously from previous performance. Instead of identifying what functionality or step is missing by the reference framework, the performance indicators reveal how economically the resources are used to handle EC and to which extent the implementation of EC agree with the expectations, which are the efficiency and effectiveness of ECM process. In other words, the performance indicators answer the question about "How well the current ECM process is doing", "What is happening within the current ECM process?", "How well the people are doing within the current ECM process?", and "Where to improve can make the process better?".

In order to answer these questions, performance indicators for both overall and local level were proposed. The functions of overall and local performance indicators are different, but they are supporting each other in a way that helps to improve the overall performance of ECM process in a balanced way. For the overall performance indicators, or key performance indicators, they are proposed to assess and give the general view on the overall performance of ECM process in terms of efficiency and effectiveness. However, if one want to know what is happening within the ECM process and where to improve, performance indicators in local level are required. Hence, performance indicators for each phase of ECM process were proposed. Instead of revealing the overall performance by KPIs, these local performance indicators reveal the performance in a disaggregated level. They identify the performance of the operation within each phase of ECM process. By referring to these local performance indicators, the area to improve can be identified.

It might be a doubt that since local performance indicators are able to assess the operation of each phase within ECM process while help to identify the weakness, there is no need to have KPIs for assessing the overall performance. The answer to the eliminating of KPIs is definitely not. KPIs proposed in this new methodology are also used to prevent sub-optimization. The improving performance of one phase in ECM process cannot sacrifice the performance of other phases. It is important to have a balanced performance improvement. Therefore, it requires both overall and local performance indicators to assess the performance of current ECM, and improve the efficiency and effectiveness by learning continuously from previous performance.

Furthermore, with the help of performance indicators, the benefits of improving ECM can be quantified, which provides the reason and motivation to improve ECM. performance indicators such as “Average EC Lead Time”, “Average EC Implementation Delay”, “Average EC Implementation Cost”, and “EC Related Customer Satisfaction Level” can all applied to identify the benefit of improving the performance of ECM. By comparing the current results of these performance indicators with previous results, the conclusion can be draw that whether the current performance of ECM has been improved or not. If the performance has been improved, the corresponding differences between these results are the great proof for the benefits of improving ECM.

There is no doubt that by applying the new methodology, improvement can be achieved either in the configuration and process or in the efficiency and effectiveness of ECM. However, who should make the decision on where to improve is vital. It was pointed out by one of the participants during the interview in the case company that a certain level of authority is required for the person because not everyone in the company has the power to make the decision on changing the process, system, configuration of ECM. It is pointless to assess the current practice of ECM without improving it. Therefore, the person or the group who can make the decision and have the authority on changing the current ECM practice should be appointed.

# 10 Conclusions

In ETO companies, ECM is challenge due to the high degree of customization and complexity in product, complicated structure in process, high quality and delivery requirement from customer, as well as distributed environment from supplier. The literature review has shown that ECs in ETO companies have the complex characteristics in terms of volume, reason, occurring phase, priority, and impact which make ECM in ETO companies even more challenging. It has further shown that despite there are various methodologies and techniques has been proposed both in theory and practice for improving ECM, very few is suitable for managing complex ECs in ETO context according to their own characteristics while providing improvement in both overall and local performance of ECM process. Despite there were performance indicators dedicated to improve the performance of ECM, those indicators were either focus on their own scope, which might result the sub-optimization or being absolute and subjective, which cannot truly reflect the performance of ECM process, not to mention improving the overall performance by identify where to improve.

The findings from the literature review were confirmed through the case study conducted in a ETO company. It was further illustrated that there was a low awareness in the current performance of ECM as well as in the benefits of improving it. Moreover, it was also reported that performance measurement on ECM has not been applied currently since its benefits are not realized by the management as well.

To solve these challenges, this thesis proposed a new methodology with a reference framework as the basis for the performance indicators in both overall and local levels. This new methodology provides a possible solution to improve the performance of ECM in terms of configuration, efficiency and effectiveness. It is impossible to improve the performance without measuring it (Fortuin, 1988). This methodology, firstly, provides the visualization of the ECM process, which provides the basis for monitoring and controlling over EC. It also helps to handle the complex ECs in ETO companies according to impact and priority of these ECs. These dimensions are vital for the EC approving and the EC implementation especially in ETO companies, which eventually impact the efficiency and the effectiveness of the ECM process. Most importantly, the new methodology raises the awareness of improving ECM by using the performance indicators and the reference framework. The reference framework enables the assessment and the improvement of current ECM process in terms of configuration and functionality by comparing the current ECM process with the framework. While the performance indicators reveal the current performance of ECM process both in overall and local level while help to improve the performance by learning continuously from the previous results. Meanwhile, through investigating into local performance indicators, the area need to improve can be identified, which eventually improve the performance of ECM as well. Moreover, through the comparison between the current performance with previous results, the trend of ECM performance can be evaluated, which provides the proof and motivation for improving ECM.

## 10.1 Research Objectives and Research Questions

This section exams research objectives and research questions defined at the beginning of this report in chapter 2 and evaluate whether these objectives are fulfilled and research questions are answered.

### 10.1.1 Research Objective

**Objective 1: Develop an understanding of ECM and the current practice of ECM in ETO companies.**

The understanding of ECM in ETO companies has been identified in terms of the characteristics of ETO that make ECM challenge in the context, which is presented in Section 5.1.2. The current practice of ECM in ETO companies have been understood through the structured literature review and case study. These understandings regarding EC, ECM and state-of-the-art research on ECM are presented in Section 5.2.

**Objective 2: Develop an understanding on how to develop performance indicators and based on this, evaluate the existing research on performance measurement for ECM.**

Definition, purposes, methods, and principles for developing performance indicators are understood and listed in Section 5.3.1 and Section 5.3.2. The evaluation of the existing research on performance measurement for ECM is presented in Section 5.3.3.

**Objective 3: Set up a foundation that shows how an efficient and effective ECM looks like.**
A reference framework that enable the efficiency and effectiveness of ECM is proposed in Section 6.1, which is worked as the best practice of ECM process.

**Objective 4: Use the foundation as the performance objectives to develop performance indicators that can be used to improve the performance of ECM in ETO companies.**
A set of performance indicators both in overall and local level has been proposed. The formula and the ways to use these performance indicators are discussed. These are presented in Section 6.2.

**Objective 5: Use the new methodology and findings from the literature and the case company to develop a solution that can help to improve ECM in ETO companies.**
The solution and discussion for the case company is presented in Chapter 8.

### 10.1.2 Research Questions

**RQ1: What are the challenges that ETO companies have for ECM?**
ECM is challenge in ETO companies due to the high degree of customization and complexity in product, complicated structure in process, high quality and delivery requirement from customer, as well as distributed environment from supplier. Detailed explanation is presented in Section 5.1.2.

**RQ2: What are current practices of ECM in ETO companies?**
The current practices of ECM can be analyzed in terms of situation of EC, current practice of ECM, existing research in ECM.

ECs in ETO companies have the complex characteristics in terms of volume, reason, occurring phase, priority, and impact which make ECM in ETO companies even more challenging. Current practices of ECM are various in ECM process, organizational structure, and tools used to support ECM. It has further shown that despite there are various methodologies and techniques has been proposed both in theory and practice for improving ECM, very few is suitable for managing complex ECs in ETO context according to their own characteristics while providing improvement in both overall and local performance of ECM process.

**RQ3: What performance indicators can be applied for improving ECM in ETO companies?**
Performance indicators are used to quantify the efficiency and the effectiveness of ECM. For the purpose of performance indicators, different principles are required to develop them. Performance indicators have to focus on both overall and local ECM performance, it should be objective than subjective, relative than absolute, as well as improve the performance in a balanced way rather than sub-optimization (Section 5.3). Performance indicators that are suitable for improving the performance of ECM in ETO companies are listed in Section 6.2.

## 10.2 Limitations

This is the first limitation is that the new methodology proposed in this thesis is based on the general situation of ECM in ETO companies. A number of perspectives in the methodology remain open while the functionality and the features within the methodology cannot be applied universally to all type of companies. On the contrary, this can be one of the advantages. Since the methodology provides a reference and a guideline for improving ECM in ETO companies, therefore, the methodology is flexible enough to make adaption. The adaption to the case company is a good example.

Another limitation is that the new methodology proposed in this thesis is based on the theory, findings from ETO context. ETO has its own characteristics that make ECM in ETO different from other product context. Although there is some flexibility in the new methodology that allow it to apply into other context, the core mechanism within the methodology, such as classification mechanism, matrix for ECM, and performance indicators cannot fit into other production strategy than ETO. Therefore, additional adaption is required if the new methodology is applied in other product strategy.

Moreover, using these performance indicators developed within the new methodology might require certain workload. Since both overall and local performance indicators are required to realize the improvement of ECM in ETO, the number of data that need to collect is considerable.

Therefore, the performance indicators are more suitable for those companies who have computer-aided ECM system. However, it is still possible to apply the methodology in the paper-based or manual ECM system as long as reduce the number of performance indicators. However, the evaluation result can be affected.

## 10.3 Further work

Some suggestions on further work can be summarized on the basis of the results of this thesis.

As mentioned in the limitation, the proposed methodology is developed based on the general situation of ETO companies. However, these is still the difference (i.e. customization degree, product complexity, scale) between ETO companies. The difference can make ECM varies from ETO companies. It can be interesting to see how the reference framework and performance indicators varies from the different clusters of ETO companies. Therefore, a multiple cases study can be carried out to make the methodology applicable to the different cluster of ETO companies.

Developing the computer-aided system by using the proposed methodology as the basis. The proposed methodology in this thesis provides the reference and the guidelines to manage ECs in ETO companies in a flexible and visualized way. It provides the opportunity to build a computer-aided system based on the concept of new methodology. This is especially helpful for performance indicators because of the automatic data collection and documentation. Data from different level of performance indicators can be easily accessed filtered and analyzed based on the two dimensions as well as the reasons of EC. The example dashboard developed for the case company is a very good example.

Moreover, the proposed methodology can also be tailored into other production strategy. Theory and empirical study from other production strategy can be added to identify the different characteristics, and to see how the different characteristics make ECM different between each production strategy.

Last but not least, the reference framework together with the performance indicators in the proposed methodology can be used to evaluate the maturity level of ECM in ETO companies. To realize this function, the standards for each maturity level both in the configuration of ECM as well as in the efficiency and effectiveness of ECM process need to be defined. The maturity level can be revealed by comparison current situation with these standards. It is for sure that more detailed work is required to realize this function.

# Reference

Ahmad, M.M. & Dhafr, N., 2002. Establishing and improving manufacturing performance measures. *Robotics and computer-integrated manufacturing*, 18(3–4), pp.171–176.

Ahmad, N., Wynn, D.C. & Clarkson, P.J., 2013. Change impact on a product and its redesign process: a tool for knowledge capture and reuse. *Research in Engineering Design*, 24(3), pp.219–244.

Ahmed, S. & Kanike, Y., 2007. Engineering change during a product's lifecycle. *Guidelines for a Decision Support Method Adapted to NPD Processes*. Available at: https://www.designsociety.org/publication/25649/engineering_change_during_a_product%E2%80%99s_lifecycle.

Alblas, A.A. & Wortmann, J.C., 2012. Managing large engineering changes: The case of a high-tech microlithography equipment manufacturer. *International Journal of Operations & Production Management*, 32(11), pp.1252–1280.

Balcerak, K.J. & Dale, B.G., 1992. Engineering change administration: the key issues. *Computer Integrated Manufacturing Systems*, 5(2), pp.125–132.

Barzizza, R., Caridi, M. & Cigolini, R., 2001. Engineering change: A theoretical assessment and a case study. *Production Planning & Control*, 12(7), pp.717–726.

Behn, R.D., 2003. Why Measure Performance? Different Purposes Require Different Measures. *Public administration review*, 63(5), pp.586–606.

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

Cao, Y. et al., 2015. Constructing the integrated strategic performance indicator system for manufacturing companies. *International Journal of Production Research*, 53(13), pp.4102–4116.

Caron, F. & Fiore, A., 1995. “Engineer to order” companies: how to integrate manufacturing and innovative processes. *International Journal of Project Management*, 13, pp.313–319.

Carter, D.E. & Baker, B.S., 1992. Concurrent engineering: The product development environment for the 1990s. *Addison-Wesley*, 10(2), pp.176–177.

de Carvalho, A.N., Oliveira, F. & Scavarda, L.F., 2015. Tactical capacity planning in a real-world ETO industry case: An action research. *International Journal of Production Economics*.

Chae, B. (kevin), 2009. Developing key performance indicators for supply chain: an industry perspective. *Supply Chain Management: An International Journal*, 14(6), pp.422–428.

Chen, Y.-M., Shir, W.-S. & Shen, C.-Y., 2002. Distributed engineering change management for allied concurrent engineering. *International Journal of Computer Integrated Manufacturing*, 15, pp.127–151.

Clarkson, P.J., Simons, C. & Eckert, C., 2004. Predicting change propagation in complex design. *Journal of Mechanical Design*, 126, pp.788–797.

Cohen, T., Navathe, S.B. & Fulton, R.E., 2000. C-FAR, change favorable representation. *Computer-aided design and applications*, 32(5–6), pp.321–338.

Collin, J., 2002. Measuring the success of building projects--improved project delivery initiatives. *Report for the Queensland Department of Public Works, Australia*.

Dale, B.G., 1982. The management of engineering change procedure. *Engineering management international*, 1, pp.201–208.

Da Silveira, G., Borenstein, D. & Fogliatto, F.S., 2001. Mass customization: Literature review and research directions. *International Journal of Production Economics*, 72(1), pp.1–13.

Dean, P.R., Tu, Y.L. & Xue, D., 2009. An information system for one-of-a-kind production. *International Journal of Production Research*, 47(4), pp.1071–1087.

Diprima, M., 1982. Engineering Change Control and Implementation Considerations. *PRODUCT. & INVENT. MGMT.*, 23(1), pp.81–87.

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

Duray, R., 2002. Mass customization origins: mass or custom manufacturing? *International Journal of Operations & Production Management*, 22(3), pp.314–328.

Eckert, C. et al., 2009. Engineering change: drivers, sources, and approaches in industry. In *DS 58-4: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 4, Product and Systems Design, Palo Alto, CA, USA, 24.-27.08. 2009*. designsociety.org. Available at: https://www.designsociety.org/publication/28648/engineering_change_drivers_sources_and_approaches_in_industry.

Eckert, C., Clarkson, P.J. & Zanker, W., 2004. Change and customisation in complex engineering domains. *Research in Engineering Design*, 15, pp.1–21.

Eckert, C.M. et al., 2006. Supporting change processes in design: Complexity, prediction and reliability. *Reliability Engineering & System Safety*, 91, pp.1521–1534.

Elfring, T. & Baven, G., 1994. Outsourcing technical services: Stages of development. *Long range planning*, 27(5), pp.42–51.

Fortuin, L., 1988. Performance indicators—why, where and how? *European journal of operational research*, 34(1), pp.1–9.

Fricke, E. et al., 2000. Coping with changes: causes, findings, and strategies. *Systems Engineering and Electronics*, 3(4), pp.169–179.

Garengo, P., Biazzo, S. & Bititci, U.S., 2005. Performance measurement systems in SMEs: A review for a research agenda. *International Journal of Management Reviews*, 7(1), pp.25–47.

Ghalayini, A.M., Noble, J.S. & Crowe, T.J., 1997. An integrated dynamic performance measurement system for improving manufacturing competitiveness. *International Journal of Production Economics*, 48(3), pp.207–225.

Giesberts, P.M.J. & Tang, L.V.D., 1992. Dynamics of the customer order decoupling point: impact on information systems for production control. *Production Planning & Control*, 3(3), pp.300–313.

Globerson, S., 1985. Issues in developing a performance criteria system for an organization. *International Journal of Production Research*, 23(4), pp.639–646.

Gomes, C.F., Yasin, M.M. & Lisboa, J.V., 2004. A literature review of manufacturing performance measures and measurement in an organizational context: a framework and direction for future research. *International Journal of Manufacturing Technology and Management*, 15(6), pp.511–530.

Grabenstetter, D.H. & Usher, J.M., 2015. Sequencing jobs in an engineer-to-order engineering environment. *Production & Manufacturing Research*, 3(1), pp.201–217.

Gries, B., Restrepo, J. & Others, 2011. KPI MEASUREMENT IN ENGINEERING DESIGN--A CASE STUDY. In *DS 68-1: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 1: Design Processes, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011*. designsociety.org. Available at: https://www.designsociety.org/publication/30450/kpi_measurement_in_engineering_design_%E2%80%93_a_case_study.

Habhouba, D., Cherkaoui, S. & Desrochers, A., 2011. Decision-Making Assistance in Engineering-Change Management Process. *IEEE transactions on systems, man and cybernetics. Part C, Applications and reviews: a publication of the IEEE Systems, Man, and Cybernetics Society*, 41(3), pp.344–349.

Hameri, A.-P. & Nihtilä, J., 1998. Product data management—exploratory study on state-of-the-art in one-of-a-kind industry. *Computers in Industry*, 35(3), pp.195–206.

Hamraz, B., 2013. *Engineering change modelling using a function-behaviour-structure scheme*. University of Cambridge. Available at: https://www.repository.cam.ac.uk/handle/1810/245074.

Hamraz, B., Caldwell, N.H.M. & Clarkson, P.J., 2013. A Holistic Categorization Framework for Literature on Engineering Change Management. *Systems Engineering*, 16(4), pp.473–505.

Hamraz, B. & Clarkson, P.J., 2015. Industrial evaluation of FBS Linkage--a method to support engineering change management. *Journal of Engineering Design*, 26(1-3), pp.24–47.

Hanna, A.S. et al., 1999. Impact of change orders on labor efficiency for mechanical construction. *Journal of construction engineering and management*, 125, pp.176–184.

Hegde, G.G., Kekre, S. & Kekre, S., 1992. Engineering changes and time delays: A field investigation. *International Journal of Production Economics*, 28, pp.341–352.

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

Huang, G.Q. & Mak, K.L., 1998. Computer aids for engineering change control. *Journal of Materials Processing Technology*, 76, pp.187–191.

Huang, G.Q. & Mak, K.L., 1999. Current practices of engineering change management in UK manufacturing industries. *International Journal of Operations & Production Management*, 19, pp.21–37.

Huang, G.Q., Yee, W.Y. & Mak, K.L., 2003. Current practice of engineering change management in Hong Kong manufacturing industries. *Journal of Materials Processing Technology*, 139, pp.481–487.

Huang, G.Q., Yee, W.Y. & Mak, K.L., 2001. Development of a web-based system for engineering change management. *Robotics and computer-integrated manufacturing*, 17, pp.255–267.

Hycast, A.S., 2016. About Us. *Hycast AS*. Available at: http://hycast.no/about-us/ [Accessed May 21, 2016].

Ibbs, C.W., Wong, C.K. & Kwak, Y.H., 2001. Project change management system. *Journal of Management in Engineering*.

Jarratt et al., 2011. Engineering change: an overview and perspective on the literature. *Research in Engineering Design*, 22(2), pp.103–124.

Jarratt, T., Eckert, C. & Clarkson, P.J., 2004. Development of a product model to support engineering change management. *Proceedings of the TCME*, pp.331–344.

Jin, G. & Thomson, V., 2003. A new framework for MRP systems to be effective in engineered-to-order environments. *Robotics and computer-integrated manufacturing*, 19(6), pp.533–541.

Joshi, N., Ameri, F. & Dutta, D., 2005. Systematic decision support for engineering change management in PLM. *ASME 2005*. Available at: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1588286.

Kaplan, R.S. & Norton, D.P., 1993. Putting the balanced scorecard to work. *Harvard Business Review (September–October)*, 71, pp.134–147.

Kaplan, R.S. & Norton, D.P., 1996. *The balanced scorecard: translating strategy into action*, Harvard Business Press.

Kidd, M.W. & Thompson, G., 2000. Engineering design change management. *Integrated Manufacturing Systems*, 11(1), pp.74–77.

Kloss-Grote, B. & Moss, M.A., 2008. How to measure the effectiveness of risk management in engineering design projects? Presentation of RMPASS: a new method for assessing risk management performance and the impact of knowledge management—including a few results. *Research in Engineering Design*, 19(2-3), pp.71–100.

Kocar, V. & Akgunduz, A., 2010. ADVICE: A virtual environment for Engineering Change Management. *Computers in Industry*, 61(1), pp.15–28.

Lampel, J. & Mintzberg, H., 1996. Customizing customization. *Sloan management review*, 38, pp.21–30.

Lee, H.J. et al., 2006. Capturing and reusing knowledge in engineering change management: A case of automobile development. *Information Systems Frontiers*, 8, pp.375–394.

Little, D. et al., 2000. Integrated planning and scheduling in the engineer-to-order sector. *International Journal of Computer Integrated Manufacturing*, 13(6), pp.545–554.

Loch, C.H. & Terwiesch, C., 1999. Accelerating the process of engineering change orders: capacity and congestion effects. *Journal of Product Innovation Management*, 16, pp.145–159.

Manoochehri, G., 1999. The road to manufacturing excellence. *INDUSTRIAL MANAGEMENT-CHICAGO THEN ATLANTA-*, pp.6–7.

McGOVERN, T., Hicks, C. & Earl, C.F., 1999. Modelling supply chain management processes in engineer-to-order companies. *International Journal of Logistics Research and Applications*, 2(2), pp.147–159.

Mokhtar, A., Bédard, C. & Fazio, P., 1998. Information model for managing design changes in a collaborative environment. *Journal of Computing in Civil Engineering*.

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

Neely, A. et al., 1997. Designing performance measures: a structured approach. *International Journal of Operations & Production Management*, 17(11), pp.1131–1152.

Neely, A., Mills, J., et al., 2000. Performance measurement system design: developing and testing a process-based approach. *International Journal of Operations & Production Management*, 20(10), pp.1119–1145.

Neely, A., Adams, C. & Others, 2000. Perspectives on performance: the performance prism. *Focus Magazine for the Performance Management Professional*, 4. Available at: https://www.som.cranfield.ac.uk/som/dinamic-content/research/cbp/prismarticle.pdf.

Neely, A., Gregory, M. & Platts, K., 2005. Performance measurement system design: a literature review and research agenda. *International Journal of Operations & Production Management*, 25(12), pp.1228–1263.

Ødegård, T., 2014. Hycast AS. *PROFF, The Business Finder*. Available at: http://www.proff.no/selskap/hycast-as/sunndals%C3%B8ra/aluminium-og-aluminiumsvarer/Z0I41E3A/ [Accessed May 23, 2016].

Olhager, J., 2003. Strategic positioning of the order penetration point. *International Journal of Production Economics*, 85(3), pp.319–329.

Olhager, J., 2010. The role of the customer order decoupling point in production and supply chain management. *Computers in Industry*, 61(9), pp.863–868.

Ouertani, M.Z., 2008. Supporting conflict management in collaborative design: An approach to assess engineering change impacts. *Computers in Industry*, 59(9), pp.882–893.

Parmenter, D., 2007. *Key performance indicators: developing, implementing, and using winning KPIs*, John Wiley & Sons.

Pikosz, P. & Malmqvist, J., 1998. A comparative study of engineering change management in three Swedish engineering companies. In *Proceedings of the DETC98 ASME design engineering technical conference*. pp. 78–85.

Porter, K. et al., 1999. Manufacturing classifications: relationships with production control systems. *Integrated Manufacturing Systems*, 10(4), pp.189–199.

Reddi, K.R. & Moon, Y.B., 2011. System dynamics modeling of engineering change management in a collaborative environment. *International Journal of Advanced Manufacturing Technology*, 55(9-12), pp.1225–1239.

Rouibah, K., Kamel, R. & Caskey, K.R., 2003. Change management in concurrent engineering from a parameter perspective. *Computers in Industry*, 50(1), pp.15–34.

Rudberg, M. & Wikner, J., 2004. Mass customization in terms of the customer order decoupling point. *Production Planning & Control*, 15(4), pp.445–458.

Santori, P.R. & Anderson, A.D., 1987. Manufacturing performance in the 1990s: measuring for excellence. *Journal of Accountancy*, 164(5), p.141.

Shankar, P., Morkos, B. & Summers, J.D., 2012. Reasons for change propagation: a case study in an automotive OEM. *Research in Engineering Design*, 23(4), pp.291–303.

Stevens, C.A. & Wright, K., 1991. Managing change with configuration management. *National Productivity Review*, 10(4), pp.509–518.

Storbjerg, S.H., Brunoe, T.D. & Nielsen, K., 2016. Towards an engineering change management maturity grid. *Journal of Engineering Design*, 0(0), pp.1–29.

Subrahmanian, E. et al., 2015. Managing and supporting product life cycle through engineering change management for a complex product. *Research in Engineering Design*, 26(3), pp.189–217.

Sudin, M.N., Ahmed, S. & Others, 2009. Investigation of change in specifications during a product's lifecycle. In *DS 58-8: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 8, Design Information and Knowledge, Palo Alto, CA, USA, 24.-27.08. 2009*. designsociety.org.

Tangen, S., 2004. PROFESSIONAL PRACTICE: Performance measurement: from philosophy to practice. *International Journal of Productivity and Performance Management*, 53(8), pp.726–737.

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

Terwiesch, C. & Loch, C.H., 1999. Managing the process of engineering change orders: the case of the climate control system in automobile development. *Journal of Product Innovation Management*, 16, pp.160–172.

Tu, Y., 1997. Production planning and control in a virtual one-of-a-kind production company. *Computers in Industry*, 34, pp.271–283.

Veldman, J. & Alblas, A., 2012. Managing design variety, process variety and engineering change: a case study of two capital good firms. *Research in Engineering Design*, 23(4). Available at:

Veldman, J. & Alblas, A., 2007. Managing Engineering Change Decisions. In 5th GTMC Doctoral Symposium. Ceram Sophia Antipolis.

Vianello, G. & Ahmed, S., 2008. Engineering Changes During the Service Phase. In *ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, pp. 117–124.

Vianello, G. & Saeema, A.K., 2012. A comparative study of changes across the lifecycle of complex products in a variant and a customised industry. *Journal of Engineering Design*, 23(2), pp.99–117.

Wänström, C. & Jonsson, P., 2006. The impact of engineering changes on materials planning. *International Journal of Manufacturing Technology and Management*, 17(5), pp.561–584.

Wasmer, A., Günter, S. & Vroom Regine, W., 2011. An industry approach to shared, cross-organisational engineering change handling - The road towards standards for product data processing. *Computer-aided design and applications*, 43, pp.533–545.

Wikner, J. & Rudberg, M., 2005. Integrating production and engineering perspectives on the customer order decoupling point. *International Journal of Operations & Production Management*, 25(7), pp.623–641.

Wortmann, J.C., 1992. Production management systems for one-of-a-kind products. *Computers in Industry*, 19(1), pp.79–88.

Wright, I.C., 1997a. A review of research into engineering change management: implications for product design. *Design Studies*, 18(1), pp.33–42.

# Appendix A Performance Indicators developed in Specialization Project

**Table 0-1: KPIs developed in Specialization Project.**

| KPIs | Definition | Attribute |
|---|---|---|
| Average EC lead time | The time from start to finish of EC. (Time should be measured with different type of ECs.) | Efficiency |
| Pending EC rate | $\frac{\text{Number of pending EC}}{\text{Total number of unfinished EC}}$ (Pending refer to EC waiting for a certain period of time. The criteria is set by company. ) | |
| Unfinished EC rate | $\frac{\text{Number of Unfinished EC}}{\text{Number of EC}}$ | |
| Unfinished urgent EC rate | $\frac{\text{Number of unfinished urgent EC}}{\text{Number of urgent EC}}$ | |
| Project schedule on time rate (PSOT Rate) | PSOT Rate = Real Date-Schedule Date. The number of day beyond or behind planned schedule. (Can be both plus or minus) | |
| EC rework rate | $\frac{\text{Number of rework EC}}{\text{Number of total EC}}$ | Effectiveness |
| EC reject rate | $\frac{\text{Number of rejected EC}}{\text{Number of total EC}}$ | |
| Quality of final product | Subjective KPI. To which degree the product is made according to specification. | |
| Customer Satisfaction Level | Customer's satisfaction to ECs they proposed in terms of the speed, clarity, and accordance to specification | |
| Scrap cost due to EC | Cost due to EC (late implementation, wrong-implementation | |

Table 0-2: PIs developed in Specialization Project.

| Phase | PIs | Definition | Attribute |
|---|---|---|---|
| **Propose Phase** | Average responding time | From customer send out the change order to officially get response about feasibility. | Efficiency |
| | Average processing time | The actual time it takes to process the task | |
| | Average waiting time | The time the task remain waiting until being processed. | |
| | Customer Satisfaction Level | Customer's satisfaction with the speed, clarity, and accordance to specification | Effectiveness |

| | | | |
|---|---|---|---|
| **Approve Phase** | Average processing time | The actual time it takes to process the task | Efficiency |
| | Average waiting time | The time the task remain waiting until being processed. | |
| | EC reference rate | Times that Engineer refer to EC history. | Data Management |
| | EC Rework Rate | $\frac{\text{Number of rework EC by various reasons}}{\text{Number of total EC}}$ | Effectiveness |
| | Accuracy of lead time estimation | $\frac{\text{Actual lead time}}{\text{Estimated lead time}}$ | |
| | Accuracy of cost estimation | $\frac{\text{Actual cost from EC}}{\text{Estimated cost from EC}}$ | |
| | Design department satisfaction level | The satisfaction from employee in design department in terms of speed, clarity, propagation, and other functions etc. | Overall performance in this phase |
| **Implementation Phase** | Average processing time | The actual time it takes to process the task | Efficiency |
| | Average waiting time | The time the task remain waiting until being processed | |
| | Document updated rate | $\frac{\text{Number of updated document}}{\text{Number of affected document}}$ | |
| | EC implementation rate | $\frac{\text{Number of EC not implemented}}{\text{Number of EC existing in this phase}}$ | |
| | Urgent EC implementation rate | $\frac{\text{Number of urgent EC not implemented}}{\text{Number of urgent EC existing in this phase}}$ | |
| | Data transfer time to supplier | Actual time to transfer the EC to supplier. | Information sharing |
| | Supplier delay rate (EC related) | Supply components delay due to EC. | |
| | Quality of Supplier's component | To which degree the product is made according to specification. | |
| | Supplier's satisfaction level | Supplier's satisfaction with the speed, clarity, and accordance to specification. | |
| | Manufacturing department satisfaction level | The satisfaction from employee in manufacturing department in terms of speed, clarity, functions etc. | Overall performance in this phase |
| **Documentation** | EC Achieve Rate | $\frac{\text{Number of Documented EC}}{\text{Received ECO}}$ | Data management |
| | EC review rate | Times that ECs have been reviewed. | |

# Appendix B Details of the Participants for the Meetings during Company Visit.

Table 0-1: Participants of the meetings during company visit.

| **Participants** | **Position** | **Gender** | **Working Experience (years)** |
|---|---|---|---|
| A | Technical Manger | M | 14 |
| B | Technical Purchaser | F | 1 |
| C | Mechanical Engineer | M | 1 |
| D | Supply Chain Management Manager | M | 15 |
| E | Project Manager | M | 2 |

# Appendix C Table of description, limitation for Each Performance Indicators for the new methodology

Table 0-1: Table of descriptions and Limitations for each performance indicators in the new methodology.

| No. | Abbre-viation | Name | Description | Limitation |
|---|---|---|---|---|
| **Key Performance Indicators for overall ECM Process** | | | | |
| EKP1 | OPEI | Overall Process Efficiency Index | Identify the efficiency of overall ECM process to handle EC with the ratio between finished ECs with all ECs in the system. | For overall performance, not very helpful for improvement. |
| EKP2 | AELT | Average EC lead time | Measure the average time spent for ECs to go through entire process. Quantitative metric to reveal the efficiency of overall ECM process. | It is an absolute metric, which requires further comparison. |
| EKP3 | AEID | Average EC Implementation Delay | By comparing the actual implementation date with the due date, it measures the efficiency of ECM process in terms of time. | Other influential factors (e.g. stroke, or power failure) should be considered. |
| EKP4 | AEIC | Average EC Implementation Cost | By comparing the actual cost with expected cost, it measures the effectiveness of overall ECM process in terms of cost. | Other cost factors within implementation (e.g. exchange rate) should be considered. |
| EKP5 | ACCQ | Average Changed Component Quality | Identify the effectiveness of ECM process by describing to which degree the changed components agree with the specifications or expectations. | Subjective KPI that can be affected by personal experience and other factors. |
| EKP6 | CSI | Customer Satisfaction Index | A qualitative metric to describe to which degree are the customers satisfied with ECM in the company. | Subjective KPI that can be affected by personal experience and other factors. |
| **Performance Indicators for Propose Phase** | | | | |
| P1 | EIP | Propose Phase Efficiency Index | Identify the efficiency of handling EC in propose phase with the ratio of processed ECs to received ECs in this phase. | Disaggregated PI, sub-optimization should be avoided. |
| P2 | ART | Average Responding Time | Measure the time spent on responding to change request with proper solutions. | An absolute metric requires measuring goal. |

| | | | | |
|---|---|---|---|---|
| P3 | KMI | Knowledge Management Index | A supporting metric to reveal the effectiveness of knowledge management system in ECM process by measuring the ratio of ECs that have been improved by referring to the system. | Require the equipment of knowledge management system. |
| P4 | ERI | EC Rework Index | Identify the rework rate in propose phase, which helps to identify the effectiveness of propose phase. | Other influential factors (e.g. change of request) should be considered. |
| P5 | ADI | Average Degree of Interaction Difficulty | A qualitative metric to describe the difficulty of interaction between initiator and different department. | Subjective KPI that can be affected by personal experience and other factors. |
| **Performance Indicators for Approving Phase** | | | | |
| A1 | EIA | Approve Phase Efficiency Index | Identify the efficiency of approving EC with the ratio of processed ECs to received ECs in this phase. It can be broke down by different urgency grade. | Disaggregated PI, sub-optimization should be avoided. |
| A2 | AAT | Average Approving Time | Time spent for approving EC in average. It can be broke down by different urgency grade. | An absolute metric requires measuring goal. |
| A3 | ERJ | EC Reject Index | A quantitative metric used to describe the effectiveness of propose phase. Too much rejection identify low effectiveness in propose phase. | Other influential factors (e.g. change of request) should be considered. |
| **Performance Indicators for Implementation Phase** | | | | |
| I1 | EII | Implementation Phase Efficiency Index | Identify the efficiency of approving EC with the ratio of implemented ECs to received ECs in this phase. It can be broke down by different urgency grade. | Disaggregated PI, sub-optimization should be avoided. |
| I2 | AIT | Average Implementation Time | Time spent for implementation EC in average. It can be broke down by different urgency grade. | An absolute metric requires measuring goal. |
| I3 | ISE | Information Sharing Efficiency Index | Identify the efficiency of information sharing in EC implementation with supplier. Ratio of ECs that has been informed with supplier to ECs that should be informed. | Disaggregated PI, sub-optimization should be avoided. |

| | | | | |
|---|---|---|---|---|
| I4 | ASCQ | Average Supplied Component Quality | A qualitative metric used to describe the quality of procured component from supplier. | Just for reference since the effectiveness of EC implementation have just partly impact on quality of supplier component. |
| I5 | ASSL | Average Supplier Satisfaction Level | A qualitative metric to describe to which degree are the suppliers satisfied with ECM in the company. | Subjective KPI that can be affected by personal experience and other factors. |
| **Performance Indicators for Documentation Phase** | | | | |
| D1 | EAI | EC Archive Index | A quantitative metric measure the documentation situation of EC, it is a ratio of archived EC to the received EC at the start of process (G0). | Difficult to have data collecting if ECM is paper based. |
| D2 | ERI | EC Review Index | A quantitative metric measure used to reveal the situation of EC reviewing function. It is a ratio of reviewed ECs to archived ECs. | Difficult to have data collecting if ECM is paper based. |

# Appendix D Technical Specification for ECM in Sovelia.

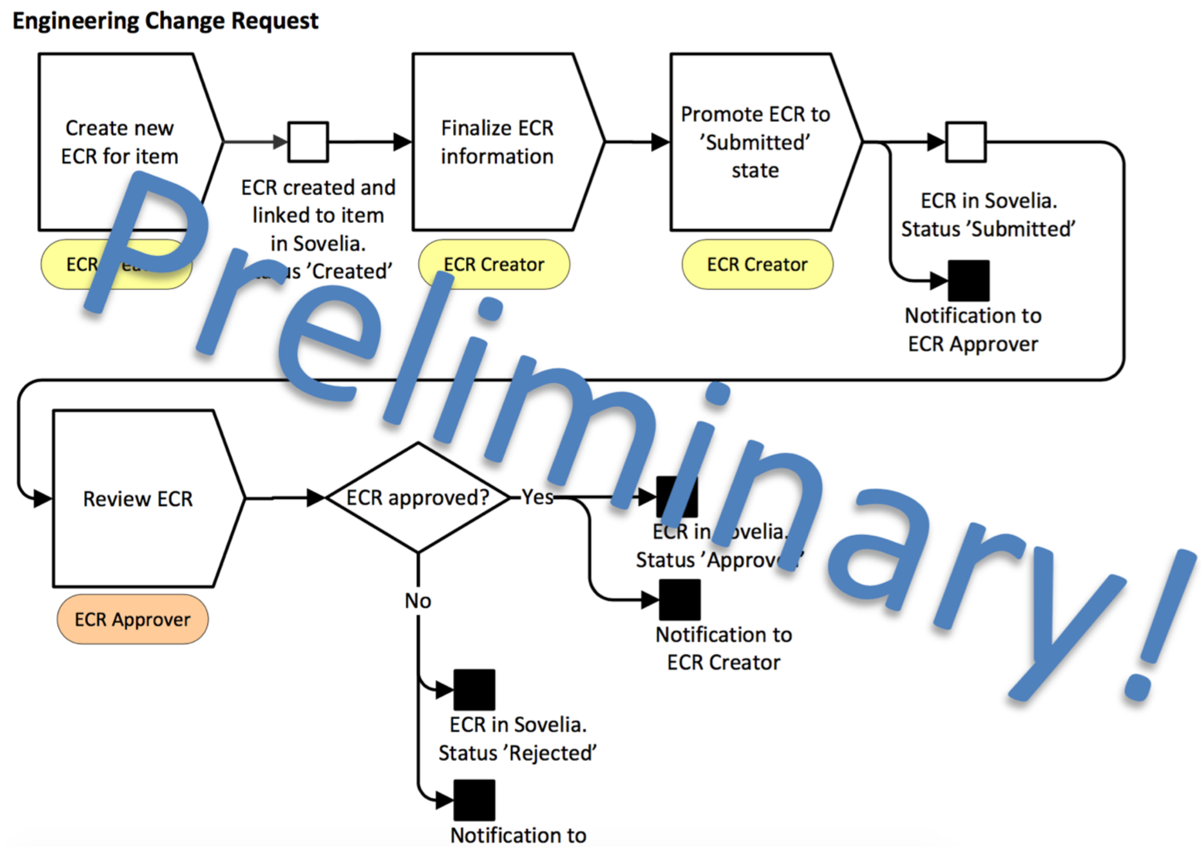


Figure 0-1: Original ECR Process in Sovelia.

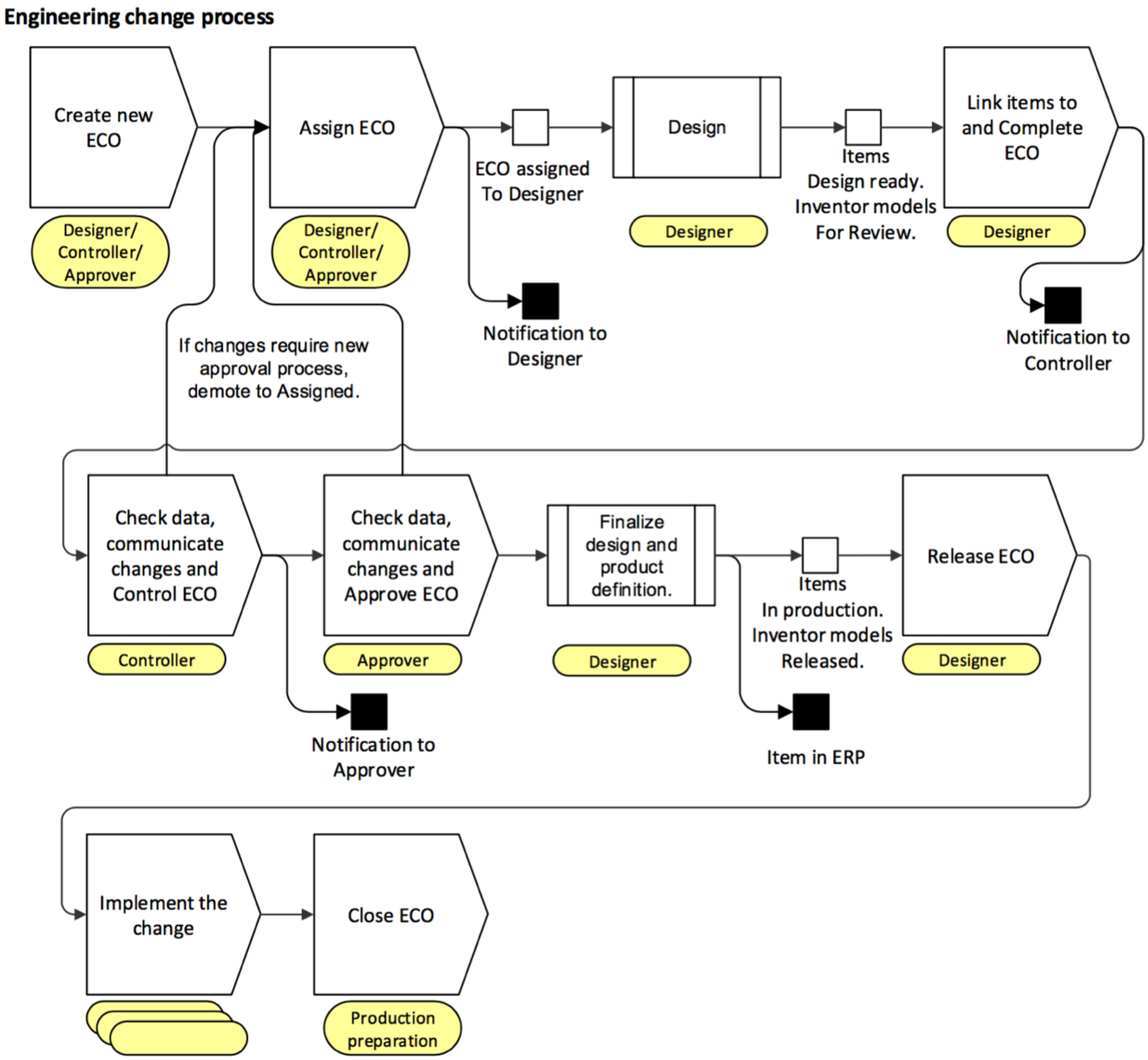


**Figure 0-2: Original ECR Process in Sovelia.**