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Improving product design phase for engineer to order (ETO) product with knowledge base engineering (KBE)

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IMPROVING PRODUCT DESIGN PHASE FOR ENGINEER TO ORDER (ETO) PRODUCT WITH KNOWLEDGE BASE ENGINEERING (KBE)

For the degree of Master of Science

Is approved by the final examining committee:

Nathan Hartman Chair	
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Approved by Major Professor(s): Nathan Hartman

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Head of the Departmental Graduate Program Date

IMPROVING PRODUCT DESIGN PHASE FOR ENGINEER TO ORDER (ETO) PRODUCT WITH KNOWLEDGE BASE ENGINEERING (KBE)

A Thesis

Submitted to the Faculty
of
Purdue University
by
Hanhdung Thi Dinh

In Partial Fulfillment of the
Requirements for the Degree
of
Master of Science

May 2015
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West Lafayette, Indiana

To my husband - for his continuous love and support

To my parents - for showing me the way of life through higher education

To my sisters and brothers – for their support through my schooling

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ABSTRACT

Dinh, Hanhdung Thi. M.S., Purdue University, May 2015. Improving product design phase for Engineer To Order (ETO) product with Knowledge Base Engineering (KBE). Major Professor: Nathan Hartman.

In industry currently Computer Aided Design (CAD) is an important tool for the modification, analysis, or optimization of the 3D virtual environment that replicates the physical product. CAD software is an efficient and reliable tool. However, as globalization increases customer demands, this process needs to be faster and more efficient to accommodate changing product design situations, especially for Engineer-to-Order (ETO) products.

The traditional method of product design process is to operate CAD software without argumentation. Design engineers create CAD prototypes and drawings based on available knowledge and information which comes from engineering experts, company standards, industrial practices as well as other sources. Research has shown that 80% of knowledge is not captured in the system. It can be time consuming for the design engineer to provide an accurate and consistent virtual product. Researchers have found that the traditional method is unreliable, inaccurate and inefficient. There is room for improvement in the product design situation for ETO products. There is a need to develop a design method that is faster and reduces costs.

Knowledge Base Engineering (KBE) is an alternative system that is built to capture and reuse knowledge. KBE technology is well known for reducing lead-time and

design errors using automation. Through integrating KBE technology with CAD software, design engineers create virtual product configurations by applying a scripting language to the CAD model. It requires time and effort invested in a different way than traditional design method, which may cost more to develop. However it is more efficient and accurate when producing multiple configurations.

This research experiment is to define a better design method for the ETO product situation by comparing the traditional design method with the KBE/CAD integration method. The research question is “Is the Knowledge-Based Engineering (KBE) and Computer Aided Design (CAD) integration design approach more efficient for the reduction of lead time and design error than the traditional method for Engineering-to-Order (ETO) product situations”.

CHAPTER 1. INTRODUCTION

With current globalization, industrial companies are required to adapt to a more complex and changing environment. By globalizing products and services, companies have increased opportunities for new customers; therefore increased sales and profits. However these advantages come with challenges as well as potential risks. Furthermore, globalization brings competitors from all around the world. These competitors are able to introduce similar products with minimal cost and improved quality. To stay competitive, industrial companies are under pressure to be more innovative, design better products at a faster rate, and lower cost (Stark, 2011). This is especially difficult for Engineer-to-Order (ETO) manufacturers.

ETO products are a great way for industrial companies to differentiate themselves and raise profit margins. ETO products are highly customized products that are specifically designed and engineered to meet individual customer requirements. They are industrial products that include large electric machines, steam turbines, boilers, ships, and significant industrial goods (Wang, Zhan, & Xu, 2006). Unfortunately, due to their unique and highly customized characters, ETO manufacturers face a tremendous challenge to shorten the lead time and ensure product quality during the product development process. Researchers mention the traditional manual design process is inaccurate and time consuming for the ETO product situations and there is a need for a more advanced methodology with current technology (Ordoobadi & Mulvaney, 2001).

One solution is to re-use the previous product design and standardize the process through Knowledge-Based Engineering (KBE) configurations in Computer Aided Design (CAD) system (Huang, Liu, Ng, Lu, Song, & Li, 2008). A number of literature reviews have discussed the methodology and technology that ETO manufacturers adopted for the configuration process. Many showed that ETO companies are not transitioning to pure product configuration, like mass customization, but rather practice a design process that helps them balance flexibility and standardization (Haug, Ladeby, & Edwards, 2009). Although the transition has taken place in the ETO industry, there is limited research dedicated to examine in detail the impact of the knowledge product configuration brought to the ETO product situation. In fact, there are only a few studies that provide quantitative descriptions on improvement of lead time of ETO products (Haug, Hvam, & Mortensen, 2011). This constitutes a great opportunity to establish quantitative research on the comparison of the efficiency between KBE configuration design and traditional design for ETO product situations.

1.1 Research Question

Is the Knowledge-Based Engineering (KBE) and Computer Aided Design (CAD) integration design approach more efficient for the reduction of lead time and design error than the traditional method for Engineering-to-Order (ETO) product situations?

1.2 Significance

Kratochvil and Carson (2005) explained that “In the 21st century, customization is becoming imperative across the marketplace, in manufacturing as well as in complex financial services, enterprise software packages or even health care” (p. 10). Being that regulation reform has taken place in many countries, economic and policy changes have lowered the barrier that leads to a larger, more competitive, and diverse global market. Concurrent with the aid of new technology, customers are more informed, connected, vocal, and demanding than ever before. Under these circumstances global organizations are pressured to build products up to the individual customer demand while reducing cost, shortening time to market, and ensuring product quality. Over time, many companies have adopted customization strategies that add flexibility in the development process in order to design products to customer demand. The extreme case of customization is Engineer-To-Order (ETO), which represents the intersection of the highest degree of customization with the lowest production volume. Due to these unique characteristics, ETO plays a significant role in a current global economy that differentiates and distinguishes industrial companies from the competitive market (Wang, Zhan, & Xu, 2006).

Distinct from the consumer product, ETO customers are capital goods industrial buyers who have expert knowledge of the related processes or products and often demand critical customer requirements (Mäkipää, Paunu, & Ingalsuo, 2012). It is important to acknowledge customer demand due to the fact that customization has been growing, and continues to grow. It is estimated that roughly 25% of all North American manufacturers provide ETO products and services. Thus, the ETO growth rate is increased at 20% due to the customer demand for customization product (Cutler, 2005). In an ETO market, an annual request for customization shows from 50 to 60 customers at each firm. Each will go through a tendering process to establish quote information. However, only 15% of quotations lead to a full order (Bertrand & Muntslag, 1993). This is a huge loss in opportunity to expand and increase profitability. Research shows that 85% to 90% of costs are committed at the tendering stage. For each quote, industrial companies have to provide information on product performance, estimated prices, delivery schedules, and commercial terms. By losing the bid, companies waste the work they put into creating the product information that the quote states. In addition, each ETO job is typically ensured through contract agreement with legal and financial security that often lasts from one to five years (Hicks & McGovern, 2009). Through successfully obtaining the job offer and developing the product to customer expectations, industrial companies are given a leverage point in the competitive global market while at the same time creating more jobs and contributing to economic growth.

Although there are many challenges for industrial companies to achieve success in the ETO environment, by finding the root challenges, companies can improve their performance. One major difficulty is the long lead time due to uncertainty of customer specifications during the product development phase. During the tendering process, companies must develop proposal information without knowing the explicit requirements from the customer. Often ETO companies propose their best estimates based on information from similar products previously developed. After the order is processed, the projects start with significant involvement from the customers. The customers directly create specifications, monitor the product development process, as well as all the details on the physical information of the product. The ETO companies must get customer approval on every design change before proceeding to manufacturing (Rahim & Baksh, 2003). A typical ETO project can take from months to years to complete. During this process there can be multiple design changes at any point during this time frame. This results in scheduling difficulties and sometime reduces product quality. Many customer specifications require labor intensive activities, especially during the CAD product design phase. Research indicates that traditional manual 3D CAD design processes can no longer accommodate the ETO process and suggest a Knowledge-Based Engineering (KBE) product configuration solution (Rahim & Baksh, 2003). KBE is a knowledge-based system technology enabled to capture and systematically re-use engineering knowledge through the use of rules, relations, and facts. By integrating this technology into or with the CAD system, the KBE/CAD integration tools are designed for users to effectively automate repetitive non-creative tasks and at the same time allow the flexibility of geometry transformation for design innovation (Amadori, Tarkian, Olvander, & Krus, 2012).

A few case studies have been completed with industrial companies to examine the implementation of KBE configuration technology for ETO products. At the Carrier Corporation, a configuration application was developed for the sales and marketing department for a complex air conditioning system product. The system was made up of complex air handling equipment that sales people had to configure and price for the customers. Company reports show 40% of the orders configured by sales people failed to assemble due to design errors. By implementing the expert application, the sales department was able to configure product systems with minimal product knowledge or interaction with the engineering department. The result showed significant reduction in lead time, design errors, and an increase in sales and competitive advantages (Heatley, Agarwal, & Tanniru, 1995).

Another case study was done at the Digital Equipment Corporation. Using product configuration technology, XNET was “an expert system which will be used to design local area networks, to select appropriate components for such networks, and to validate the technical correctness of the resultant network configurations.” (Barker, O'Connor, Bachant, & Soloway, 1989, p. 299). The XNET system allowed users to configure complex hardware and software systems from prerequisite considerations selection of components to validating the complete system configuration including compatibility, licensing issues and environmental data and other requirements. XNET was used across major operations within the organization such as sales, manufacturing, field service, and engineering. XNET successfully provided improved customer experiences, reduced the production costs, and increased productivity (Barker et al., 1989).

From the previous case studies, KBE configuration systems were most suited to ETO products that required expert knowledge to examine the selection of components and equipment to best fit the design specification. Configuration technology provided a way to capture knowledge from expert users to a computer system that would be available to other less experienced users to reuse the captured knowledge. In some organizations, the system enabled users across multiple functions become more competent by using the KBE system as a resource to learn about company products.

(Barker et al., 1989; Fleischanderl, Friedrich, Haselbock, Schreiner, & Stumptner, 1998; Forza & Salvador, 2002).

To utilize the KBE automated configuration system, ETO companies must look for a way to organize a majority of their products to a level that can allow for customized configuration. ETO organizations must exclude the extreme cases of customization to avoid diminishing returns of KBE technology. In addition, KBE configuration technology will not work for products that are purely customized. Pure customization provides unique products that are built from a blank sheet and go through the entire development process as a new system. Some pure customized products are found in construction projects, such as architect designed homes, or buildings, and in manufacturing one-of-a-kind products for individual customers or specific tasks such as special purpose machines or instrumentation (Swamidass, 2000).

Although some companies have successfully implemented KBE/CAD integration as part of their production, many are hesitant to fully implement and integrate KBE/CAD as a potential investment, despite the fact that traditional design has been deemed inaccurate and time consuming (Sjobakk, Thomassen, & Alfnes, 2014). By providing a quantitative study on the comparison between the two design methodologies for an ETO product situation, industrial companies are provided with additional evidence and information in order to make better business decisions. In addition, this study serves as an academic contribution to knowledge of the impact of KBE/CAD integration design methodologies to the ETO product situation.

1.3 Scope of Study

Being that there are few studies done on the topic of Engineer-to-Order (ETO) product and there is a variety of research on product configuration, it is important to define the scope of this study. This research project will focus on the comparison of the efficiency of the KBE/CAD integration design approach and the traditional method in the ETO product environment. The critical factors that drive ETO in this study are the ability to redcue lead time and design errors that are needed to perform Engineering Change (EC) orders that are requested by the customers during the non-physical state of development.

For this research project, Engineer-to-Order (ETO) is defined as "a type of manufacturing process for highly customized products which are required to be designed and engineered in detail as per specifications in the order placed by the customers" (Pandit & Zhu, 2007, p. 759). By definition, the ETO environment is differentiated from other mass customization approaches, such as Assembly-to-Order (ATO) and Make-to-Order (MTO) in terms of product volume and degree of customization. This is because the motivation for implementation of these production customizations is not relevant to ETO (Mäkipää, Paunu, & Ingalsuo, 2012). The ETO products must be defined as physical capital industrial equipment that have a high degree of complexity and customization, and are low volume. Some examples are machinery, equipment plans, power generators, or oil exploration equipment. They are especially developed for industrial downstream operation (Rahim & Baksh, 2003). This study focused on the non-physical stage of the product, which is the process of tendering, engineering, design, and process planning activities. During this state, ETO companies develop conceptual designs for quotation purposes for product specifications, manage engineering change, test designs, and integration through the 3D CAD system (Hicks & McGovern, 2009). Under these conditions, a case study is developed through a sample ETO product.

The sample ETO product was created for two design scenarios: KBE/CAD integration and traditional manual design approaches. To avoid misunderstanding from the variety of KBE systems currently in use, the KBE/CAD integration is defined as a merged KBE language or capability in the CAD environment that enables the engineering user to embed engineering knowledge to create or manipulate geometry through the use of parameters, functions, rules, relations, and scripts. Some of these tools are Knowledgeware in CATIA, Knowledge Fusion in Unigraphic NX, Behavioral Modeling in Creo, AutodeskIntent in Autodesk, and Engineering Intent Corporation and others (Amadori et al., 2012; La Rocca, 2012; Penoyer, Burnett, Fawcett & Liou, 2000). This is considered a low level Application Programming Interface (API) that the users are assumed to be the expert at both ends of user interface and geometric construction techniques in order to capture the knowledge to generate the system (Penoyer et al., 2000). The traditional manual design is referred to the use of 3D CAD system to create virtual products with minimum criteria and no automation involved.

The case study was based on a scenario of a system process skid that is on the market for ETO services in the oil industry. For the KBE/CAD integration case, a 3D master model was prepared with knowledge rules, functions, and scripts, embedded to capture up to 80% of all possible product design configurations, including what has been requested by ETO customers from past orders. At the same time, a traditional design approach started with complete 3D products that are used from past orders. To examine the effectiveness of the two methodologies, moderate Engineering Changes (ECs) were developed. The subject of experiment received training on the knowledge of the product, CAD software training for traditional design and KBE/CAD integration design. Each subject performed the given ECs after the training for both design methodologies. The order of the design methodologies was switched between subjects. Subjects of experiment were volunteers who have experience with the CAD system from the College of Technology at the Purdue University during the semester of Spring 2015. Task manuscripts were provided for the subjects along with a place to record time and survey questions.

The data collected during the experiment were lead-time and design errors for both KBE/CAD integration and traditional design methodologies. The lead time is defined as the total of the time required to develop the system and the time required to complete the EC. An answer key is created for the EC scenario and is assumed to be the correct design model. The completed design of the EC task will be compared to the answer key. The design errors are defined as incorrect information that conflicts with the engineering knowledge given in the EC.

1.4 Assumptions

The following assumptions for this research project include:

- The need to collect quantitative data for ETO product based on the comparison of KBE/CAD integration design methodology and traditional methodology.

- The subjects of this experiment provided accurate and honest data during the testing process concerning their own experience, knowledge, and background in the virtual product domain.
- The subjects of this experiment would complete the test to the best of their abilities.
- The sample size of this experiment would provide adequate data for analysis.
- The subjects of this experiment were able to attend one hour of testing.
- The product that was used for the study was a prototype; meaning for demonstration purposes only and not to be generalized for real-world application.

1.5 Limitations

The following limitations for this research project include:

- The study was limited to the experience level of the user of CAD software either in context of academic or industrial setting.
- The study was limited to the volunteer experience available during Purdue Universities Spring semester of 2015, which encompasses a 100 miles radius of West Lafayette, Indiana.

1.6 Delimitations

The following delimitations for this research project include:

- The experimental tests were developed based on the researcher's knowledge of engineering design and technology.
- The results of the experiment were dependent on how well the subjects interact with the training materials.
- The study used the facilities available at the Computer Graphics Technology Department at Purdue University, West Lafayette, Indiana.
- The time limit for collecting and data analysis was one semester.

1.7 Definitions of Key Terms

Artificial intelligence (AI): "an area of computer science that deals with giving machines the ability to seem like they have human intelligence" (Artificial intelligence, 2014).

Assemble-to-Order (ATO): Standard parts and subassemblies of the product are made to stock. Customers have customization options, however the finished product is built with standardized components. After an order is received, productions is started with a semi-finished product and fabricated in house. Production volumes are low to medium (Amaro, Hendry, & Kingsman, 1999; New & Szwejczewski, 1994; Sjobakk, Thomassen, & Alfnes, 2014; Wortmann, Muntslag, & Timmermans, 1997).

Computer-aided Design (CAD): "used to design physical products in a wide range of industries, where the software performs calculations for determining an optimum shape and size for a variety of product and industrial design applications" (Siemens, 2014).

Customer Order Decoupling Point (CODP): The point in time where a product is in transition from sales forecast to customer order. It is also known as Order Penetration Point (OPP) (Olhager, 2003, 2012; Sharman, 1984; Sjobakk, Thomassen, & Alfnes, 2014).

Engineering Change (EC): Modification that happens to the complete design task and can happen at any stage during product lifecycle (Ahmed & Kanike, 2007).

Engineer-to-Order (ETO): "a type of manufacturing process for highly customized products which are required to be designed and engineered in detail as per specifications in the order placed by customers" (Pandit & Zhu, 2007, p. 759).

Information technology (IT): "the technology involving the development, maintenance, and use of computer systems, software, and networks for the processing and distribution of data" (Information Technology, 2014).

Knowledge-based Engineering (KBE): "Knowledge-based engineering (KBE) is a technology based on the use of dedicated software tools called KBE systems, which are able to capture and systematically reuse product and processes engineering knowledge, with the final goal of reducing time and costs of product development by means of the following:

- Automation of repetitive and non-creative design tasks.
- Support of multidisciplinary design optimization in all the phases of the design process" (La Rocca, 2011, p. 57).

Make-to-Order (MTO): Goods are built according to customer order using standard or predefined components; however the products are fabricated at the time of order. Customers have a higher degree of customization than ATO. For specific orders specialized components are needed. Thus, customer specifications are firm for each order through a low to medium production volume (Amaro, Hendry, & Kingsman, 1999; New & Szwejczewski, 1994; Sjobakk, Thomassen, & Alfnes, 2014; Wortmann, Muntslag, & Timmermans, 1997).

Market-to-stock (MTS): Goods are produced in advance based on sale forecasts. Products involve high volume and stock inventory (Amaro, Hendry, & Kingsman, 1999; New & Szwejczewski, 1994; Sjobakk, Thomassen, & Alfnes, 2014; Wortmann, Muntslag, & Timmermans, 1997).

Mass customization (MC): “the ability to provide customized products or services through flexible processes in high volumes and at reasonably low costs” (Silveira, Borenstein, & Fogliatto, 2001, p. 1).

Mass production: “to produce very large amounts of (something) usually by using machinery” (Mass-production, 2014).

Non-physical stage: Non-physical stage of the product that is the process of tendering, engineering, design and process planning activities (Hicks & McGovern, 2009).

Pure customization: product that is built from scratch and went through the entire new operation system (Swamidass, 2000).

Tendering process: “At this stage, a conceptual design is produced to meet customer requirements. The tender will include information on product performance, price, delivery and commercial terms.” (Hicks & McGovern, 2009, p. 158).

1.8 Summary

This chapter has covered the overview of this research project which includes background, research question, significance, scope of study, assumptions, limitations, delimitations, and definition of key terms. It explained the importance of improving the ETO product to the organization as well as the national economy. It provided an overview of the setup of the research project in order to collect quantitative data from an ETO perspective and its boundaries. It organized the terms that are used throughout the research literature and further explained the meanings of those being used. The next chapter outlines the fundamental information of ETO product and its situation, introducing the concept of KBE, its technology, and how to improve ETO products with KBE/CAD integration technology.

CHAPTER 2. LITERATURE REVIEW

The idea of mass customization of products was adopted in the late 1980s in order to respond to the customer's desire for an individually designed product. This was an opportunity for organizations to expand sales and increase profitability at the same time distinguish them in a fiercely competitive global market. While exploring the concept of mass customization, Silveira, Borenstein, and Fogliatto (2001) provided an extensive review on mass customization by classifying eight specific levels of customization: standardization, usage, package and distribution, additional services, additional custom work, assembly, fabrication, and design. The last and highest level of customization is when the customer is directly involved in the process of design and development. This is the case of Engineering-to-Order (ETO) product.

2.1 Overview of ETO

According to Amaro, Hendry, and Kingsman (1999), Engineer-to-Order (ETO) products are "manufactured to meet a specific customer's needs and to require unique engineering design or significant customization" (p. 351). The ETO product is an exclusive design of a particular product such that each product has its own process of design and fabrication. Occasionally, similar or repeat orders are possible which enables production re-use (Rahim & Baksh, 2003). ETO has a distinct business model in which design and development are the first activities. All other production processes will not happen until the order is placed. Customers are the direct owner of the product. The customer defines the specifications of every aspect of the product which includes features, components, operating conditions, functional performance, etc. For certain orders, customers can be very strict and/or uncertain of the requirements. This can trigger significant design changes that might distort processes downstream of the planning process (Caron & Fiore, 1995). To get a better understanding of an ETO product, it is important to review what type of products are ETO, who the customers are, and who the manufacturers are.

2.1.1 What ETO products are

Different from consumer products, ETO products are capital goods products that require a high degree of customization or an entirely new design and developmental process. ETO products are custom-made physical products that can include some software but is not entirely virtual (Peterson & Friedrich, 2007). It has a highly complex product structure with diversity of sub-assemblies and components. Some examples include turbine generators, cranes, boilers, large electric machines, power generators, oil exploration equipment, etc. (Hicks & Braiden, 2000; Rahim & Baksh, 2003; Wang, Zhan, & Xu, 2006). Elfving (2003) studied long lead-time problems in ETO product situations based on power distribution equipment. Hicks, McGovern and Earl (2000) examined supply chain methodologies for products constrained to ETO processes by participating in the business activities of seven companies that specify power generation, high-integrity materials handling equipment, as well as offshore equipment. Their ETO products are steam turbine-generators, oil platforms, power station boilers, material handling equipments, electronic control systems, and switchgear.

2.1.2 Who the ETO customers are

ETO customers are industrial buyers who specialize in similar or related products or processes. Occasionally, ETO products are used directly in customer production systems or as a component of a finished process (Mäkipää, Paunu, & Ingalsuo, 2012). By ordering customized capital goods, ETO customers often search for a broad solution for their existing problems. Tollner, Blut and Holzmuller (2011) explain that “in the specific situation of the capital goods industry, the buyer is strongly interested in reducing risks when choosing suppliers because a wrong decision may negatively affect the production capability of the firm” (p. 718). ETO manufacturers, or suppliers, are expected to exhibit the ability to deliver the product or service on time, at specification, as well as perform their responsibilities and commitment during the extensive and long duration of the ETO project. It is often written into contracts that ETO manufacture/suppliers are expected to have immediate responses and solutions in the occurrence of a malfunction. To maintain a lasting relationship with ETO customers it is critical that companies consider customer viewpoints to solve their business problems and reduce customer effort (Davies, Brady, & Hobday, 2007; Tollner, Blut, & Holzmuller, 2011).

2.1.3 What the ETO manufacturers are

Depending on the product order, ETO manufactures can provide pure customization or development based on similar products. In pure customization cases, companies must complete an entirely new design and fabrication process. In current business practices, ETO companies are experts of a particular product or related types of work. Rahim and Baksh (2003) explained ETO companies become production experts "due to constraints in technical know-how, experience, skills, capacity, production equipment, and parts procurement or product design" (p. 184). Although this is a production advantage, ETO companies are responsible for the entire process of transforming customer requirements and specifications to a complete delivered product. Furthermore, ETO companies are not engineering and contracting companies. This is because ETO product fabricating and assembly processes take place in-house, where production processes are subject to their control. Engineering and contracting companies often out-source or relocate their manufacturing processes externally (Caron & Fiore, 1995).

2.2 Economic growth and the Production Possibilities Curve

Engineer-to-order (ETO) manufacturers play an important role in the national economy (Hicks & Braiden, 2000; Wang, Zhan, & Xu, 2006). This is mainly because ETO products are considered capital goods. Figure 2.1 shows the graph of the Production Possibility Frontier (PPF) (Riley, 2012). The PPF is the hypothetical representation of capital and consumer goods. Capital goods are complex products and systems that are used by industries in the production of consumer goods and services. When countries invest resources to produce more consumer goods (point B), the opportunity cost decreases the capital goods production due to the removing of resources. Similarly, a trade-off is made when there are more resources going to capital goods investment (point

C). This is the nature of the shape of the Production Possibility Curve (Production Possibility curves, 2014).

The economy grows when there is an increase in quantity and quality factors of production and development of new technology. Figure 2.2 shows the PPF is shifted outward when there is economic growth. The PPF2 curve illustrate the opportunity to produce more capital and consumer goods and services (Riley, 2012). By increasing resources, countries can expand their capacity to produce consumer goods (line BD and CD). Capital goods are complex products and systems that are used by businesses in the production of goods and services. By producing more capital goods, the economy will experience more economic benefit in the future. Therefore, capability to produce capital goods is important to economic development (Production Possibility curves, 2014; Rittenberg & Tregarthen, 2014).

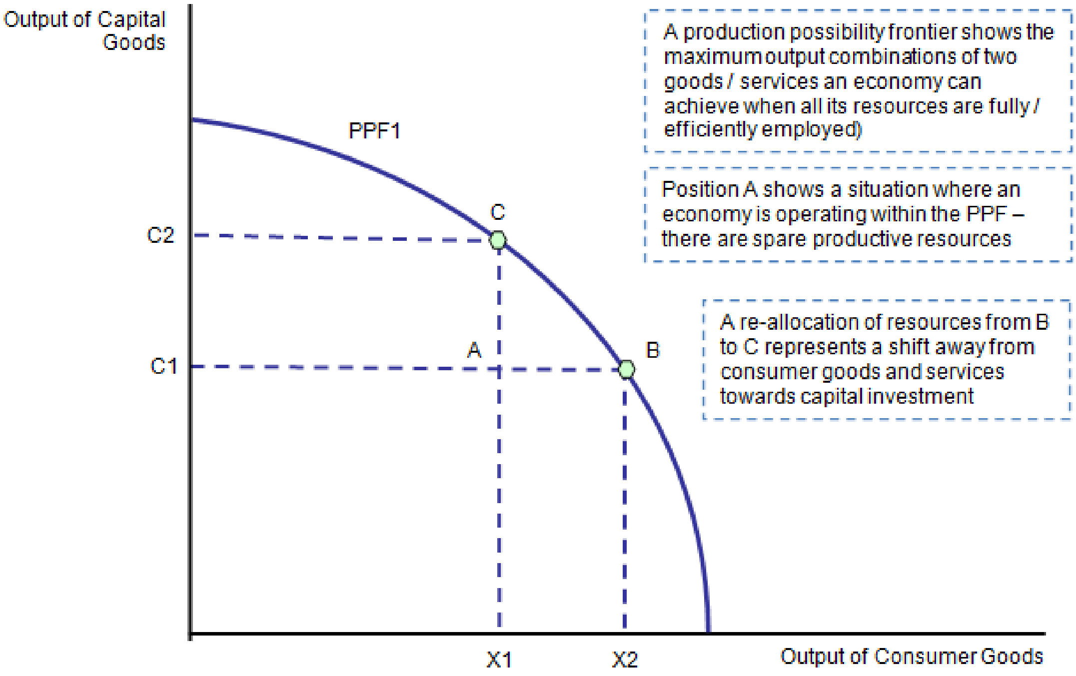


Figure 2.1. The Production Possibility Frontier (PPF) (Riley, 2012).

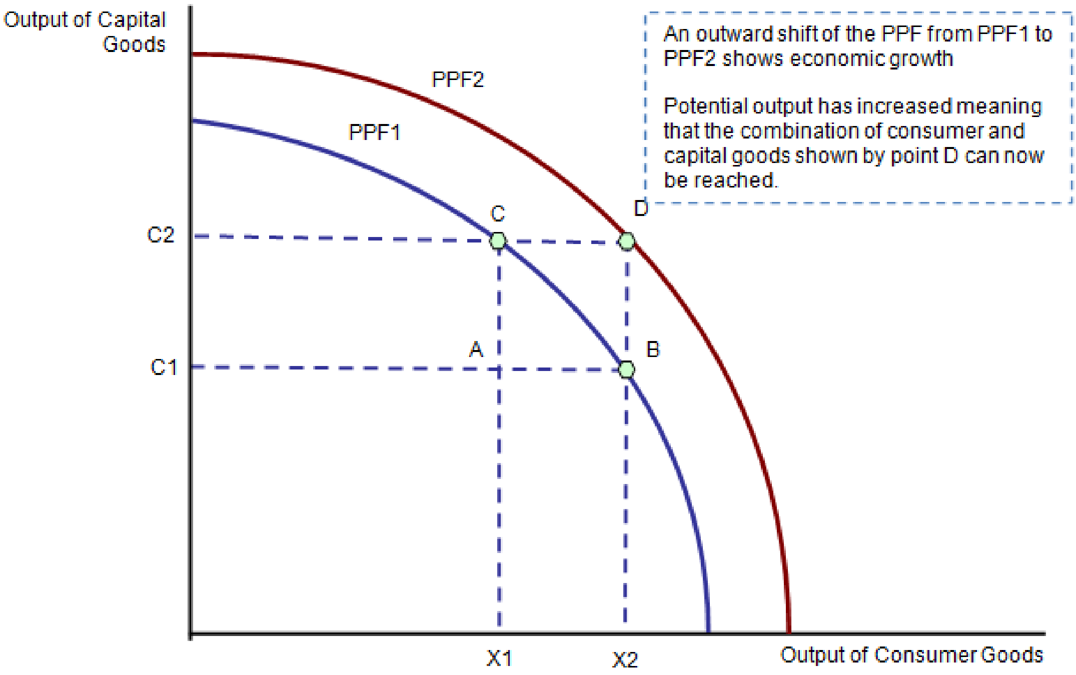


Figure 2.2. The Production Possibility Frontier (PPF) is shifted outward with economic growth (Riley, 2012).

Reports show that 80% of the world is capital goods production belongs to only 10 countries. Other nations import a large number of industrial products either because there are trading barriers or an incompatibility in the development of capital goods. Countries that depend on importing capital goods are negatively affected by their income level due to declining capital stock. On average, countries can experience 17% to 30% loss in income when they depend on capital goods imports (Mutreja, Ravikumar, & Sposi, 2014). Therefore, it is important for countries to produce more capital products than they import. Cutler (2005) mentions opportunities for ETO products and services continue to grow as more and more customers demand individual solutions. Currently the growth rate is increasing at a 20% rate, and it is estimated that 25% of all of North America supplied products are ETO products and services. Utilizing the opportunities of a correct business model and technology, ETO manufactures can increase their profitability while making a difference to the parent nation's economy.

2.3 Engineer-to-Order (ETO) and other product operations

Industrial companies are classified into four types of product operations: Market-to-Stock (MTS), Assemble-to-Order (ATO), Make-to-Order (MTO), and Engineer-to-Order (ETO). Each production operation offers a different degree of customization; therefore manufacturers approach them with different implementations. It is important to understand each product operation type in order to fully recognize an ETO product situation. There are many instances in literature that define the product operation types as below (Amaro, Hendry, & Kingsman, 1999; New & Szwejczewski, 1994; Sjobakk, Thomassen, & Alfnes, 2014; Wortmann, Muntslag, & Timmermans, 1997):

- Market-to-Stock (MTS) - goods are produced in advance based on sale forecasts. Products involve high volume and stock inventory.
- Assemble-to-Order (ATO) - standard parts and subassemblies are used to make products. Customers have customization options, however the finished product is built with standardized components. After an order is received, production starts with a semi-finished product and assembled in house. Production volumes are low to medium.
- Make-to-Order (MTO) – goods are built according to a customer order using standard or predefined components, however the products are fabricated at the time of the order. Customers have a higher degree of customization than ATO. For specific orders, specialized components are needed. Thus, customer specifications are firm for each order through a low to medium production volume.
- Engineer-to-Order (ETO) – high degree of customization allows for distinctive customer specifications that spreads the design scope outside of the companies practice but still restricts the product definition. Every order is treated as a unique engineering project with necessary lead-time. Predefined components are utilized but to a lower degree. Order volume is low. Each order is a unique process of engineering design and manufacturing.

2.3.1 Customer Order Decoupling Point (CODP)

The concept of Customer Order Decoupling Point (CODP) has significant impact on businesses in all product operations: MTS, ATO, MTO and ETO. By definition CODP is the point in time where a product transitions from sales forecast to customer order (another term: Order Penetration Point (OPP)) (Olhager, 2003, 2012; Sharman, 1984; Sjobakk, Thomassen, & Alfnes, 2014). Figure 2.3 shows CODP locations according to four types of production operations: MTS, ATO, MTO and ETO (Olhager, 2012; Sharman, 1984). There are two main factors affecting the CODP location: if the product is the forecast-driven or customer order-driven. In figure 2.3, the forecast-driven is represented with dashed lines and is triggered by downstream CODP. The customer-order-driven is represented with solid lines and is triggered by upstream CODP.

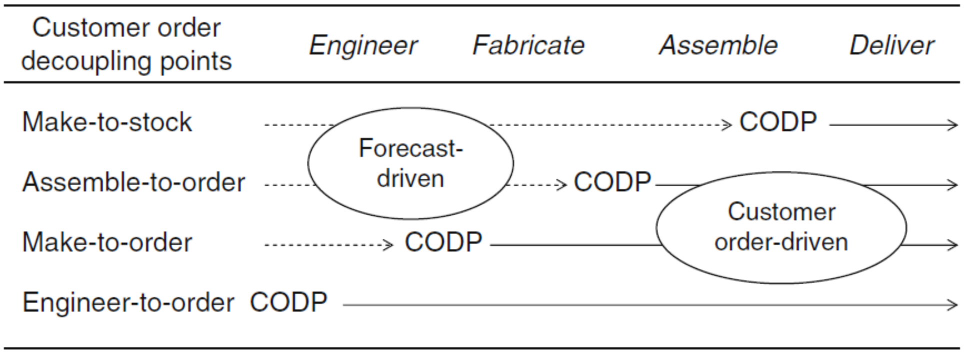


Figure 2.3. Locations of Customer Order Decoupling Points according to different types of product operations (Olhager, 2012; Sharman, 1984)

Depending on the production operation type, CODP can be positioned upstream or downstream along the material value flow. The further downstream, CODP shows a lower level of customer involvement that result in lower production cost. Depending on the type of product and customer demand, industrial companies adjust the CODP location to further upstream. This results in equivalent change of cost and customization. In ETO the CODP is located at the design engineer activity, which is the most upstream of all production operation types. ETO starts with re-engineering the design according to customer specifications, followed by procurement, fabrication, assembly, delivery, and other necessary activities. During this process, companies put in robust effort to meet customer demand, since customer involvement is at the beginning of the product design activity (Qin & Geng, 2012, 2013).

2.4 Key characteristic of ETO

In the article *'Engineering to order' companies: how to integrate manufacturing and innovative processes*, Caron and Fiore (1995) study differences of managing standard and non-standard product systems. The authors found that ETO has a distinct business process separate from other mass production as well as mass customization product scenarios in which sales is the first activity in the business plan. In other cases of mass production and mass customization, products went through the design and engineering process before being introduced to market. Figure 2.2 shows the comparisons of key business processes of mass production, mass customization, and Engineer-to-Order product situation (Lu, Peterson, & Storch, 2009).

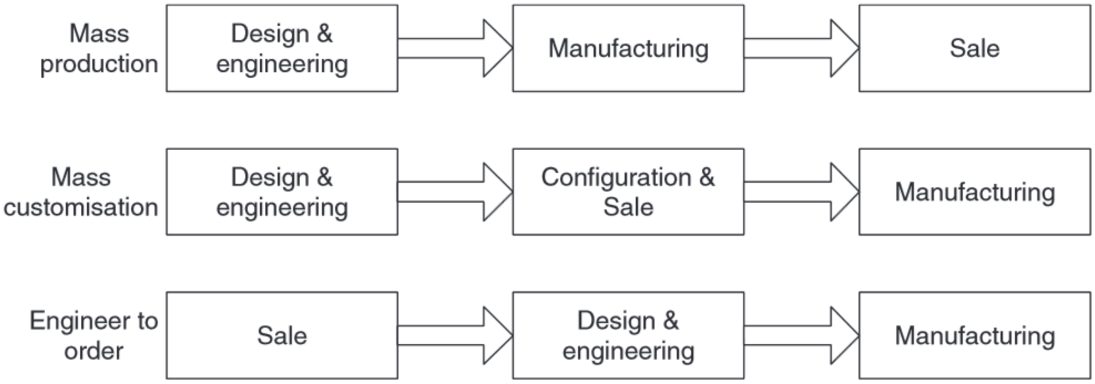


Figure 2.4. Key business processes of mass production, mass customization, engineer to order operations (Lu, Peterson, & Storch, 2009).

Another key characteristic of ETO is that the production situation stands on the intersection of low production volume and extremely high level of customization. Although there is a high level of customer demand, ETO products are often designed to fix a specific problem for the individual customer. This results in low production volume of one to a few for each unit without any prototypes. Concurrently, the highest level of customization comes from customer participation at the onset of the design process. Since the design intent for the ETO customer is to define the solution to their own problem, the design requirements and specifications will vary for each customer order. There is a significant effort for customers and ETO manufacturers to communicate so that the final product is as is expected (Coronado et al., 2004; Rahim & Baksh, 2003). Figure 2.3 shows the relationship between production volume and variety for mass production, mass customization, and the Engineer-to-Order product situation (Coronado et al., 2004; Lu, Peterson, & Storch, 2009).

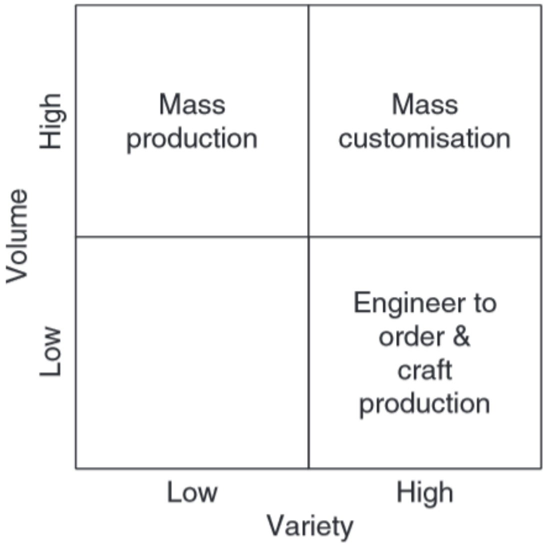


Figure 2.5. Relationships between production volume and variety for different types of product situation (Coronado et al., 2004; Lu, Peterson, & Storch, 2009).

Furthermore, ETO products are very complex and highly technical capital goods that require re-engineering the design and manufacturing processes along with necessary production procedures for each order. Compared with mass produced and mass customized products, ETO products are large physical products that are very expensive to make. Although there is a possibility for repeat orders of a certain a product, each ETO product is unique. ETO revenue depends heavily on high profit margins rather than volume of unit sales (Rahim & Baksh, 2003). Product specifications and requirements are established through a partnership between the customer and the manufacturers. The effort of the partnership is to study the ambiguous needs and problems of the individual industrial customer. Manufacturers must understand the customer business model and take that into consideration in order to implement a proper solution to the design. ETO industrial customers are very strict and specific on their requirements with the possibility of changing the design specification at any point in time. To demonstrate the significance, Tollner, Blut and Holzmuller (2011) state:

> Customers expect the supplier to demonstrate competence and experience, as well as to provide detailed information of how to generate the solution. Customers emphasize that a critical aspect of choosing a solution provider is that suppliers should show commitment toward the project from the beginning stages (p. 716).

The manufacturers must be engaged and committed to their products and services for their customers. It is critical that the ETO manufacturers are not only expected to provide solutions to the existing business problem but to engage in building a long lasting relationship by satisfying customer demand at all times (Tollner, Blut, & Holzmuller, 2011). Appendix A shows the typical ETO characteristic (Sjobakk, Thomassen, & Alfnes, 2014).

2.5 Challenges of ETO products

Like many other product operation types, ETO manufacturers face many challenges to produce high quality and provide high levels of customer service while reducing cost and delivery time. For highly complex capital goods, it is difficult to estimate accurate delivery dates and minimize expensive rework due to the production errors. It is critical to get an accurate design and estimate during the non-physical stage due to the expensive nature of the physical material. The ETO non-physical phase of the product is the process of tendering, engineering, designing, and process planning activities. Research has found that the important factors that significantly affect lead-time include data quality, information uncertainty, and production complexity (Hicks & McGovern, 2009; Little, Rollins, Peck, & Porter, 2000; Pandit & Zhu, 2007).

2.5.1 Information Uncertainty

Information uncertainty has major impact on the lead-time and rework of ETO production, especially during the non-physical phase. The information uncertainty refers to the knowledge and experience of an organization and the difference from the information needed to perform the customers' demands (Galbraith, 1973). There are three aspects of information uncertainty in ETO: uncertainty of product specification, uncertainty of mix and volume, and uncertainty of processes:

- First, uncertainties of product specifications have a large impact on the ETO tendering stage. This stage is the first stage of the non-physical phase where ETO manufactures provide the customer a conceptual design to compete for the customer order. The tender documentation presents customers with product performance, price, and schedule for delivery. By estimating accurate tender information, ETO manufactures can reduce overall cost and lead-time (Hicks & McGovern, 2009). However, it is extremely difficult to provide exact information regarding cost and delivery date due to the many unknowns about the product. Manufacturers use their best knowledge and experience from similar previous projects to provide the best estimate. When decisions are made based on uncertainty, ETO firms made equal adjustments between reductions of delivery time and costs. The initial estimates are often inaccurate due to the unique customization and high complexity of the product. During re-engineering, firms learn more information about the necessary design specifications and resources to produce the order. An accurate process plan at this point could be very different from the initial estimate and might cost twice as much as before. This directly affects the lead-time (Bertrand & Muntslag, 1993; Hendry & Kingsman, 1993; Wang, Zhan, & Xu, 2006).
- Second is the uncertainty of mix and volume of the future demand. For capital goods, ETO sales are influenced by the macro-economic fluctuations, especially in sales volume. Although there are ways to predict the market fluctuation, sales are always different from year to year. In addition to the customer driven nature of ETO production, it is extremely difficult to forecast sales and therefore

impossible to plan for capacity and production. This has direct influence on the preparation time that companies need to produce ETO products and services. People in an organization may be committed to many projects at any given time. Companies might not able to devote their best time and efforts affecting accurate and quality work for ETO quote/order (Bertrand & Muntslag, 1993, Gosling & Naim, 2009).

- Third is the uncertainty of the process. This matter deals with the unknown information from the customer during the production process. Since ETO is customer driven, customers have the control over product design, production processes, and engineering changes. It is difficult to predict the resources needed when part of the design is unknown. This means the information for the specific components used in the physical product might be unknown. Thus, resource planning is a complex process. Each operation on a component or sub-assembly of the product might require large amounts or multiple types of sourcing. Even when ETO companies reserve the capacity for ETO production, it is uncertain what or when an individual component costs more than estimated (Bertrand & Muntslag, 1993; Muntslag, 1994).

2.5.2 Product and process complexity

According to research, long lead times are heavily affected by the design phase. This is mainly due to the heavy work load and limited design capacity in combination with ETO product complexity. During the quotation period, a large number of hours from design and engineering are needed. Typically ETO firms divide the unplanned work among people who might already be involved with other projects. This interference may have short term or long term effects depending on if the quote can obtain the full order. However, companies might be distracted from giving the best work quality in overall measure (Bertrand & Muntslag, 1993).

After the order is acquired, customers and ETO manufactures have to cooperate closely to ensure the product performance achieves expectations. Since the project can take up to five years, there is a large quantity of data exchanged between different members of the project at different phases of the design. Thus, request for engineering changes are very typical and numerous. This triggers a tremendous amount of rework, design modification, and repetitive checks to assure multiple design solutions (Wang, Zhan, & Xu, 2006). Often there are time limits on the due date for design changes that make it very difficult to provide high quality work. Other related reasons for changes are poor coordination and poor communication between participants, early decisions made based on lack of knowledge, design errors, level of complexity that requires specialists and others (Pandit & Zhu, 2007). Researchers found that because of the complicated nature of ETO product, many companies have used the manual, traditional approach (Silveira, Borenstein, & Fogliatto, 2001). However, these traditional, manual design processes are inaccurate and time consuming (Ordoobadi & Mulvaney, 2001).

2.6 Justification of ETO product situation

Although the research mentioned above describes the ETO product situation thoroughly, this section will offer justification to the findings in order to extend present knowledge. ETO and MTO are categorized differently, however, ETO can be considered as the extreme case of MTO product situation with the highest level of customization and lowest production volume. In many cases, it is necessary for ETO manufacturers to make a transition to become MTO in order to reduce the risk and cost of producing “one-of-a-kind” product.

As customer-driven products, MTO is different from ETO because the engineering work is completed before sale and has boundaries on what they will offer during customization. Although this limits the potential sales, MTO manufacturers still offer a wide range of configurations that will satisfy their customers. The ETO marketing scheme is to grant the customer the maximum level of customization and involvement to the design and development process. This is to capture sales but it is a huge burden for the manufacturers to take on. The main goal of ETO customers is to find a reliable manufacturer that can provide effective solutions to their existing problem. When the order is placed, ETO customers are satisfied by the price that is provided from the return quote. By engineering complex capital products to the extreme level of customization, ETO companies will run into unknown and costly risks that the customers are not responsible for. Since all customers look for profits from buying products and services without additional obligations, ETO companies are responsible for the additional cost, effort and unknown risks of the extreme level of customization. Therefore, it is not a good investment for ETO companies to provide individual design and development processes for each customer order.

By adopting a mass customization business model, ETO companies can take advantage of product configuration as a way to provide customization. The key is to build connections between customer problems and the product configuration by aligning the products critical functions and features that directly relate to the customers interests. To provide ETO the right balance between flexibility and standardization needs to be met. However, there are various KBE technologies; organizations must understand the concept and evaluate their need in order to find a right fit for configuration development.

2.7 Knowledge-Based Engineering (KBE)

In the 21st century, Knowledge-Based Engineering (KBE) and its technology are known for enabling design reuse and automation in the application of design engineering. Despite its powerful capability, very little research literature is provided on topic of KBE. This is because KBE was previously only utilized by few highly competitive companies in the aerospace and automotive industries and has not yet been studied in academia. In order to effectively apply the KBE concept and its technology, it is important to understand the scientific literature of the KBE domain. La Rocca (2011) defined:

> Knowledge-Based Engineering (KBE) is a technology based on the use of dedicated software tools called KBE systems, which are able to capture and systematically re-use product and process engineering knowledge, with the final goal of reducing time and cost of product development by means of the following:
>
> - Automation of repetitive and non-creative design tasks.
> - Support of multidisciplinary design optimization in all the phases of the design process (p. 57).

Standing on the intersection of Artificial Intelligence (AI), Computer Aided Design (CAD), and Computer Programming, KBE systems are a specific class of systems that can merge the capabilities of CAD and CAE systems with reasoning, competence, knowledge capture, and representation ability of Knowledge-Based Systems (KBS). KBE is the best practice in highly rule-driven, multidisciplinary, and repetitive design environments that demand geometric manipulation and product configuration (La Rocca, 2012; Liening & Gordon, 1998; Milton, 2008; Negnevitsky, 2005).

Research has indicated that in industrial companies approximately 80% of the time spent in engineering is devoted to routine engineering activities and the remainder 20% is dedicated to innovation. The process from design to manufacturing requires signficant amounts of data and information, which typically relies on the experience gathered from the development of previous projects (Gomes, Varret, Bluntzer, & Sagot, 2009). This knowledge often does not get captured or managed properly for future use. Because a limited number of experts have the information, organizations will run into time-wasting project delays (Gomes et al., 2009; McMahon, Lowe, & Culley, 2004). Therefore, KBE was developed with the intent of capturing and reusing knowledge and information that organization experts collected over the years and embed into a computer system.

2.8 KBE technology evolution

Knowledge-Based Engineering (KBE) technology was first introduced as knowledge management instrumentation to design and engineering processes in mainly capital-intensive industries such as automotive, civil engineering, and especially, aerospace. The Boeing Company successfully developed a prototype KBE system for generating the geometry of thousands of stringer clips fitted and shaped for precise locations in an aircraft (Cooper & La Rocca, 2007).

In the 1980's the ICAD system was the first commercial success of KBE technology, which was created by the integration of Artificial Intelligence (AI) techniques in CAD. The ICAD system uses a LISP-based language closely integrated with a geometric model so engineers can encode engineering knowledge and run data generation programs (Bermell-Garcia & Fan, 2008). The system had an extremely high price tag, which was hundreds of thousands of US dollars for a single installation of hardware and software. The early systems were geared toward expert developers, such as aerospace and automotive industry while not much toward the casual user (Cooper & La Rocca, 2007).

As the design and engineering workplace uses primarily CAD-based models, state-of-the-art KBE technology is embedded within the CAD system understanding that KBE is a wide-spectrum general-purpose programming and geometric modeling concept (Cooper & La Rocca, 2007). CAD developers have recognized the potential of knowledge management and KBE technology to implement PLM concepts. By the early

1990’s, the high end of the market, such as Catia and Unigraphics, included KBE functionalities in their CAD units (La Rocca, 2012):

- In 1999 PTC released the Pro/Engineer 2000i Behavioral Modelling package with comprehensive functionalities to capture design knowledge, enable geometry automation and interact with external applications. The software was developed with and used C programming language which does not require Pro/Engineer users to buy additional license to run the application (PTC, 2014).
- In 2001 UGS introduced Unigraphics NX Knowledge Fusion that was based on by KBE language Intent!, from Heide Corporation. Knowledge Fusion application used a true KBE language that is compatible with the traditional KBE technologies and is extended to NX end-users. In 2007 Siemens bought UGS and used it as part of PLM software (PLM World, 2014).
- In 2002 Dassault System absorbed Knowledge Technologies International (KTI), an independent organization that was well known leader of KBE solutions and was the developer of ICAD. Dassault System retired ICAD and concentrated KTI resources to create Knowledgeware, a KBE add-on for CATIA V (Dassault Systemes, 2002).
- In 2005 Autodesk acquired Engineering Intent Corporation, an expert on the development of Engineer-to-Order (ETO) software and services. Autodesk exploited their KBE applications Autodesk Inventor to advance a technological solution of mass customization as customer demand. AutodeskIntent was introduced as a way to capture and reuse working knowledge for standardization

and automation. AutodeskIntent was also known as Inventor Automation Professional and now as Autodesk Inventor Ilogic (Autodesk, 2005).

As KBE became part of CAD systems, many medium sized engineering firms increasingly used KBE technology. However, in order to succeed, KBE must be enabled to complement the existing CAD system so that explicate engineering knowledge can be embedded (Cooper & La Rocca, 2007). Figure 2.6 illustrated the time line of major branch in KBE evolution (Milton, 2008).

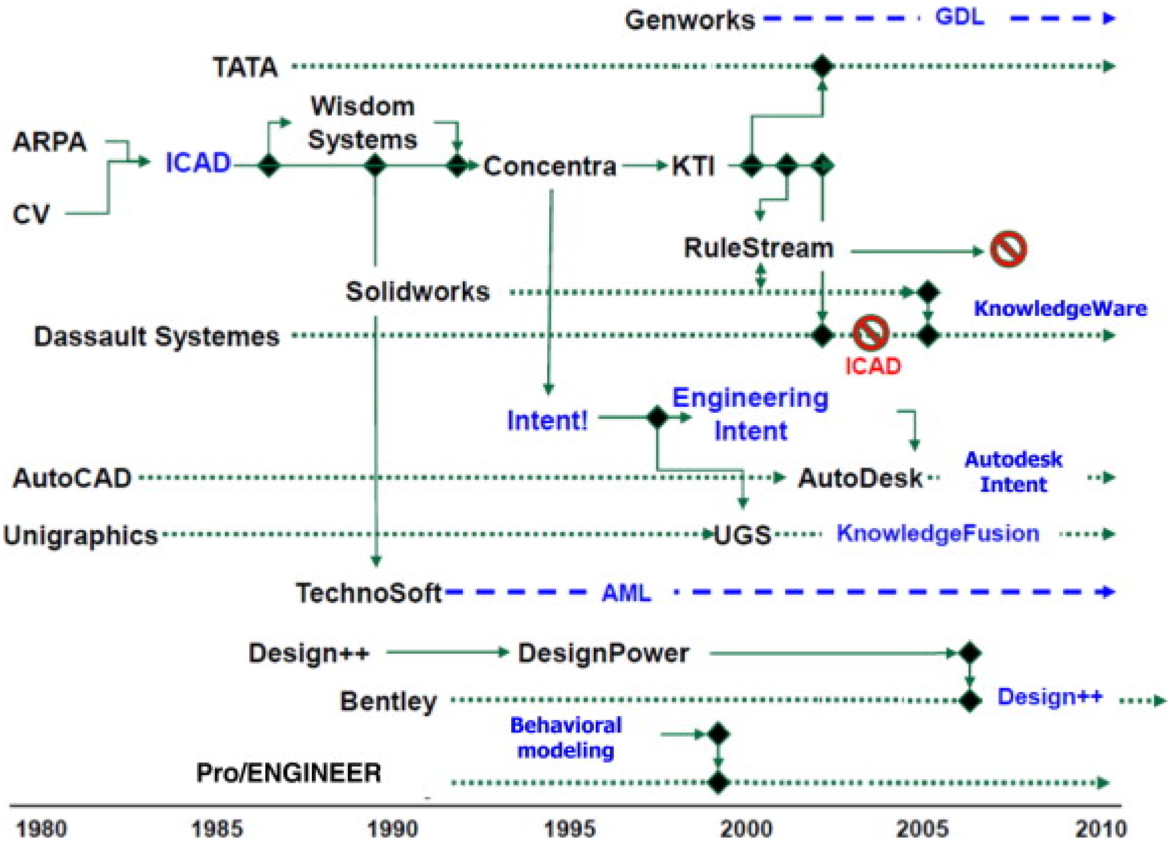


Figure 2.6. The time line of major branch in KBE evolution (Milton, 2008)

2.9 KBE technology as a transitioning tool for ETO toward Mass Customization

To address the problem of long lead-time and reduction of errors in production, mass customized companies utilized KBE technology to capture and reuse product design. Although this concept might not be the best fit for the significant customer driven nature of ETO products, research shows there are ETO companies that made the transition to mass customization in order to inherit many benefits of a customer driven product. Although many possible KBE technologies are available for the development of product configuration, there is little research literature that shows the use of KBE application for ETO product situation. The results show a reduction of long lead time and product errors, an increase in knowledge capture and reserve, less routine work, fewer resources for specification, and others (Felfernig, Jannach, & Zanker, 2000; Forza & Salvador, 2002; Hvam, 2004).

Hvam (2006) and Hvam, Pape and Nielsen (2006) documented a case study of a large cement processing plant manufacturing. They implemented product configuration systems to automate the quotation process. By using the application, the sales department was able to respond to all customer quotation requests without the need to collaborate with an engineering specialist. The company was able to provide quality quotes at early stages and with very little input information. The company reported a normal three to five week task of preparing quotes which was improved to one to two days. However the application often directed customers to options of company standard product instead of follow-up with an individual design request.

Hong, Hu, Xue, Tu and Xiong (2008) identified a case study at a window and door manufacturer in Canada. The company developed a configuration application that was specialized for one-of-a-kind product using generic programming. The system allowed for two types of product variation: configuration variations and parameter variation, to create a random form of product specification tree base. As a result, the lead time was reduced from two months to three weeks. However, the system is IT dependent in that the engineering organization does not directly work with the virtual product development or modification.

Forza and Salvador (2002) presented a case study of implementing a product configurator to a voltage transformer company. ETO characteristics are found in the company business process: define product variant, design and engineer variants, and production. With the configuration technology, the company found no error in product release, reduced lead-time for tendering process, increased productivity, and formalized company knowledge and many others. However, the ETO complexity in this product is not very high.

Jiao and Zhang (2005) presented a product portfolio that can customize product families according to specific customer requirements for purposes of engineering oriented companies. The methodology used data mining and mining rules to find the associations from history data, product evolutionary paths, and customer feedback. The product portfolio transformed the customer requirements in customer databases to functional requirements in the functional domain. It was a great way to recapture knowledge domain for a more effective use.

Although literature presents successful KBE implementations for ETO product configurations, these applications are initiated from the IT or KBE specialist perspective that use generic programming. With this approach, the applications are heavily dependent on the expert programmers for development, modification, and maintenance. This contradicts the original target user of KBE system, the engineers. Unless engineers are trained for professional programming skills, they don’t directly work with the product configuration. In addition, this research does not provide quantitative data for the reduction of lead time.

2.10 KBE architectures

Before KBE systems were built into CAD software, KBE and CAD were two separate domains with different design intents. Knutson (KBE history) explained “CAD systems focus on geometry. KBE systems focus on rule capture and knowledge, with geometry merely being one of many kinds of rules and outputs that can be generated.” To successfully implement automation in engineering design, organizations must recognize various paths of development and define the method that is most convenient for their business model.

Figure 2.7 shows different levels of KBE architectures (Shintre & Shakir, 2011). When the priority is to interact with geometry generation and manipulation, deploying from a CAD based system is more appropriate. Engineering organizations will have direct control of the product model that uses a lower level of automation through mathematical expression and parameter features (Coronado et al., 2004). On the pyramid, the first two levels of KBE architect are dedicated to engineering users. The first level is based on KBE features available in CAD. To get further control of engineering rules and design knowledge, the second level offers a scripting/automation base with VB, VB.net language (Shintre & Shakir, 2011). When the priority is to capture engineering rules and design intent, a programming approach is the best solution for KBE systems. The third level of the pyramid utilizes API based programming that is often deployed by IT or KBE specialists. These systems are more difficult to maintain, higher in cost, and require separate licenses. Each architecture level has its own pros and cons "in terms of development cost, ease of maintenance, knowledge protection, ability to manipulate low level details, among others" (Shintre & Shakir, 2011, p. 11).

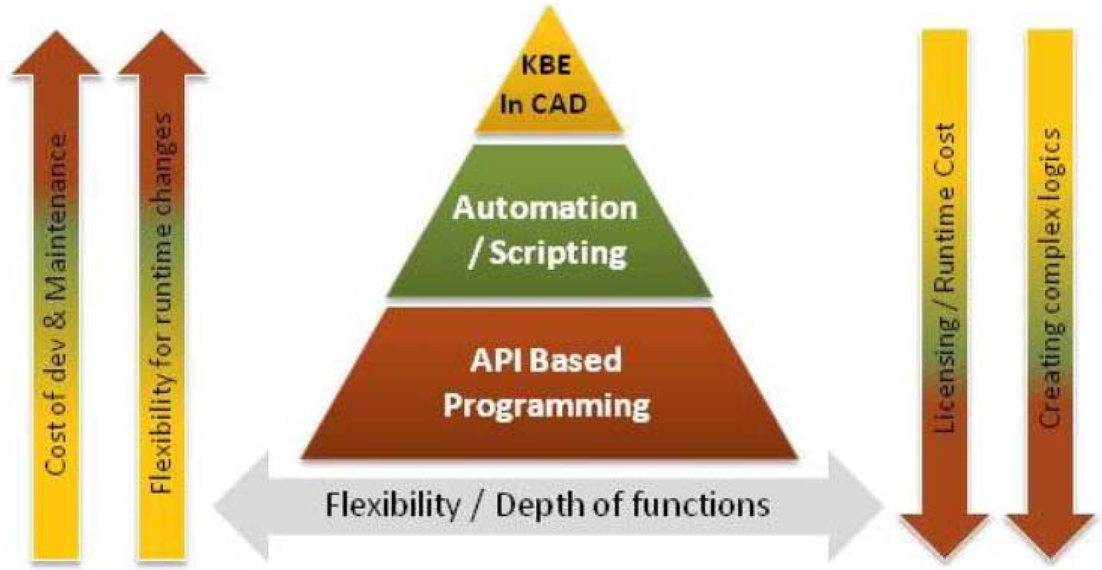


Figure 2.7. Levels of KBE architectures (Shintre & Shakir, 2011).

2.11 KBE/CAD integration design methodology

In this study, a KBE/CAD integration system is used because the focus is to configure the product model according to EC order and to be ready for the fabrication process. KBE/CAD integration includes all the KBE features and scripting ability that are available in the CAD software. To enhance design reuse and automation through KBE, these CAD modeling strategies are used to incorporate KBE/CAD integration, dynamic top-down design approaches, high level CAD modeling, and rule based design.

2.11.1 Dynamic Top-down design

Traditionally the CAD product model can be assembled in two types of design approaches: top-down and bottom-up. Top-down design methodology starts with the top level assembly that represents the overview of the whole system. In this top level assembly, all significant information is formulated and breaks down to its component sub-systems. The top level assembly maintains control over the product structures (McFarland, 1986). However, it is rare that the system is a pure top-down design.

In the bottom-up design approach, all the lower level components are built separately based on the incoming information during the early development process. After the design is known, all the components are integrated into higher levels of the system (Loew, 2013). Often the bottom-up design provides opportunity for more design modification of the components; however, it is difficult to incorporate multiple design concepts.

Figure 2.8 illustrates the model development process in relationship with design reuse and automation (Tarkian, 2009). The bottom-up design is the least appropriate for the design automation structure because there is no linked relationship between the components. Often this approach results into poor morphological and topological stages. The top-down design is more suitable for automation in morphological design but not for the topological stage. To truly achieve design automation and reuse, dynamic top-down design is introduced as an advanced top-down design structure. In dynamic top-down design, the design geometry, shape, placement, and number of CAD models must be structured in a way that will allow automation capabilities (Tarkian, 2009).

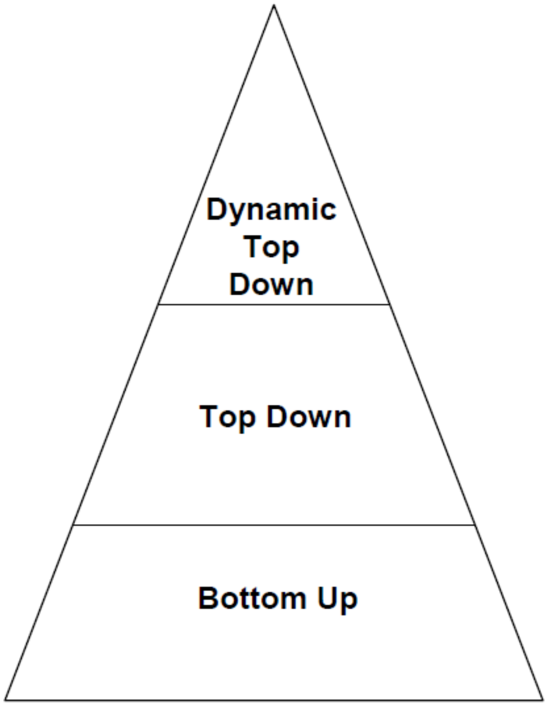


Figure 2.8. The model developments process in relationship with design reuse and automation (Tarkian, 2009).

2.11.2 High level CAD modeling

For automation design and reuse, high level CAD modeling is categorized into divisions of morphological and topological concepts. Morphological is concerned with the modification logic that made up the geometric shape. Topological refers to the effectiveness of the representation of the geometry such as to be added, to be replaced, or to be removed (Tarkian, 2009).

2.11.2.1 Morphological transformation

Morphological transformation are changes “that occur within the same instance of a given class, i.e. it is enough to re-evaluate the instance” (Amadori et al., 2012, p. 182). There are four different levels of morphological stages. Figure 2.9 illustrates the morphological stages of geometric modeling (Tarkian, 2009). These stages are arranged in a pyramid system that each higher step gains complexity in modification.

- Fixed object is the first level and has no morphological value. These objects are static and cannot be changed in shape because geometry is built based on a fixed set of values.
- Parameterization is the second level and built in a way that allows for geometric values to change. However, there is no relation between the parameters. These objects are only useful for non-complex geometries.
- Equation based relations make up the third level and carries mathematical relationships between parameters. By nature, there are less input parameters needed as result of the relationships.
- Script based relations are the fourth and highest level of the morphological stages. In this stage, parametric relationships are captured using programming languages inside the CAD system that allow for higher complexity in geometric modifications (Amadori et al., 2012; Tarkian, 2009).

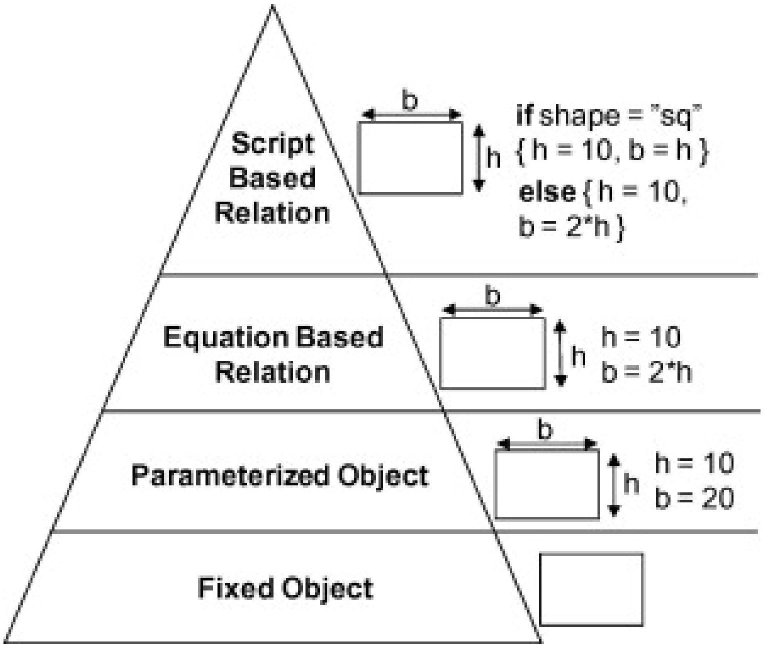


Figure 2.9. The morphological stage of geometry modeling (Tarkian, 2009)

2.11.2.2 Topological transformation

Topological transformation is change that is associated with the number and placement of the object in the model (Amadori et al., 2012). Below are three types of events that can take effect in this stage:

- Adding an instance is when the new object is brought to the model and located at a specific place.
- Removing an instance is when an object is discarded from the model at a specific location.
- Replacing an instance is when an object is removed and another is added to the model at a specific location (Amadori et al., 2012).

Below are four levels of topological stages that are organized in a pyramid setting. Figure 2.10 illustrates the topological stages of geometry modeling (Tarkian, 2009). These levels are:

- Manual instantiation is the first level and is manually performed. The instances of the object in this level are manipulated by copy, paste, and delete functions which cannot be re-instantiated. There is no constraint definition.
- Automatic instantiation is the second level and has a defined template. The instance of the object is controlled by the template model and does not have a constraint relationship with the surrounding geometry of the instance because there is no constraint definition. In this level, the number of instances is parameterized.
- Generic Manual Instantiation is the third level and provided constraint dependency to the surrounding geometry of the instance from manually produced templates and constraints. The instance is completely defined within the template and is constrained to the surrounding geometry. Reusability is increased.
- Generic Automatic Instantiation is the fourth and highest level of topological transformation. In this level, the pre-defined instance can be automatically generated and/or deleted by user input. Thus, the instance of the object has parametric value. Design automation and reusability are successfully defined (Amadori et al., 2012; Tarkian, 2009).

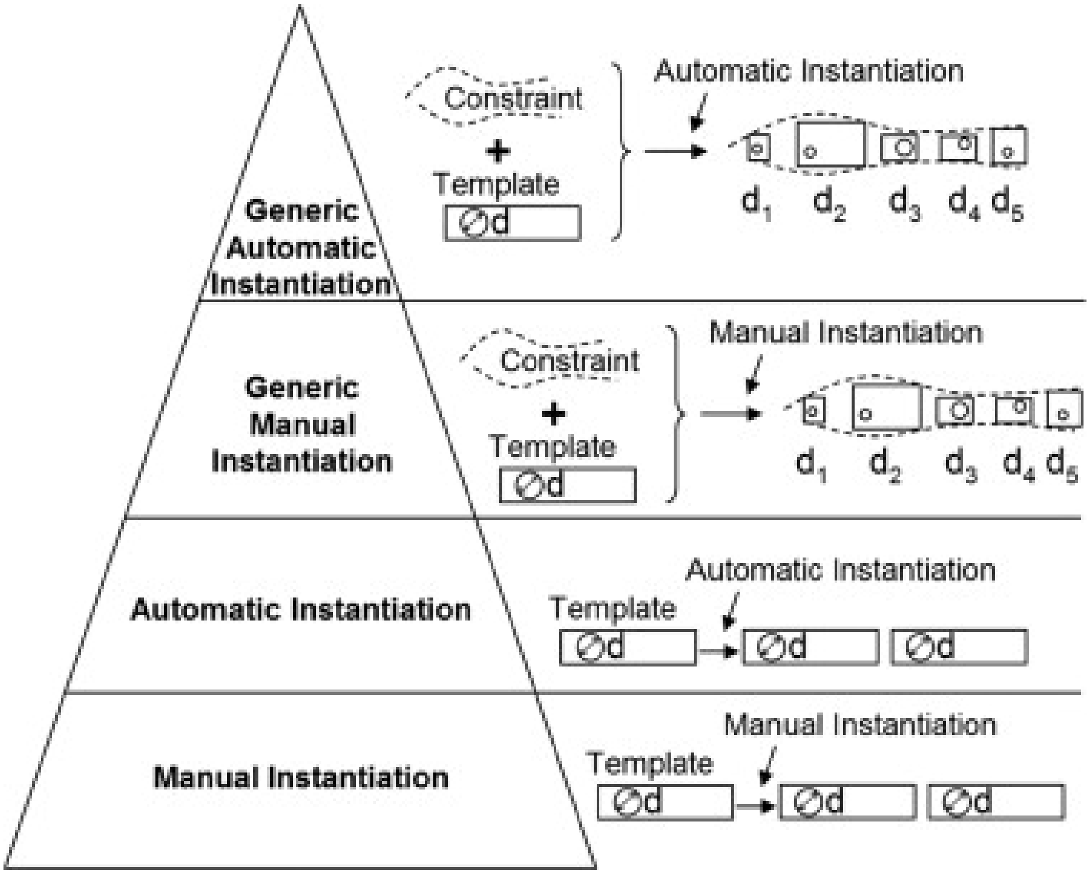


Figure 2.10. The topological stages of geometric modeling (Tarkian, 2009).

2.11.3 KBE Rule base design

KBE technology is often known as rule-based design. La Rocca (2012) explained, "In KBE parlance, all the possible expressions used to define attributes (slots), specify the number and type of objects, communicate with external tools, and so on, are addressed with the generic term of rules (or engineering rules)" (p. 168). It is important to recognize the differences between KBE rule based design and the conventional rule based design system. KBE rules are written in the form of If-Then statements and separated into reasoning mechanisms and knowledge bases. Some of KBE rules are logic rules, math rules, geometry manipulation rules, configuration selection rules, and communication rules, to name a few (La Rocca, 2012).

2.12 Associated risks in ETO transitioning to Mass Customization

Many researchers have proven that knowledge-based configuration can significantly reduce lead-time and design errors. By transitioning from ETO towards mass customization, organizations must be aware of the associated risks involved. The major difference between the two types of production are that mass customization has some redefined solutions before being accepted as customer order and less extreme customized work (Rudlberg & Wikner, 2004). This indicates that ETO companies must standardize their products to a level that can allow for configuration. However, even with less customization, developing knowledge-based product configuration for ETO is still a challenge (Edwards & Ladeby, 2005; Hansen, Riis, & Hvam, 2003). Other associated risks are limited ability to innovate, increased opportunity for competitors to imitate the design, and organizational agreement toward the process of standardizing engineering work (Edwards, Hvam, Pedersen, Moldrup, & Moller, 2005).

However, ETO actually never became a real mass customizer. The purpose is to find the right balance between flexibility and standardization. Thus, ETO companies take costs of standardization into consideration. When the level of complexity is too high, the cost of the configuration project might be too high to be profitable (Haug, Ladeby, & Edwards, 2009).

2.13 Summary

This chapter provided the in-depth study of the ETO domain that included what ETO products are, who the customers are, and who the manufacturers are. It explored the complexity of the ETO product situation by presenting the characteristics and challenges surrounding ETO. As a result, KBE/CAD product configuration was found as a potential solution to improve the design and development process and a possibility of transitioning ETO business models to become more like MTO. This chapter also explained the concept of KBE and its technology as the foundation to navigate to the KBE architecture solutions that are the best fit for the organization business model during product development and configuration. The following chapter outlines the research project methodology that includes the framework, the procedure, a description of the subjects of the experiment, the use of tool, and analysis.

CHAPTER 3. METHODOLOGY

The purpose of this research is to determine if there is a positive effect when using the KBE/CAD integration design method versus the traditional design method for the Engineer-to-Order (ETO) product situation. The research framework and methodology were identified based on an experiment based case-study and analyzed through quantitative statistics. The experiment is a comparison between two design methodologies: KBE/CAD integration and traditional methods.

3.1 Research Framework

Following Knowledge-Based Engineering (KBE) being introduced to Computer Aid Design (CAD), it has been well documented that through the ability to capture and re-use knowledge for automation, KBE has enabled shorter the lead times and reduced human error (Huang et al., 2008). There is extensive literature related to the topic of product configuration. However, there are limited research documents that have integrated the use of KBE in lead time reduction in the complex enviroment of ETO product manufacturers (Haug, Hvam, & Mortensen, 2011). There is a need to develop quantitative data in the impact of KBE on lead time reduction, and product data quality on the ETO product environment. Hvam (2006), Hong et al. (2008), Forza and Salvador (2002) conducted case studies with different engineering-oriented companies on the “before and after” phases of product configuration. Haug, Hvam and Mortensen (2011) collected surveys from 14 companies that adopted product configuration for similar business situations of ETO products. Another way to provide quantitative data is to design a comparative experiment based on the previous research of ETO product environment. The intention of this research is to recognize a better design approach for ETO products. The data collected from this case study would guide ETO manufactures to better understand their product situation in order to invest more prudently and be more committed to their decisions.

3.2 Research Methodology

The research methodology was based on the question “Is the Knowledge-Based Engineering (KBE) and Computer Aided Design (CAD) integrated design approach more efficient in the reduction of time and design error than the traditional method for Engineering to Order (ETO) product situations?” An experiment case-study was designed with a pairwise comparison method in order to collect data for this research. Benbasat, Goldstein and Mead (1987) defined “A case study examines a phenomenon in its natural setting, employing multiple methods of data collection to gather information from one or a few entities (people, groups, or organizations)” (p. 370). It allows researchers to understand the complex ETO environment in order to analyze and confront current problems. Pairwise comparison is also known as two-way testing. It is very practical and effective for many types of software systems (Cohen, Dalal, Parelius, & Patton, 1996, 1997). By using the pairwise testing, the data collected from the KBE/CAD design methodology can be compared with the reference data from the traditional design methodology. The intent was to determine whether there are differences within the statistical data from both design methodologies.

3.3 Procedure

The experiment was divided into two phases; the developmental phase and the design-change phase. The developmental phase considers the process of creating the 3D CAD product assemblies for both design methodologies: KBE/CAD and traditional. The design-change phase is the process of applying an Engineering Change (EC) order to existing product assemblies. Figure 3.1 illustrates the structure of the research methodology.

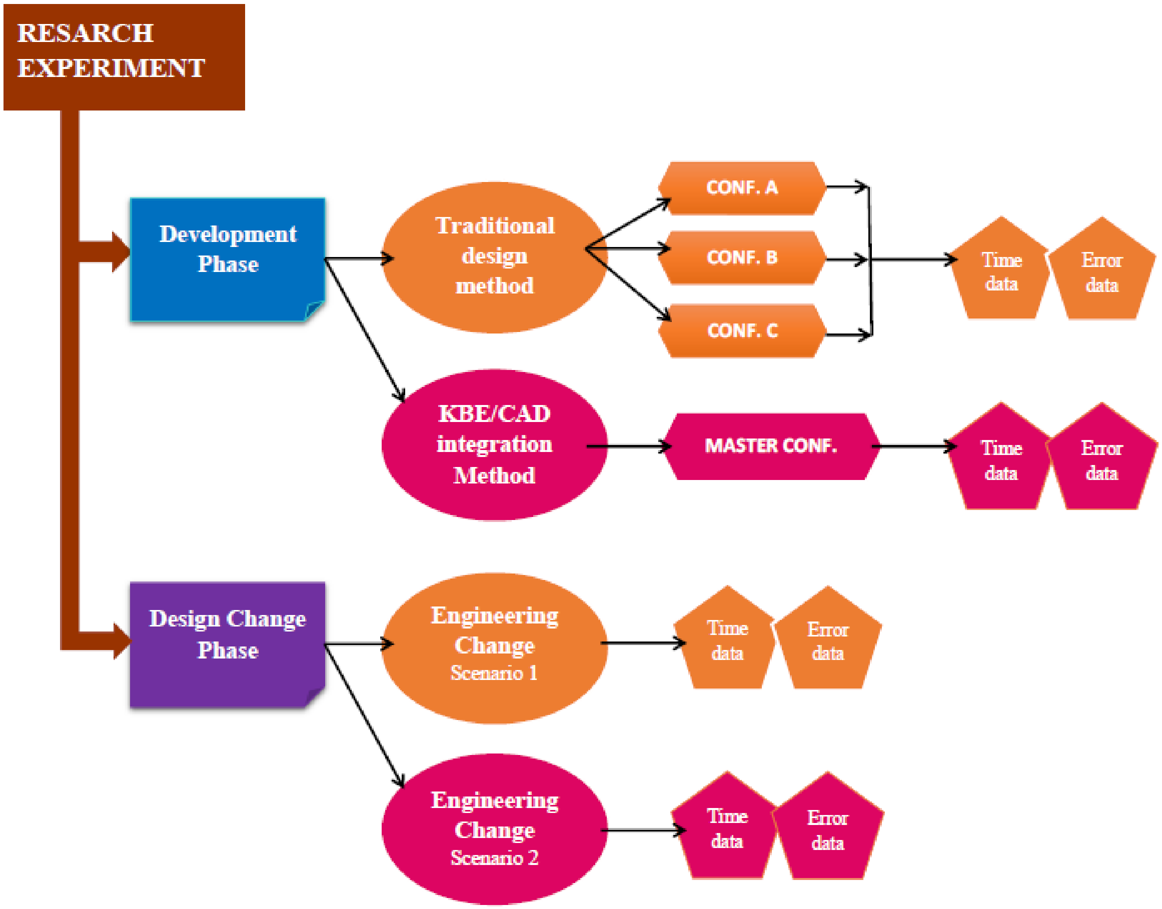


Figure 3.1. The structure of the research methodology.

The critical dependent variables of reduction in lead-time and design errors were relevant for both phases. The lead-time is defined as the total time required to develop the virtual product model and to complete the EC order. The number design errors is the number of conflicts with the answer key version of the EC order. The study designed the product system and other related information based on industrial standard practice of steel and piping systems (American Institute of Steel Construction, 2005; Smith & Thomas, 1987).

The design methodologies were developed using different CAD modeling strategies. Table 3.1 shows the differences between the modeling methodologies (Amadori et al., 2012; Bodein, Rose, & Caillaud, 2013; Shintre & Shakir, 2011).

Table 3.1.
The differences between the modeling methodologies

	KBE/CAD method	**Traditional method**
Method of geometry infrastructure	Dynamic-top down design	Bottom up design
Method of morphological transformation	Script base relation	Parameterization
Method of topological transformation	Generic automatic instantiation	Generic manual instantiation
Method of CAD template	3D automated master model	Finished product models from previous work
Method of capture and reuse knowledge	Script based rules Automatic check Automatic calculation	User knowledge and documentation Manual check Manual calculation
User expert	Automation and scripting (VB, VB.Net) CAD user	No programming CAD user

The experiment was formulated into two scenarios of null and alternate hypotheses:

Ho1: There is no change in the reduction of the lead-time between the design methodologies in ETO environments.

Ha1: There is a positive change in the reduction of the lead-time between the design methodologies in ETO environment.

Ho2: There is no change in the reduction of the design errors between the design methodologies in the ETO environment.

Ha2: There is a positive change in the reduction of the design errors between the design methodologies in the ETO environment.

3.4 Subjects of Experiment

The subjects of the experiment were volunteers who have experience utilizing 3D CAD software in the College of Technology at the Purdue University during the Spring semester of 2015. The resources and time were taken in consideration when determining the sample size. When the sample size is too small, the calculation may not identify the statistical significance. When the sample size is too large, the experiment might consume costly resources that are not necessarily needed to detect important effects (Noordzij et al., 2010). The Statistic Consulting Service at Purdue University considered the experiment setting and population with the assumption of 0.05 significant levels and power of 0.80 to estimate the appropriate sample size of the study. The sample size was 30 subjects at mininum (Noordzij et al., 2010; Purdue Statistics, 2014).

Each volunteer received three different kinds of training to prepare them for the research experiment: the product system training, CAD traditional design training and KBE/CAD integration design training. Appendix B shows the training materials created to provide the volunteer knowledge for the research experiment. The training material is described below:

- The product system training took was a narrative document. It was designed to provide users with engineering knowledge about the product. It included information about all of the components of the product and how to assemble them together.
- The traditional design method training was a training video and a 3D CAD assembly. It was designed to prepare subjects for using AutoDesk Inventor software, its interface, common tools and features.
- The KBE/CAD integration design method training was a training video and a 3D CAD automated configured assembly. It was designed to prepare subjects for using AutoDesk Inventor iLogic, its interface, common tools and features.

Each test subject performed the Engineering Change (EC) order for both design methodologies: KBE/CAD integration and traditional. However the order of the two methodologies was randomly decided. This was to offset the effect of method doing one experiment before the other. This case study was defined as a pair t-test for comparing two different design methodologies that are completed by the same subjects (Shier, 2004).

After the subject of the experiment completed testing, a survey was collected to determine if the training materials had a positive effect on the individual subject. This information was used to help understand if there were deviations in the measurement of results.

3.5 Development phase

During the development phase, the virtual product models were created based on both KBE/CAD design methodology and traditional methodology. The product was an example of the industrial equipment that is used in oil refinery industries. It was a suction line sub-assembly of a system process skid. The pipe sizes included in the design were 2, 3, and 4 inches.

The development time and design error were recorded for each design methodology. Figure 3.2 illustrates the research structure of the development phase.

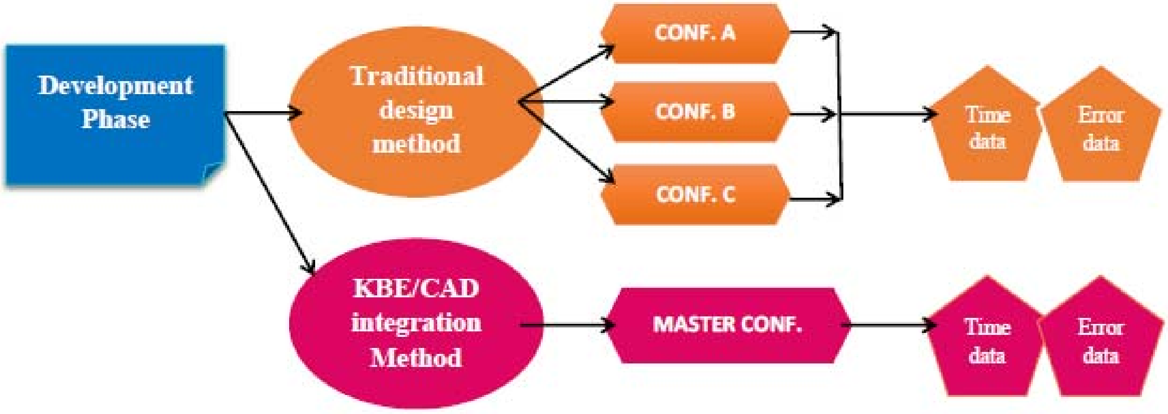


Figure 3.2. The research structure of the development phase.

For the traditional design methodology there were three complete and separate product assemblies that represent the different product configurations (A), (B), and (C). These product assemblies were designed manually using bottom-up design, manual instantiation of the model, and manual knowledge capture and reuse. A product library was created for all the piping equipment and piping fittings for pipe sizes of 2, 3 and 4 inches. To perform the EC order for the traditional design method, an initial product assembly was created according to the before EC product diagram. The subject performed the test using this initial product assembly for the traditional design method.

For the KBE/CAD design approach, the 3D master model was created with dynamic top-down design, automatic model instantiation and scrip for knowledge capture and reuse. The 3D master model had the ability to be configured to all three standard designs (A), (B), (C) and others. The purpose of the 3D master model was to automate most of the design scenarios that had been done in previous customer specifications. In this case, the 3D master model was designed to contain up to 80% of possible design scenarios. To perform the EC order for the KBE/CAD design method, the 3D master model was configured according to the before EC product diagram. The subject performed the test starting with this configuration for the KBE/CAD design method.

3.5.1 Preliminary data for Development phase

To prepare for this research experiment the preliminary data was developed from CGT 590000 Knowledge-Based Engineering, a graduate independent study course from the Computer Graphics Technology department at Purdue University. The course focused on researching information on KBE theory and technology. The virtual product models were developed for both the traditional and KBE/CAD integration methods used during the study. For the traditional design method, the preliminary data were 3D assembly models for product configurations A, B, C. For the KBE/CAD integration design method, the product configurations were automated in the 3D master assembly model.

Table 3.2 shows the development time for the product configuration A, B and C using the traditional design methodology. Figure 3.3 shows graphical representation for the development time using Traditional design method. The data was collected from October 13, 2014 to November 10, 2014. The total time of development was 16 hours.

Table 3.2.
The development time for the product configuration A, B and C using the traditional design methodology.

Traditional development time	
Date (2014)	Time (hrs)
10/13	1.82
10/14	5.12
10/17	0.27
10/30	3.22
11/1	1.98
11/5	0.68
11/9	2.35
11/10	0.57

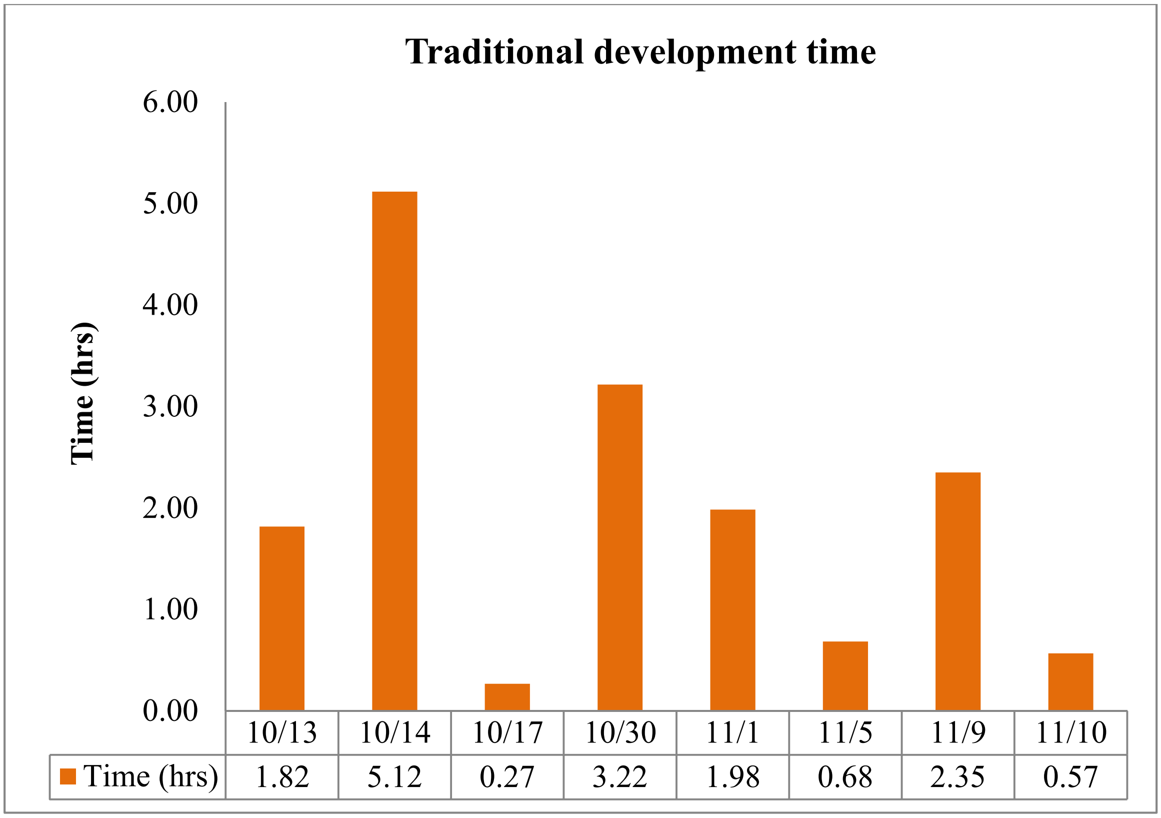


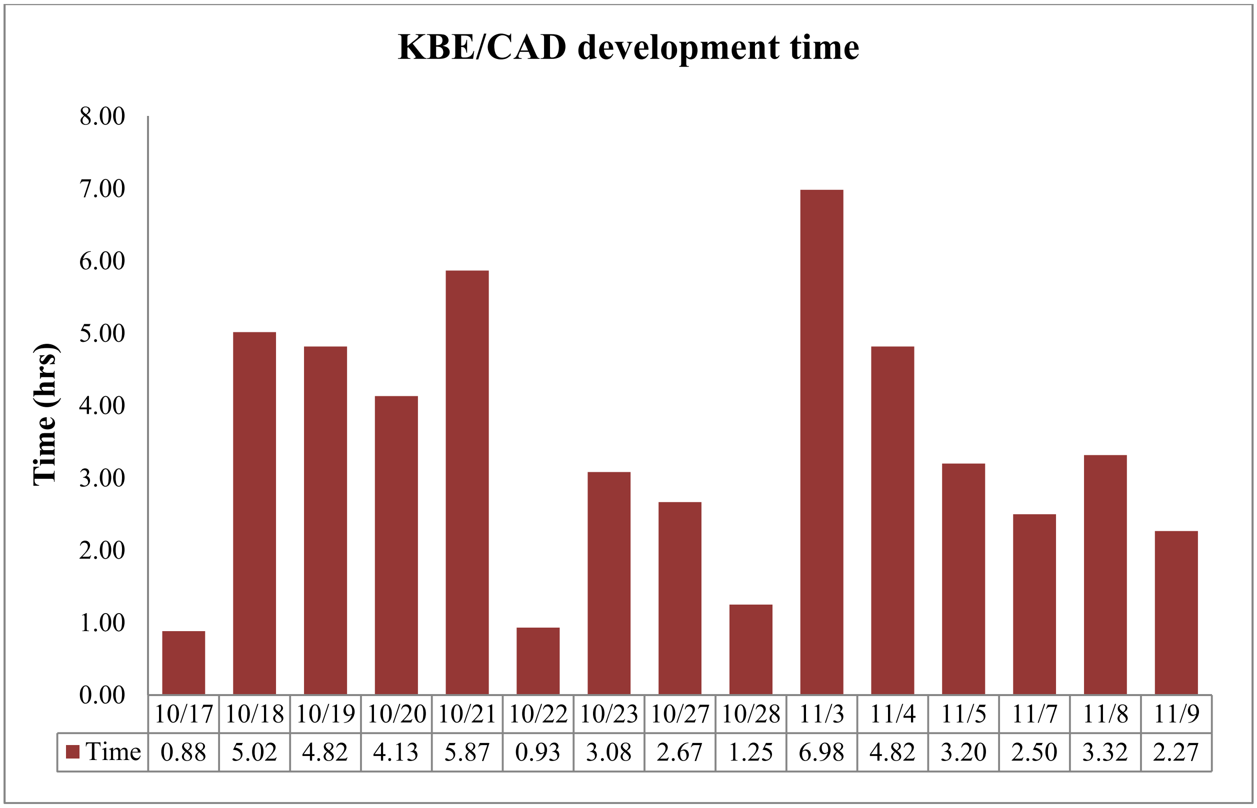
Figure 3.3. Development time using the traditional design method.

Table 3.3 shows the development time for the 3D automated product configuration master model using the KBE/CAD integration design methodology. Figure 3.4 shows graphical representation for the development time using the KBE/CAD integration design methodology. The data was collected from October 17, 2014 to November 9, 2014. The total time of development was 49.47 hours.

Table 3.3.

The development time for the 3D automated product configuration master model using the KBE/CAD integration design methodology.

KBE/CAD development time	
Date (2014)	Time (hrs)
10/17	0.88
10/18	5.02
10/19	4.82
10/20	4.13
10/21	5.87
10/22	0.93
10/23	3.08
10/27	2.67
10/28	1.25
11/3	6.98
11/4	4.82
11/5	3.20
11/7	2.50
11/8	3.32
11/9	2.27



	10/17	10/18	10/19	10/20	10/21	10/22	10/23	10/27	10/28	11/3	11/4	11/5	11/7	11/8	11/9
■ Time	0.88	5.02	4.82	4.13	5.87	0.93	3.08	2.67	1.25	6.98	4.82	3.20	2.50	3.32	2.27

Figure 3.4. Development time using the KBE/CAD integration design method.

Figure 3.5 shows the comparison of the development time between the design methodologies. The development time for KBE/CAD integration design method was three times the development time of the traditional design. This was due to the additional time spent on coding to automate the CAD modeling technique. The techniques used were dynamic top down design, script based relations for morphological concept, generic automatic instantiation for topological concept design and rule based design. However, the results showed the master model can configure a design in seconds.

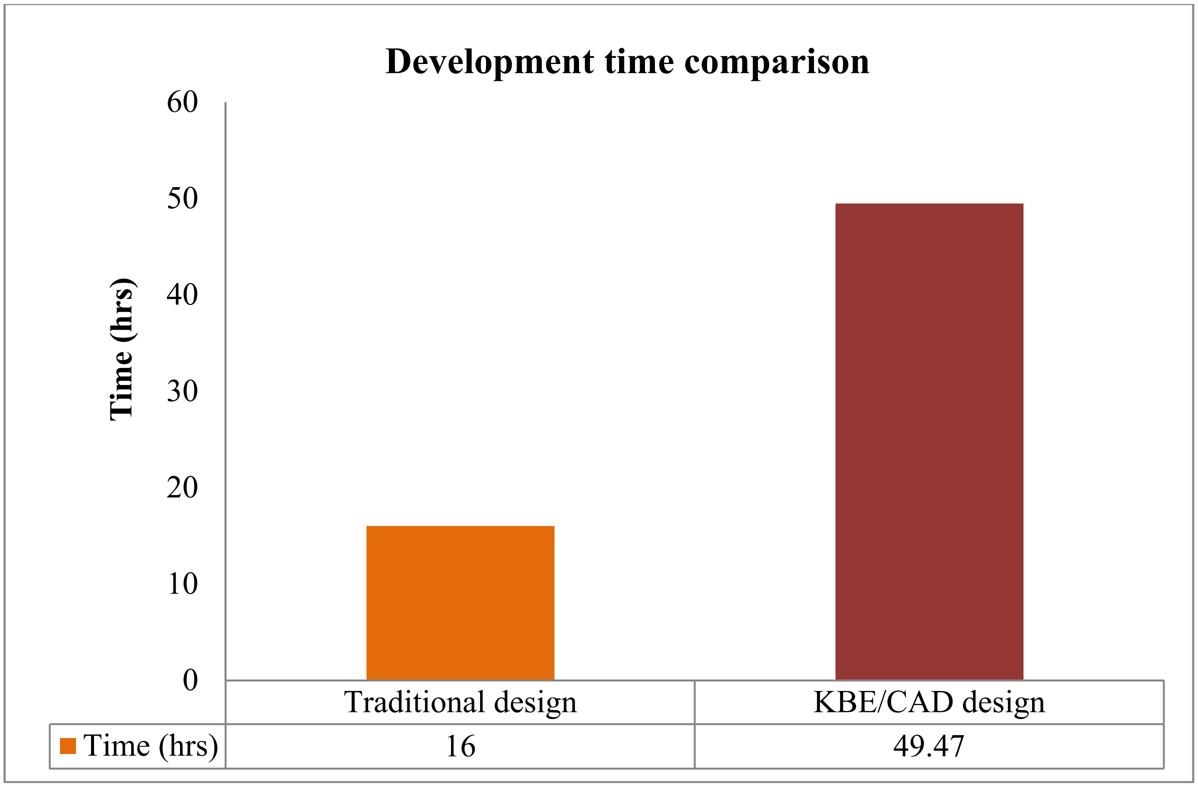


Figure 3.5. Development time between the traditional and KBE/CAD integration design methods.

3.6 Design-Change phase

For the design change phase, the Engineering Changes (ECs) were developed with product diagram and descriptions. There were moderate level ECs and included five tasks to be performed on the product configuration. The EC document included an instruction sheet with step-by-step directions on how to complete the experiment. Instruction I was for subjects who performed the first design scenario. Instruction II was for subjects who performed the second design scenario. Appendix C shows the EC order documents.

The subject of the experiment applied the EC order by both design methodologies: the traditional design methodology and the KBE/CAD design methodology. The order of the design methodologies were switched between subjects. There was limited time given to complete the EC order. However, users had a choice to submit the document on time or extend the deadline as necessary. The time was recorded for the EC modification process and the completed EC change document was checked for design errors.

Figure 3.6 illustrates the research structure of the design change phase for the first scenario where the traditional design method was performed before the KBE/CAD design method. The first scenario was organized as follows:

- The subject of experiment was given the product system training.
- After the product system training was completed, the subject was trained for the CAD software and performed the EC order with the traditional design method. The initial product assembly for the traditional design method was used.
- After the ECs were completed with the traditional design method, the subject was trained for using the KBE/CAD script and performed the EC order with the KBE/CAD integration design method. The 3D master model was used with the initial product configuration that represented the before EC change.

Figure 3.7 illustrates the research structure of the design change phase for the second scenario. The second scenario was organized with the KBE/CAD integration method given before the traditional design scenario.

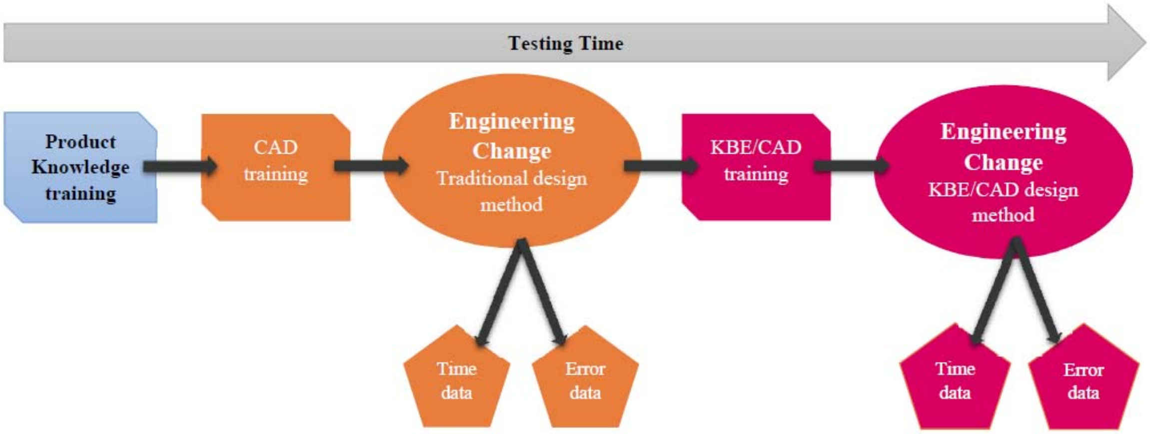


Figure 3.6. The research structure of the design change phase for the first scenario.

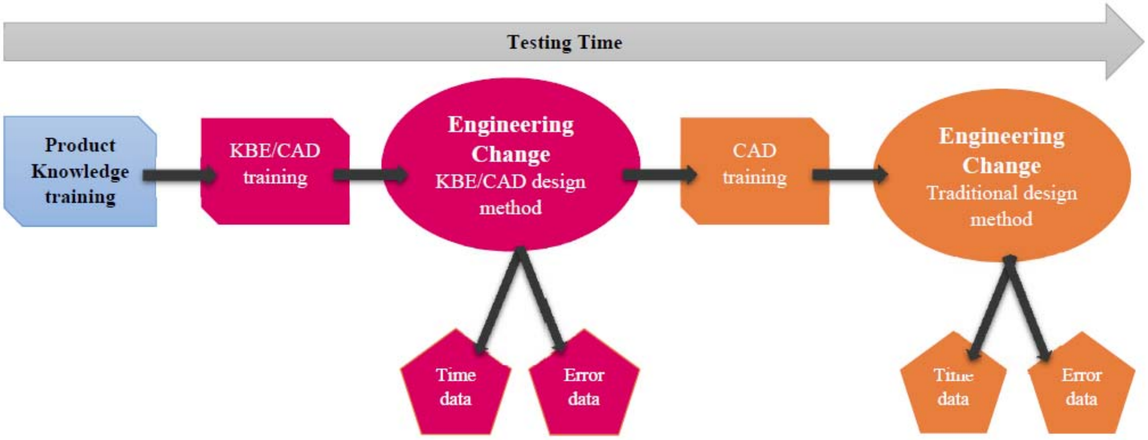


Figure 3.7. The research structure of the design change phase for the second scenario.

During the experiment, data were collected for the time to complete the tasks and design errors. Table 3.4 shows the collected data during the design-change phase. Each subject of the experiment provided four data:

- Time to complete the tasks for the traditional design methodology.
- Number of design errors for the traditional design methodology.
- Time to complete the tasks for the KBE/CAD integration design methodology.
- Number of design errors for the KBE/CAD integration design methodology.

Table 3.4.

Collected data during design-change phase.

		1st test		2nd test	
		Traditional Method		KBE/CAD method	
#	Subject	Time	Design error	Time	Design error
1	A	A1	A2	A3	A4
2	B	B1	B2	B3	B4
3	C	C1	C2	C3	C4
4	D	D1	D2	D3	D4
5	E	E1	E2	E3	E4
6	F	F1	F2	F3	F4
7	G	G1	G2	G3	G4
8	H	H1	H2	H3	H4
9	I	I1	I2	I3	I4
10	J	J1	J2	J3	J4
11	K	K1	K2	K3	K4
12	L	L1	L2	L3	L4
13	M	M1	M2	M3	M4
14	N	N1	N2	N3	N4
15	O	O1	O2	O3	O4
		KBE/CAD method		Traditional Method	
		Time	Design error	Time	Design error
16	P	P1	P2	P3	P4
17	Q	Q1	Q2	Q3	Q4
18	R	R1	R2	R3	R4
19	S	S1	S2	S3	S4
20	T	T1	T2	T3	T4
21	U	U1	U2	U3	U4
22	V	V1	V2	V3	V4
23	W	W1	W2	W3	W4
24	X	X1	X2	X3	X4
25	Y	Y1	Y2	Y3	Y4
26	Z	Z1	Z2	Z3	Z4
27	AA	AA1	AA2	AA3	AA4
28	AB	AB1	AB2	AB3	AB4
29	AC	AC1	AC2	AC3	AC4
30	AD	AD1	AD2	AD3	AD4

3.7 Use of tools

The CAD software used for the experiment was Autodesk Inventor 2014. The KBE/CAD integration package was I-logic Inventor 2014. This is one of the most commonly used CAD software combinations for ETO manufacturers.

3.8 Data Analysis

The collected data of the lead time and design errors were analyzed using descriptive statistics. The statistical consulting service at Purdue University was used as a professional resource to run data through statistical software and evaluate quantitative data (Purdue Statistics, 2014). A paired t-test was selected for the study since it is best used to "compare two population means where you have two samples in which observations in one sample can be paired with observations in the other sample" (Shier, 2004, p. 1). In this study, a comparison of the two product design methodologies was applied to each subject of the experiment. A paired t-test evaluated differences between the paired values of lead time and the number of design errors of the two methodologies. The results decided the acceptance or rejection of the null and alternate hypothesis of the study.

If there were no differences found in the data of time on task and user errors, the null hypothesis would be accepted and the alternate hypothesis would be rejected.

If there were positive differences found in the data of time on task and user errors, the null hypothesis would be rejected and the alternate hypothesis would be accepted. Table 3.5 shows the null and alternate hypothesizes and the data that needed to be collected for the experiment.

Table 3.5.
The null and alternate hypotheses and data needed to be collected for the experiment.

Hypothesis	Ho1	Ha1	Ho2	Ha2
	There is no change in the reduction of the lead-time between the design methodologies in ETO environments.	There is a positive change in the reduction of the lead-time between the design methodologies in ETO environment.	There is no change in the reduction of the design errors between the design methodologies in the ETO environment.	There is a positive change in the reduction of the design errors between the design methodologies in the ETO environment.
Data Collected	Trad. Time (hrs)	Trad. Time (hrs)	Trad. Design Errors (ers)	Trad. Design Errors (ers)
	KBE Time (hrs)	KBE Time (hrs)	KBE Design Errors (ers)	KBE Design Errors (ers)
	CAD Package (quantity)			
	CAD Education and Experience (month)			
	Product System Training (Rating and Comments)			
	Traditional CAD Training (Rating and Comments)			
	KBE/CAD Training (Rating and Comments)			

3.9 Summary

This chapter explained the research project methodology including the framework, the procedure, the subjects of experiment and the use of tool. It introduced the null and alternate hypothesis of the study and how to collect and analyze the data. The next chapter will present and analyze the data collected from the experiment.

CHAPTER 4. DATA RESULTS ANALYSIS

This chapter presents the research experiment data, the statistical analysis of the data, the examination of Pearson's correlation between data variables, and the evaluation of the training material used in the experiment. The lead-time was re-evaluated from the previous chapter and compared with the data of the time investment to balance the decision making between the Traditional and KBE/CAD integration design methodologies. The experiment sample is analyzed.

4.1 Demographics

The study looked at subjects from the engineering and technology student population at Purdue University. Data were collected from students taking CGT 423, AT 402, MET 102 and a small number of graduate students from the College of Technology during the Spring semester of 2015 at Purdue University. A total of 86 students participated in the research study. Out of these 86 students, the results from16 were scrapped due to missing information leaving data from 70 students available to analyze.

All subjects had previous education and experience with CAD software and were at least second year (sophomore) students of the College of Technology at Purdue University. The levels of CAD experience varied between subjects. Subjects were asked to provide the number of classes and the amount of work experience with CAD software. A semester class is based on the 14-17 weeks calendar (Ashford, 2001). The study counted each class as 4 months of CAD training which includes high school and college courses. Work experience was counted by months. Figure 4.1 shows the overall CAD experience level of subjects by months. The average CAD experience was 25 months, with a minimum of 3 months, and a maximum of 120 months.

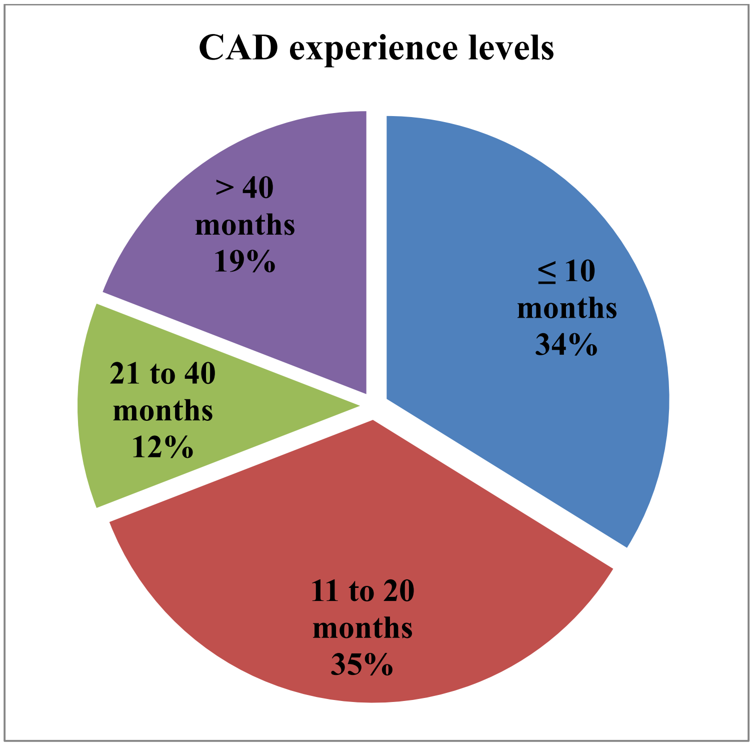


*Figure 4.1.*CAD experience levels of subjects.

4.2 Outlier Analysis

Before analyzing the data, it is important to examine and remove the data errors. Researchers have found at least 30% of samples that are drawn from a normally distributed population will contain more than one outlier (Dawson, 2011), which applied to all sample sizes. Outliers are data errors that were caused either by experimental error or inherent variability. Experimental error is inaccurate information that is collected by human or measurement procedures during data gathering, recording, or entry. Inherent variability is based on the variant of individual samples that represents the population (Anscombe, 1960). Through careful identification of outliers and their cause, the study could achieve statistical significance. The Boxplot procedure was used to define the outlier (Institute S. A. S., 2008). The quartile method was used to analyze the difference between the mild and the extreme outliers. The extreme outliers were assumed to be experimental errors and were removed from the data set (Manoj & Senthamarai, 2013). There were 70 data available to analyze from the previous section. This section examines data outliers from this 70 data.

4.2.1 Outlier Analysis for the Time to complete Engineering Change (EC) tasks

The time to complete the Engineering Change (EC) tasks was calculated based on the difference between the start time and end time of the EC tasks from each subject. The collected time data for both the traditional and the KBE/CAD integration design methodologies were processed by the outlier test using boxplot procedures and quartile methodology.

Figure 4.2 shows boxplot of time to complete the EC task data for the traditional and the KBE/CAD integration design methods. The data showed one outlier for the traditional design methodology and three outliers for the KBE/CAD integration design methodology. Table 4.1 shows the outlier test results for the time to complete the EC tasks for both design methods.

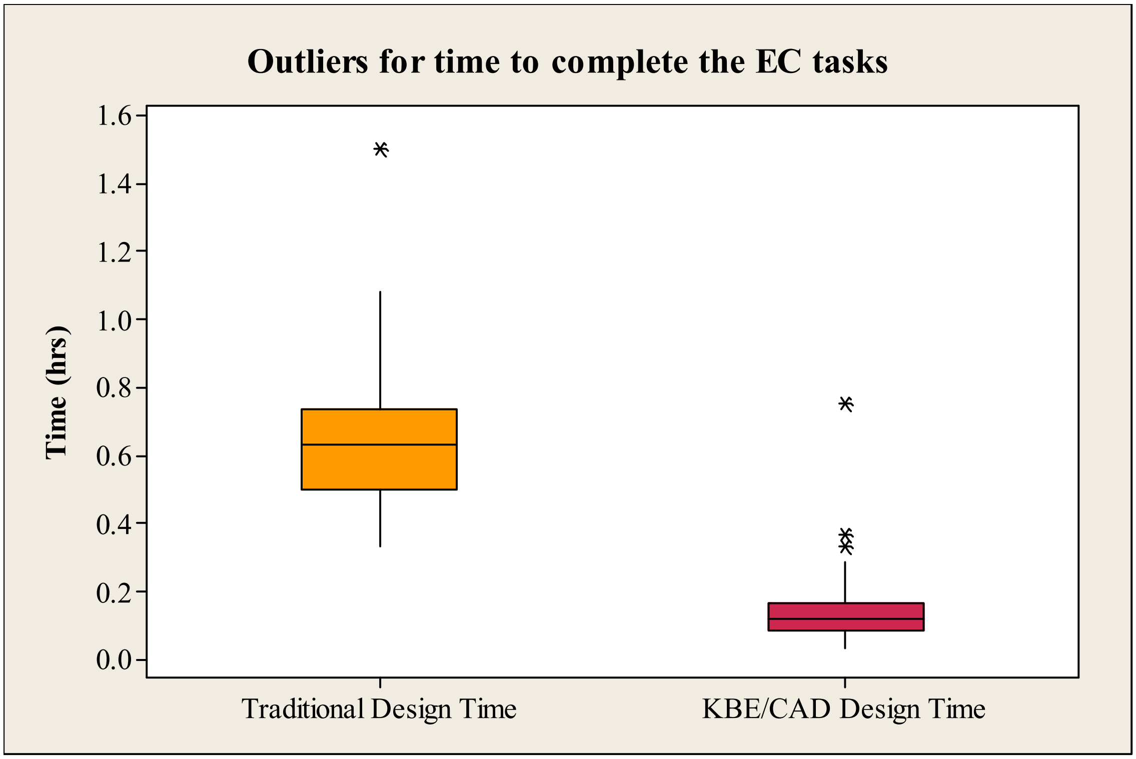


Figure 4.2. Boxplot graph of the time to complete the EC tasks for the traditional and the KBE/CAD integration design methods.

Table 4.1.

The outliers test results for the time to complete the EC tasks for the traditional and the KBE/CAD integration design methods.

	Traditional Time	**KBE/CAD Time**		
Outlier Time (hrs)	1.50	0.33	0.37	0.75
Data	25	57	36	34

In the article *Comparing of methods for detecting outliers*, Manoj and Senthamarai (2013) stated “A value lower than Q1 – 1.5.H and higher than Q3+1. 5. H is considered to be a mild outlier. A value lower than Q1-3.H and higher than Q3+3.H is considered to be an extreme outlier” (p. 711). Using this method, the extreme outliers were removed from the data set. Table 4.2 shows the quartile values of the time to complete EC tasks for the Traditional and the KBE/CAD integration design methods.

Table 4.2.
Quartile values for the time to complete EC tasks for the traditional and the KBE/CAD integration design methodologies.

	Traditional Time	**KBE/CAD Time**
Q1-1.5H	0.15	-0.04
Q3+1.5H	1.08	0.29
Q1-3.H	-0.20	-0.17
Q3+3.H	1.43	0.42

For the traditional design method, the outlier 1.5 hours (Data 25) was greater than Q3+3.H (1.5 hours > 1.43 hours). This value was the extreme outlier and was removed from the data set.

For the KBE/CAD integration design method, the value of 0.75 hours (Data 34) was greater than Q3+3.H (0.75 hours > 0.42 hours). This value was the extreme outlier and was removed from the data set. The values of 0.367 hours (Data 26) and 0.333 (Data 57) were lower than Q3+3.H (0.42 hours). These values were considered mild outliers and were kept for the data set.

4.2.2 Outlier Analysis for the Engineering Change (EC) design errors

An EC design error is the information from the user’s finished EC model that conflicts with the product training information and the answer key, which was developed by the researcher. Following the outlier test for the time to complete the EC order, there were 68 data available for analysis. This section analyzes the outliers for the EC design errors in this data set of 68.

Figure 4.3 shows the boxplot of EC design errors for the Traditional and the KBE/CAD integration design methodology. The data shows three outliers for the traditional design method and six outliers for the KBE/CAD integration design method. Table 4.2 shows the outlier test results for the EC design error outliers from both design methods.

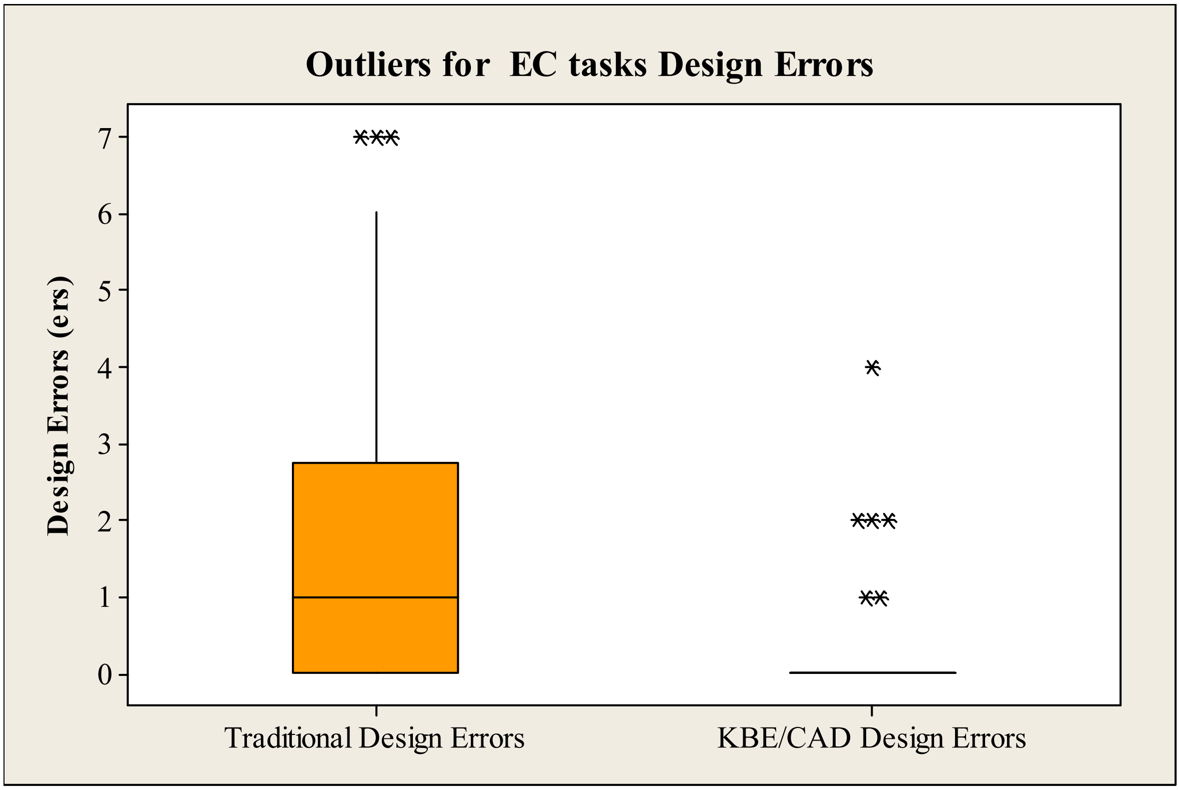


Figure 4.3. Boxplot graphs of the EC tasks design errors data for the traditional and the KBE/CAD integration design methods.

Table 4.3.
The outlier test results for the EC design errors of the traditional and the KBE/CAD integration design methods.

	Traditional Errors	**KBE/CAD Errors**		
Outlier Errors	**7**	**1**	**2**	**5**
Data	**40, 45, 67**	**17, 27**	**20, 41, 44**	**15**

Using the quartile method, these outliers were compared to define the extreme value. Table 4.4 shows the quartile values of the EC design errors for the traditional and the KBE/CAD integration design methods.

Table 4.4.
Quartile values for the EC design errors of the traditional and the KBE/CAD integration design methods.

	Traditional Errors	**KBE/CAD Errors**
Q1-1.5H	-3	0
Q3+1.5H	5	0
Q1-3.H	-6	0
Q3+3.H	8	0

For the traditional design method, the outliers value of 7 errors (Data 40, 45 and 67) were lower than Q3+3.H (6 errors< 7 errors). These were considered mild outliers and were kept in the data set.

For the KBE/CAD integration design method, the value of one error (Data 17, 27), two errors (Data 20, 41 and 44) and 5 errors (Data 15) were greater than Q3+3.H (0 errors). These values were the extreme outliers and were removed from the data set.

4.2.3. Outlier Analysis results

After the outlier analysis for time to complete the EC tasks and the EC design errors, the extreme outliers were found and removed from the data set. There were two extreme outliers from time to complete EC tasks (data 25 and 34) and six extreme outliers from the EC design errors (Data 15, 17, 20, 27, 41 and 44). The final sample size was 62. Appendix D shows the actual data.

4.3 Analyzing time to complete Engineering Change (EC) tasks

This section presents the statistical analysis for the time to complete Engineering Change (EC) tasks for the traditional design methodology, KBE/CAD integration design methods, and the time difference. The population mean of time to complete the EC tasks was estimated for each design method. The difference in time to complete the EC tasks was calculated and analyzed.

4.3.1 Estimating population mean of the time to complete EC tasks

Table 4.5 shows descriptive statistical data of the time to complete the EC request for the traditional design method and the KBE/CAD integration design method. The sample size was 62. The margin of error and 95% confidence interval are calculated for each design methodology. Figure 4.4 shows a graphical representation of the estimated population mean for time to complete the EC tasks for the traditional and KBE/CAD integration design methods. The margin of error was marked to demonstrate upper bound and lower bound limits of the estimated population mean.

Table 4.5.

Descriptive statistical data of the time to complete the EC request for the traditional and the KBE/CAD integration design methods.

	Traditional time	**KBE/CAD Time**
Sample size (n)	62	62
Mean (hrs)	0.63	0.13
Standard Deviation (hrs)	0.17	0.06
Margin of Error (hrs)	0.04	0.02
95% Confidence Coefficient (hrs)	2.00	2.00
Lower Bound (hrs)	0.58	0.11
Upper Bound (hrs)	0.67	0.14
Minimum (hrs)	0.33	0.03
Maximum (hrs)	1.08	0.37
Range (hrs)	0.75	0.33

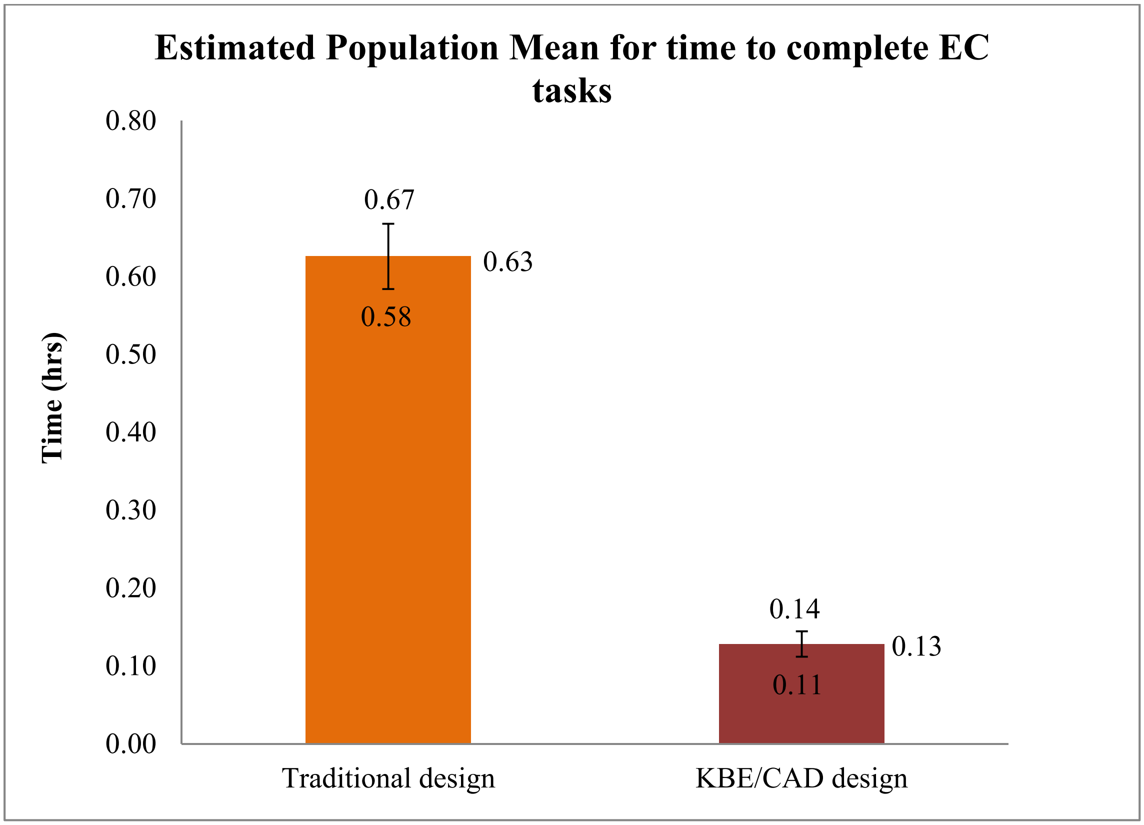


Figure 4.4. The estimated population mean for time to complete EC tasks for the traditional and KBE/CAD integration design methods.

4.3.1.1 Population mean of the time to complete EC tasks using the traditional design methodology

For the traditional design methodology, the average time to complete the EC order was 0.63 hours with a standard deviation of 0.17 hours. Based on the margin of error this study found the difference between the sample mean and the population mean of the traditional design time is within 0.04 hours. There is a 95% chance that the population mean time to complete the EC tasks for the traditional design is between 0.58 hours and 0.67 hours.

By arranging the data in ascending order, the frequencies were calculated. Table 4.6 shows a frequency table of the time to complete EC tasks for the traditional design method. Figure 4.5 shows the graphical representation of the time to complete EC tasks for the traditional design method.

Table 4.6.
Frequency table of the time to complete EC tasks for the traditional design method.

Traditional design time	
Time	Frequency
0-0.4 hrs	6
0.4-0.5 hrs	13
0.5-0.6 hrs	10
0.6-0.7 hrs	14
0.7-0.8 hrs	12
0.8-0.9 hrs	3
0.9-1.0 hrs	3
1.0-1.1 hrs	1

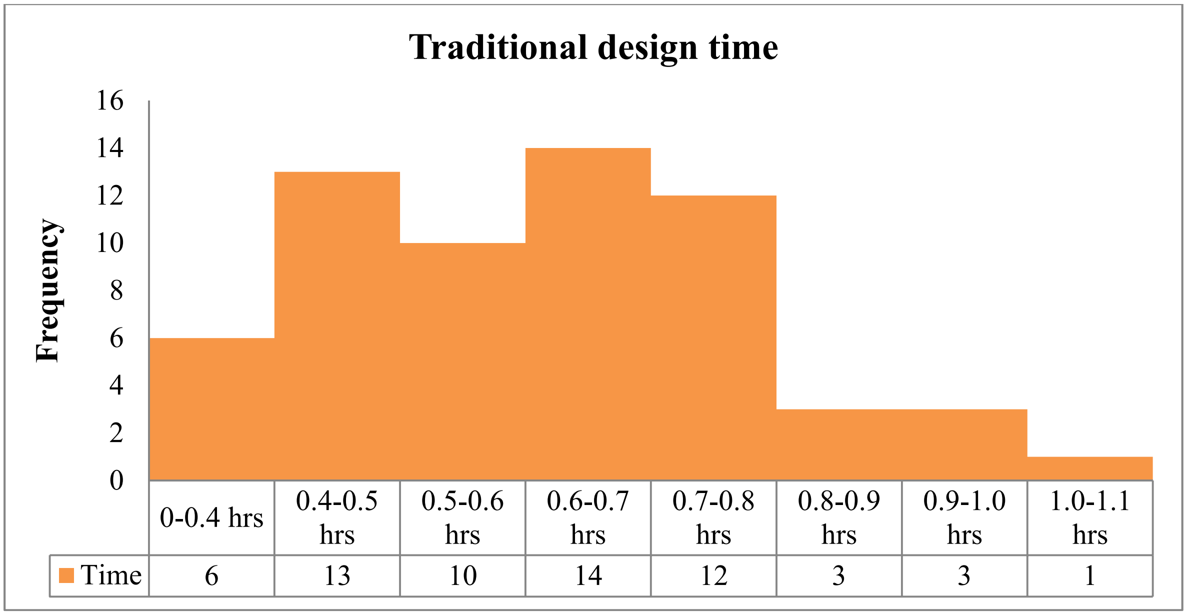


Figure 4.5. The time to complete EC tasks for the traditional design method.

4.3.1.2 Population mean for the time to complete EC tasks using the KBE/CAD integration design methodology

For the KBE/CAD integration design methodology, the average time to complete EC tasks was 0.13 hours with a standard deviation of 0.06 hours. Based on the margin of error, this study found the difference between the sample mean and the population mean of the traditional design time is within 0.02 hours. There is a 95% chance that the population mean time for the traditional design is between 0.11 hours and 0.14 hours.

By arranging the data in ascending order, the frequencies were calculated. Table 4.7 shows the frequency table of the time to complete EC tasks for the KBE/CAD integration design method. Figure 4.6 shows the graphical representation of the time to complete EC tasks for the KBE/CAD integration design method.

Table 4.7.
Frequency table of the time to complete EC tasks for the KBE/CAD integration design method.

KBE/CAD design time	
Time	Frequency
0-0.05 hrs	5
0.05-0.1 hrs	22
0.1-0.15 hrs	18
0.15-0.2 hrs	13
0.2-0.25 hrs	1
0.25-0.3 hrs	1
0.3-0.35 hrs	1

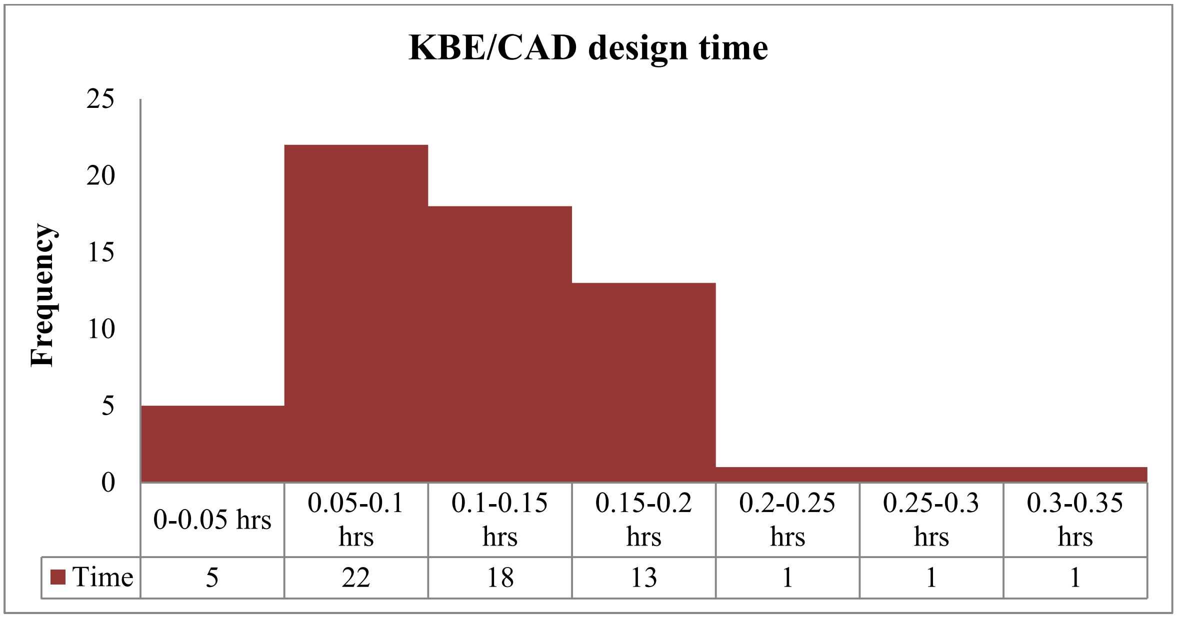


Figure 4.6. The time to complete EC tasks for the KBE/CAD integration design method.

4.3.2 Analyzing time to complete EC tasks differences between the traditional and KBE/CAD integration methodologies

Table 4.8 shows descriptive statistical data of the time to complete EC tasks differences between the traditional and the KBE/CAD integration design methodology.

The average time difference to complete EC change was 0.50 hours with standard deviation of 0.17 hours.

Table 4.8.
Descriptive statistical data of the time to complete EC tasks differences between the traditional and the KBE/CAD integration design methods.

Time differences	
Sample Size (n)	62
Degree of freedom (n)	61
Mean (hrs)	0.50
Standard Deviation (hrs)	0.17
Standard Error (hrs)	0.02
Significant level	0.05
t_{obs} (hrs)	22.81
t_{crt} (hrs)	2.00
95% Confidence Coefficient (hrs)	2.00
Lower Bound (hrs)	0.45
Upper Bound (hrs)	0.54

With a significance level of 0.05, the time to complete EC tasks differences between the design methods showed the t_{obs} value of 22.81 hours and the t_{crt} value of 2.00 hours. By comparison, the t_{obs} value was 20.81 hours greater than the t_{crt} which made it fall in the rejection region. Based on the interval estimated for the time differences, the time to complete the EC tasks of the traditional design were likely to be within 0.45 hours to 0.54 hours longer than the KBE/CAD integration design times. The study provided a 95% confidence interval which contained the true differences between the design methodologies. The interval region of 0.45 hours to 0.55 hours did not include zero. There was a positive significant difference between the time to complete EC tasks between the Traditional design and KBE/CAD integration design methodologies. By ratio, the KBE/CAD integration design was 4.85 times faster than the Traditional design method. The data has proven that the KBE/CAD design methodology has improved the time to complete EC tasks significantly.

By arranging the data in ascending order, the frequencies were calculated. Table 4.9 shows the frequency table of the time to complete EC tasks differences between traditional and the KBE/CAD integration design methods. Figure 4.7 shows the graphical representation of the time to complete EC task differences between the design methodologies.

Table 4.9.
Frequency table of the time to complete EC tasks differences between the traditional and the KBE/CAD integration design methods.

Time differences	
Time	Frequency
0-0.2 hrs	2
0.2-0.3 hrs	4
0.3-0.4 hrs	15
0.4-0.5 hrs	13
0.5-0.6 hrs	14
0.6-0.7 hrs	9
0.7-0.8 hrs	2
0.8-0.9 hrs	1
0.9-1.0 hrs	2

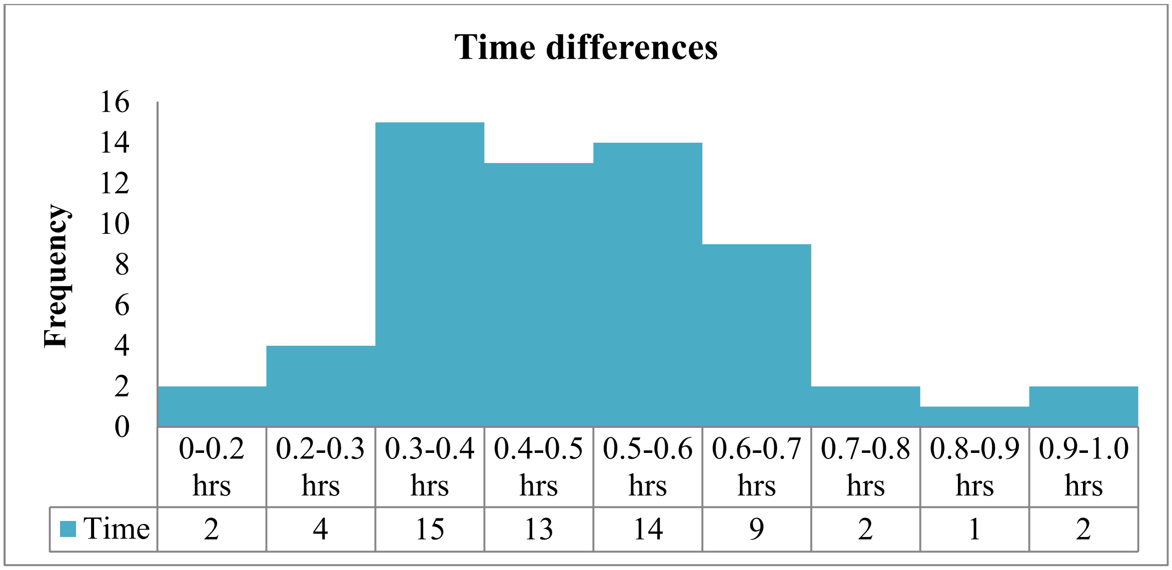


Figure 4.7. The time to complete EC task differences between the traditional and the KBE/CAD integration design methods.

4.4 Analyzing Engineering Change (EC) design errors

This section presents the statistical analysis for the Engineering Change (EC) design errors for the traditional design method, the KBE/CAD integration design method, and the time differences. The population mean for the EC design errors was estimated for each design method. The differences in EC design errors were calculated and analyzed.

4.4.1 Estimating population mean for EC design errors

Table 4.10 shows descriptive statistical data of the design errors for the EC tasks based on the Traditional and the KBE/CAD integration design methodologies. The sample size was 62. The margin of error and 95% confidence interval were calculated for each sample. Figure 4.8 shows a graphical representation of the estimated population mean for EC design errors for the traditional and the KBE/CAD integration design methods. The margin of error was marked to demonstrate the upper bound and lower bound limits of the estimated population mean. For KBE/CAD integration design method, there was no bar shown because the value was 0.

Table 4.10.
Descriptive statistical data of EC design errors for the traditional and the KBE/CAD integration design methods.

	Traditional Error	**KBE/CAD Error**
Sample size (n)	62	62
Mean (ers)	2	0
Standard Deviation (ers)	1.91	0.00
Margin of Error (ers)	0.49	0.00
95% Confidence Coefficient (ers)	2.00	2.00
Lower Bound (ers)	1	0
Upper Bound (ers)	2	0
Minimum (ers)	0	0
Maximum (ers)	7	0
Range (ers)	7	0

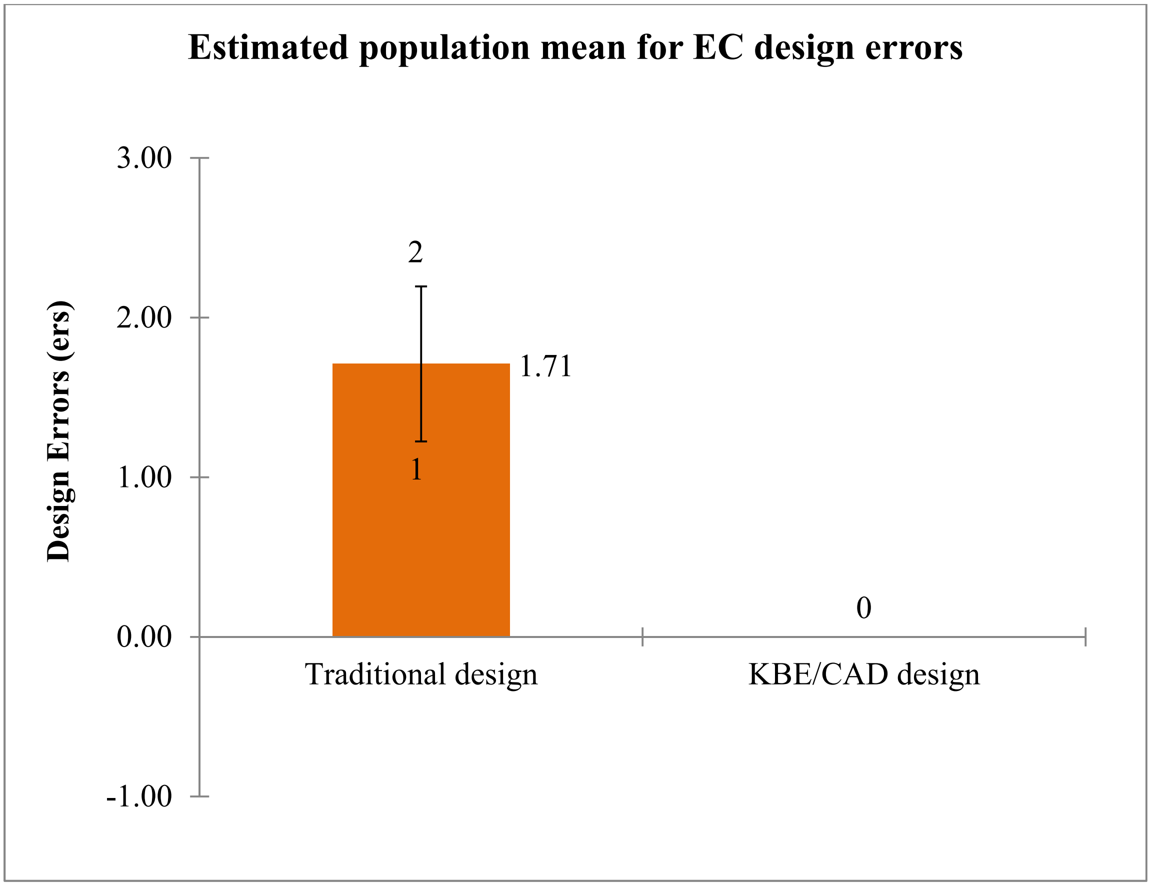


Figure 4.8. The estimated population mean for EC design errors for the traditional and the KBE/CAD integration design methods.

4.4.1.1 Population mean for the EC design errors using the traditional design methodology

For the traditional design methodology, the average design error for EC tasks was 2 errors with a standard deviation of 1.91 (≈ 2) errors. Based on the margin of error, this study found the difference between the sample mean and the population mean of design errors using the traditional methodology was within 0.49 (≈ 0) errors. There was 95% chance that the population mean errors for the traditional design was between 1 and 2 errors.

By arranging the data in ascending order, the frequencies were calculated. Table 4.11 shows a frequency table of the EC design errors for the traditional design method. Figure 4.9 shows the graphical representation of the EC design errors for the traditional design methodology.

Table 4.11.
The frequency table of the EC design errors for the traditional design method.

Traditional design errors	
Errors	Frequency
0 er	18
1 ers	21
2 ers	8
3 ers	5
4 ers	3
5 ers	3
6 ers	1
7 ers	3

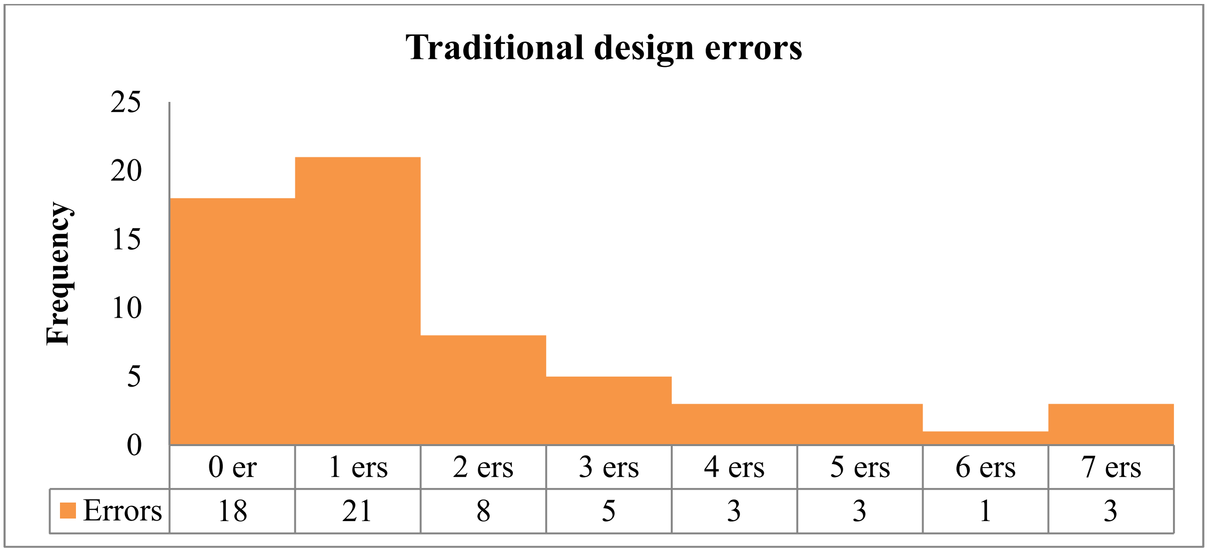


Figure 4.9. The EC design errors for the traditional methodology.

4.4.1.2 Population mean for the EC design errors using the KBE/CAD integration design methodology

For the KBE/CAD design methodology, the average design error for EC tasks was 0 errors with a standard deviation of 0 errors. Based on the margin of error, this study found the difference between the sample mean and the population mean of design errors using the KBE/CAD integration methodology is within 0 errors. There was 95% chance that the true error for the traditional design was 0 errors. This study provides 95% confidence that the true mean of the design error using KBE/CAD methodology was 0.

4.4.2 Analyzing EC design error differences between the traditional and the KBE/CAD integration design methodologies

Table 4.12 shows descriptive statistical data of the EC design error differences between the Traditional and the KBE/CAD integration design methods. The average EC design error difference to complete the EC was 2 errors with a standard deviation of 1.91 (≈ 2) errors.

Table 4.12.
Descriptive statistical data of the EC design error differences between the traditional and the KBE/CAD integration design methods.

Design error differences	
Sample size (n)	62
Degree of freedom (n)	61
Mean (ers)	2
Standard Deviation (ers)	1.91
Standard Error (ers)	0.24
Significant level	0.05
t_{obs} (ers)	7.04
t_{crt} (ers)	2.00
95% Confidence Coefficient (ers)	2.00
Lower Bound (ers)	1
Upper Bound (ers)	2

With a significance level of 0.05, the EC design error differences between the design methods showed the t_{obs} value of 7.04 (≈ 7) errors and the t_{crt} value of 2.00 (≈ 2) errors. By comparison, the t_{obs} value was 5 errors greater than the t_{crt} which made it fall within the rejection region. Based on the interval estimated for the design error differences, the EC design errors of the traditional design method were likely to be within 1 to 2 errors more than the KBE/CAD integration design method. This study provided a 95% confidence interval which contained the true differences between the design methodologies. The interval region of 1 to 2 errors did not include zero. Therefore, there was a positive significant design error difference of the EC tasks between the traditional and the KBE/CAD integration design methodologies. The data has proven that the KBE/CAD design methodology has improved EC design errors significantly.

By arranging the data in ascending order, the frequencies were calculated. Table 4.13 shows a frequency table of the EC design error differences for the traditional and the KBE/CAD integration design methodologies. Figure 4.10 shows the graphical representation of the EC design error differences for the design methods.

Table 4.13.
The frequency table of the EC design error differences for the traditional and the KBE/CAD integration design methodologies.

Design error differences	
Errors	Frequency
0 er	18
1 ers	21
2 ers	8
3 ers	5
4 ers	3
5 ers	3
6 ers	1
7 ers	3

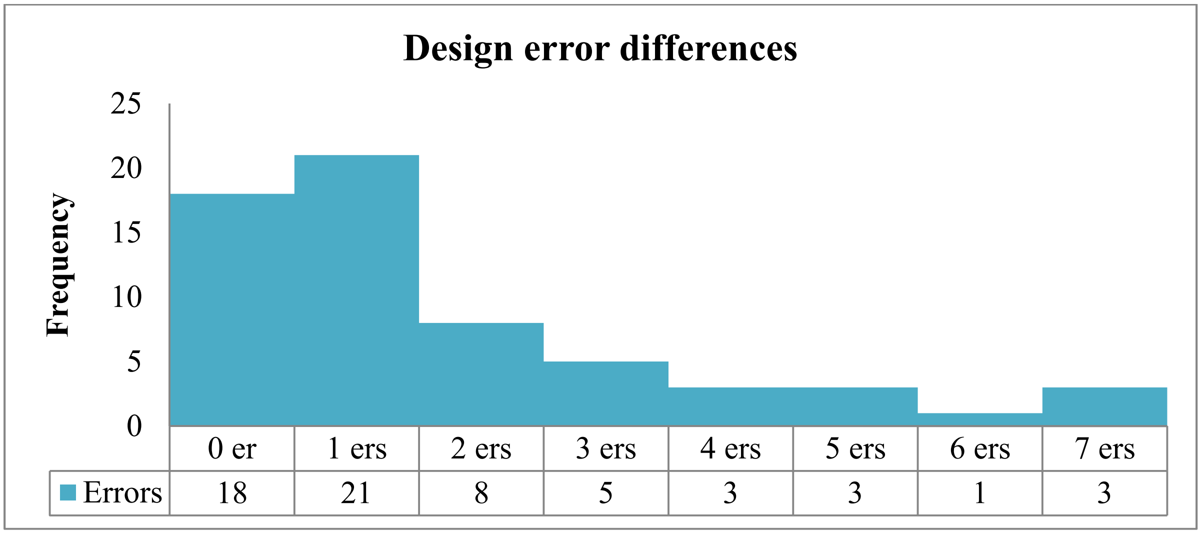


Figure 4.10. The EC design error differences for the traditional and the KBE/CAD integration design methods.

4.5 Defining relationships based on Level of CAD Education and Experience

This section presents the correlation analysis between the time to complete Engineering Change (EC) tasks and design errors with CAD experience level of subject. The Pearson’s correlation is used.

4.5.1 Correlation analysis between the time to complete EC tasks and user level of CAD education and experience

This section examines the relationship between the time to complete EC tasks and the user's level of CAD education and experience using Pearson's correlation (Boslaugh, 2012). Table 4.14 shows correlation test results between the time to complete EC tasks and the user's level of CAD education and experience for traditional and KBE/CAD integration design methods.

Table 4.14.
Correlation test result between the time to complete EC tasks and the user's level of CAD education and experiments for traditional and KBE/CAD integration design methods.

	Traditional time and CAD level of education and experience	**KBE/CAD time and CAD level of education and experience**
n	62	62
r	-0.17	0.08
P-Value	0.17	0.56

The Pearson's correlation value *r* between the time to complete EC tasks for the traditional design method and the user's level of CAD education and experience is about -0.17 with a P-value of 0.17. This indicates the time to complete EC tasks for the traditional design method and the user's level of CAD education and experience is weakly related with a negative linear relationship. However, the P-value found is 0.17. This number is relatively large compared to a typical P-value of 0.01 to 0.05. Figure 4.11 shows the scatter plot graph for the correlation test results between the time to complete EC tasks for the traditional design method and the user's level of CAD education and experience.

The data was not sufficient enough to support correlation values between time to complete EC tasks for the traditional design method and the user's level of CAD education and experience.

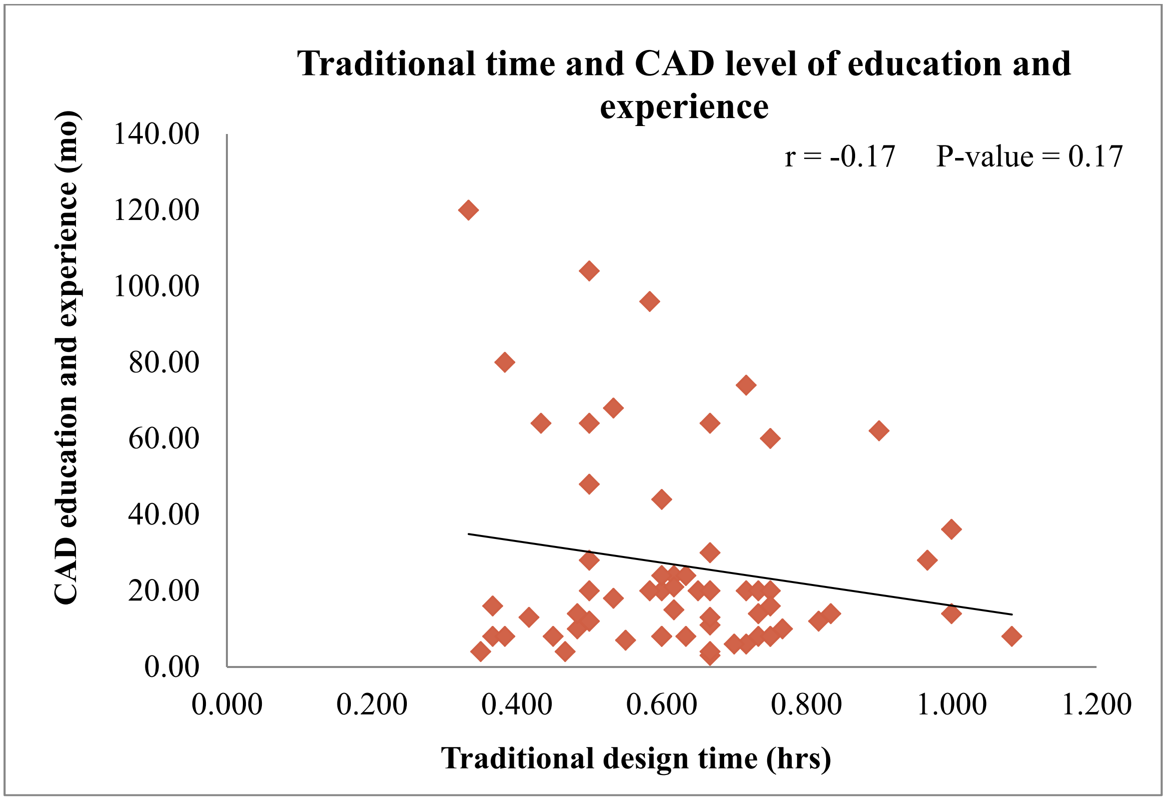


Figure 4.11. Correlation test result between the time to complete the EC tasks for the traditional design method and the user's CAD level of experience.

The Pearson's correlation value *r* between the time to complete the EC tasks for the KBE/CAD integration design method and the user's level of CAD education and experience was about 0.08 with a P-value of 0.56. This indicates the time to complete EC tasks for the KBE/CAD integration design method and the user's level of CAD education and experience had little to no relationship. However, the P-value is 0.56. This number is relatively large compared to a typical P-value of 0.01 to 0.05. Figure 4.12 shows the scatter plot graph for the correlation test results between the time to complete the EC tasks for the KBE/CAD integration and the user's level of CAD education and experience.

The data was not sufficient enough to support a correlation value between the KBE/CAD integration and the user's level of CAD education and experience.

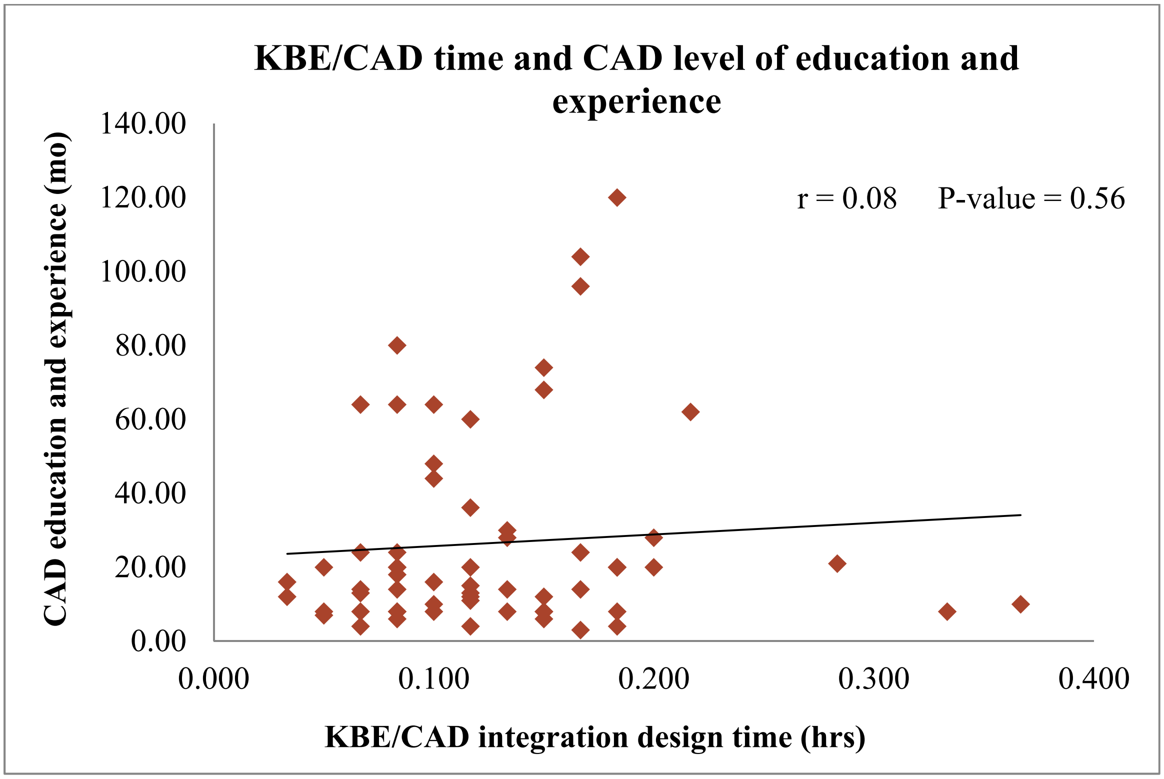


Figure 4.12. Correlation test results between the time to complete the EC tasks for the KBE/CAD integration design method and the user's level of CAD education and experience.

4.5.2 Correlation analysis between the EC design errors and the user's level of CAD education and experience

This section examines the relationship between the EC design errors and the user's level of CAD education and experience using the Pearson's correlation (Boslaugh, 2012). Table 4.15 shows correlation test results between the EC design errors and the user's level of CAD education and experience for the traditional and the KBE/CAD integration design methods (* indicates value is not found).

Table 4.15.
Correlation test results between the EC design errors and the user's level of CAD education and experience for the traditional and the KBE/CAD integration design methods.

	Traditional design errors CAD level of education and experience	**KBE/CAD design errors CAD level of education and experience**
n	62	62
r	-0.25	*
P-Value	0.05	*

The Pearson's correlation value *r* between the EC tasks design errors for the traditional design method and user level of CAD education and experience was about -0.25 with a P-value of 0.05. This indicated the EC tasks design errors for the traditional design method and user level of CAD education and experience was weakly correlated with a negative linear relationship. Subjects with higher level of education and experience in the use of CAD tend to have a lower value of design errors. However, knowing the exact value of user level of CAD education and experience would not provide precise prediction of the amount of design error subjects would have. The P-value indicated that there was a 5% chance that found observations were due to random sampling. This study has found statistical significance that there is a 95% chance that there is a negative linear relationship between data. Figure 4.13 shows the scatter plot graph for the correlation test result between the EC tasks for the traditional design method and user's level of CAD education and experience.

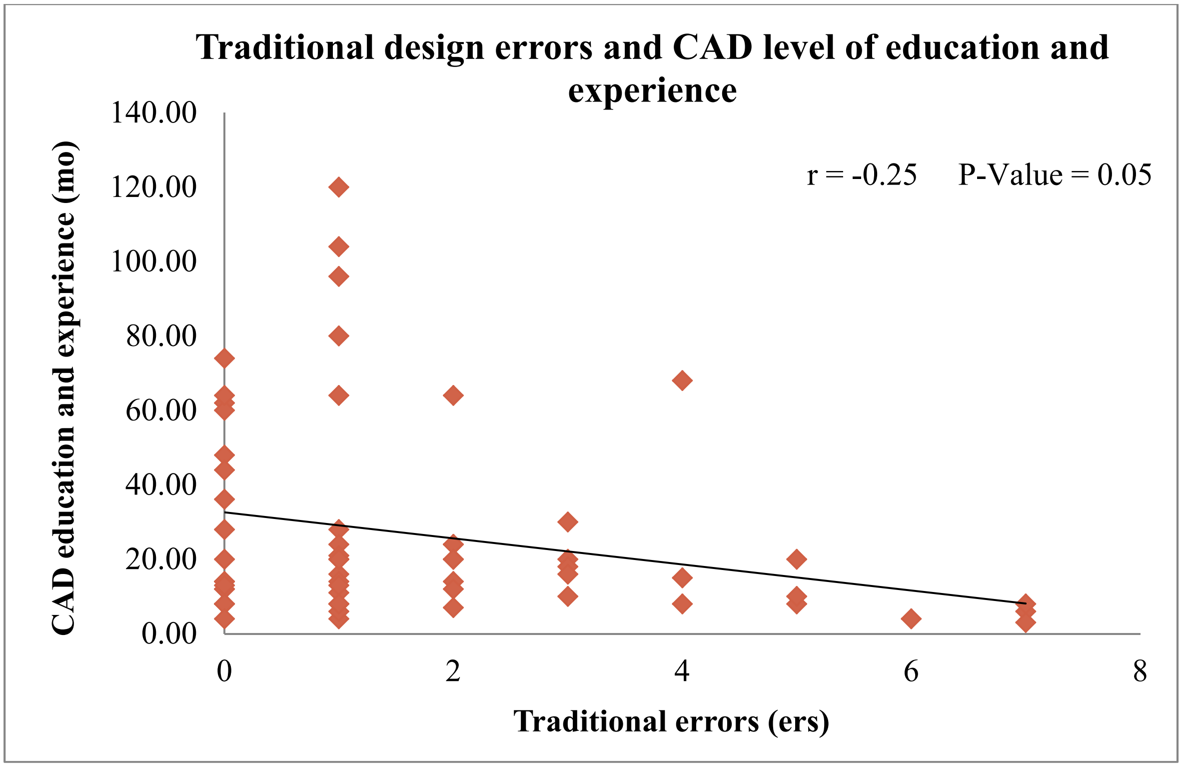


Figure 4.13. Correlation test results between the EC design errors for the traditional design method and the user's level of CAD education and experience.

The correlation (Pearson's *r*) between the EC design errors for the KBE/CAD integration design method and the user's level of CAD education and experience was not found with unknown P-value (Table 4.15 shows * as value is not found). This was due to the 0 constant values of the EC design errors for the KBE/CAD integration design method. It indicated there was no dependency between the EC design errors for the KBE/CAD integration design method and the user's level of CAD education and experience. The data showed that there was no correlation between the data.

4.6 Evaluating research experiment training material

This section evaluates the training materials that prepared the subjects for the experiments. Each subject was asked to give a rating for the training material and comment on how to improve this information. The training material included product system training, CAD traditional training, and the KBE/CAD integration training.

4.6.1 Evaluating the product system training

The product system training provided subjects with the engineering knowledge related to the products. It introduced all the product components used in this study. It also provided assembly instructions so the subject could put the component together. The subjects were asked to give a rating from a 1 to 5 Likert scale, with 1 being the least effective and 5 being the most effective. Table 4.16 shows quantitative counts of the product system training rating. Figure 4.14 shows a pie chart of the product system training rating based on percentages. The average rating score was 3.89 with 5 as the highest and 1 as the lowest. There were 54 out of 62 subjects that agreed the product system training was at least a rating of 3 or greater. The product system training was helpful to most subjects.

Table 4.16.

The quantitative counts of the product system training rating.

Product system training	
Rating	Quantity
R.1	2
R.2	6
R.3	10
R.4	23
R.5	21

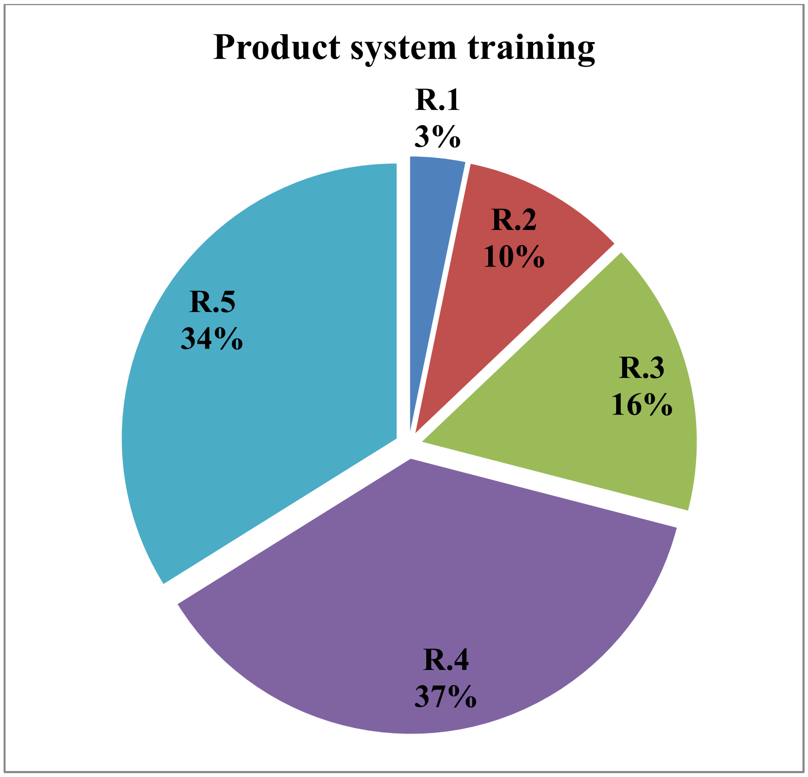


Figure 4.14. The product system training rating.

The subjects were asked to provide comments on how they thought the product system training could be improved. There were 14 comments and 48 no-answers out of 62 subjects. The 14 comments were coded and grouped into meaningful categories. Some comments were assigned to more than one category depending on their meaning. Table 4.17 shows the categorization of responses to the product system training. In 14 comments, most subjects thought the product system training provided relevant information to the experiment. However, this information was complex and difficult to follow. A small portion thought providing more explanation would help.

Table 4.17.
Categorization of responses to the product system training.

Comment on how to improve the Product Training Document	
Inductive categories	**Subject responses**
Too much information	There was too much information presented at once
	Is better if you gave just one PDF for doing by itself
	Simpler Instruction
	Just a lot of info to take in
	Too fast, ok if could pause which working
	Slow down
Good Information	Was good for information, just hard to follow because I wasn't sure what it was going to be use for
Difficult to follow or relate information from trainings to practice	Phasing/terminology, more detail
	Was good for information, just hard to follow because I wasn't sure what it was going to be use for
	More details about seemingly intuitive steps
	Instructions extremely vauge, no reason for steps
Need more information/ explanation	Phasing/terminology, more detail
	Could use more information
Need more proofreading	Phasing/terminology, more detail
	Typos could be fixed
	Double check directions for error
	Fix errors and contradictions. Have someone proofread it for grammar

4.6.2 Evaluating the CAD traditional design training

The CAD traditional design training was designed to prepare the subjects with information about the CAD software and how design work is traditionally done. It familiarized the subjects with the AutoDesk Inventor interface as well as its common tools and functions. The subjects watched a training video and worked along with a training model using AutoDesk Inventor 2014. The subjects were asked to give a rating from a 1 to 5 Likert scale, with 1 being the least effective and 5 being the most effective. Table 4.18 shows quantitative counts of the CAD traditional design training rating.

Figure 4.15 shows the pie chart of the CAD traditional design training rating based on percentages. The average rating score was 3.77 with 5 as the highest and 1 as the lowest. There were 55 out of 62 of the participants agreed that the CAD traditional design training was at least a rating of 3 or greater. The CAD traditional design training was helpful for most subjects.

Table 4.18.
The quantitative counts of the CAD traditional design training rating.

CAD traditional design training	
Rating	Quantity
R.1	3
R.2	4
R.3	13
R.4	26
R.5	16

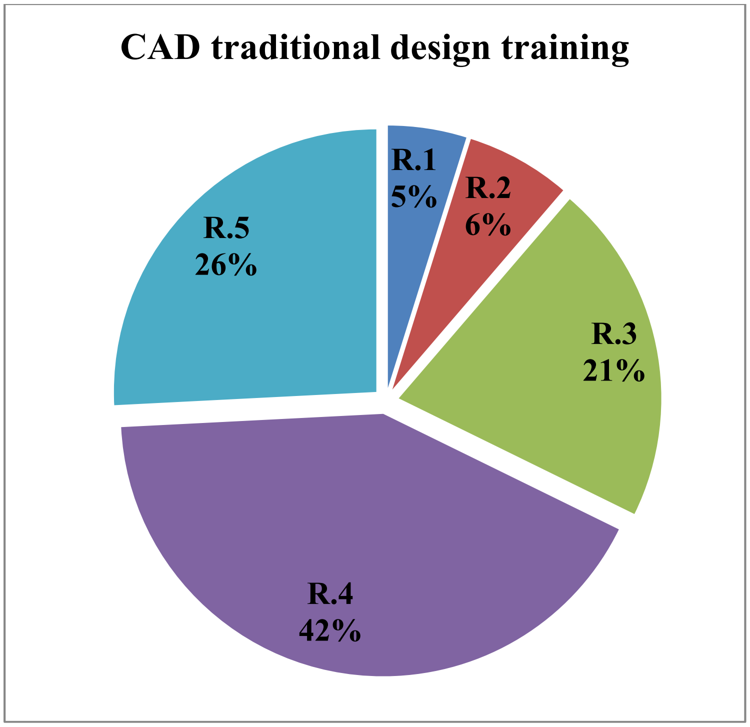


Figure 4.15. The CAD traditional design training rating.

The subjects were asked to give comments on how they thought the CAD traditional design training could be improved. There were 12 comments and 50 no answers out of 62 subjects. The 12 comments were coded and grouped into meaningful categories. Some comments were assigned to more than one category depending on their meaning. Table 4.19 shows the categorization of responses to the CAD traditional design training. In 12 comments, most subjects thought the CAD traditional design training provided relevant information and was helpful. However, the training video was too fast for subjects to watch and follow along. Some thought there was too much information to absorb and the tasks were challenging.

Table 4.19.
Categorization of responses to the CAD traditional design training.

Comment on how to improve the CAD traditional training	
Inductive categories	**Subject responses**
Video was too fast	The video was too fast to follow Time to watch Too fast, ok if could pause which working Slow down
Good and helpful	Good Effective in instructing me to Inventor and showing what I'd be doing Very specific steps, but good guidance Only thing that you got me through
More information/ explanation	More details about seemingly intuitive steps
Challenging	Adding the additional red pipe was challenge to constrain
Too much information	Just a lot of info to take in I'm already familiar with basic Inventor

4.6.3 Evaluating the KBE/CAD integration design training

The KBE/CAD integration design training prepared subjects by providing information about the KBE/CAD integration software and how to make changes to the KBE/CAD automation model. Subjects were not required to develop the KBE/CAD integration model. They used the existing automated model to complete the EC request. The KBE/CAD integration training familiarized the subjects with the AutoDesk Inventor iLogic interface as well as its common tools and functions. Subjects watched a training video on AutoDesk Inventor iLogic. The subjects were asked to give a rating from a 1 to 5 Likert scale, with 1 being the least effective and 5 being the most effective. Table 4.20 shows quantitative counts of the KBE/CAD integration design training rating. Figure 4.16 shows the pie chart of the KBE/CAD integration design training rating based on percentages. The average rating score was 4.24 with 5 as the highest and 1 as the lowest. There were 58 out of 62 subjects that agreed the KBE/CAD integration design training had at least a rating of 3 or more. The KBE/CAD integration design training was reported as being helpful for most subjects.

Table 4.20.
The quantitative counts of the KBE/CAD integration design training rating.

KBE/CAD design training	
Rating	Quantity
R.1	2
R.2	2
R.3	6
R.4	21
R.5	31

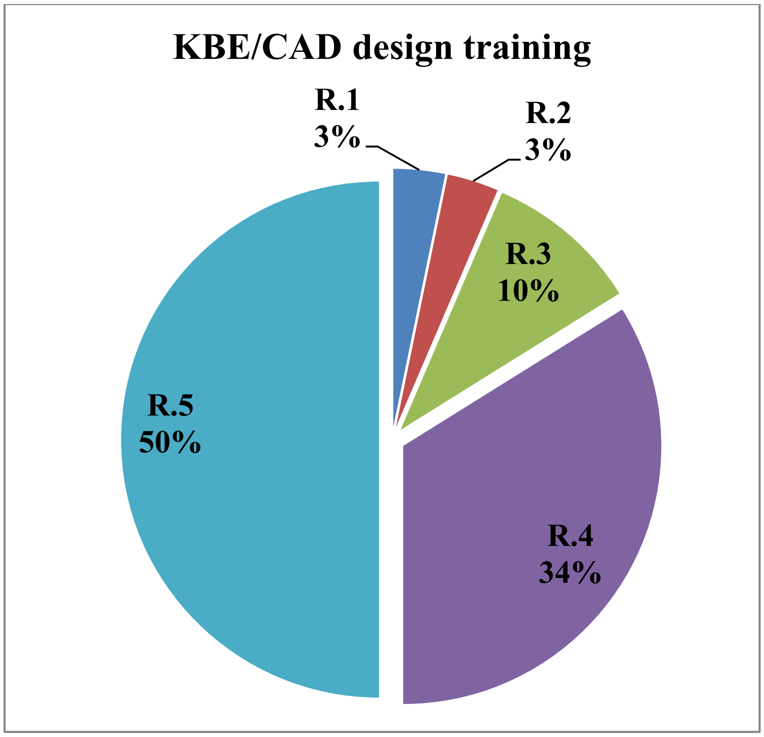


Figure 4.16. The KBE/CAD integration design training rating.

The subjects were asked to give comments on how they think the KBE/CAD integration design training could be improved. There were 14 comments and 48 no answers out of 62 subjects. The 14 comments were coded and grouped into meaningful categories. Some comments were assigned to more than one category depending on their meaning. Table 4.21 shows the categorization of responses to the KBE/CAD integration design training. In 14 comments, most subjects think the KBE/CAD integration design training provides relevant information and was new and interesting. However, the training video was too fast for subjects to watch. Some subjects thought there should be more information explaining how the KBE/CAD was developed.

Table 4.21.
Categorization of responses to the CAD traditional design training.

Comment on how to improve the KBE/CAD training	
Inductive categories	**Subject responses**
Video was too fast	Could speak slower Move slower Slow down Too fast, ok if could pause which working
Good and helpful	Effective in instructing me to Inventor and showing what I'd be doing Good Seem fine The best
More information/ explanation	Just maybe one last sentence explaining why to use constrains More details about seemingly intuitive steps Make it clear that the parameters and scripts have to be manually done by someone. Explain how the scripts are actually built or whatever. That info probably isn't necessary but I would have found it interesting. More detail in how this method works
New and interesting	Make it clear that the parameters and scripts have to be manually done by someone. Explain how the scripts are actually built or whatever. That info probably isn't necessary but I would have found it interesting. Much quicker in KBE More detail in how this method works
Too much information	Just a lot of info to take in

4.7 Lead-time analysis

From previous chapters, the lead-time was defined as the total time required to develop the virtual product model to complete EC tasks. As experimental data were collected and analyzed, the definition of lead-time need to be re-evaluated. In the article *Economic evaluation of lead-time reduction*, Wouters (1991) defined lead-time as "the time production departments need between accepting a production order and completing it" (p. 111). Based on this concept, the lead-time should not include the invested time before the order is placed.

The development time mention from section 3.5.1 is the required time to complete 3D CAD product assemblies for both traditional and KBE/CAD integration design. When the design is completed, the 3D CAD components or models will get reused for future orders. The development time is a one-time investment. As described in previous chapters, ETO companies develop proposal information which is based on information from similar products previously developed. Design engineering will reuse the CAD assembly that is similar to the new design requirement and modify the virtual product to fit the new requirements (Rahim & Baksh, 2003). Based on this information, the development time should not be included in lead-time. It is the fixed investment cost that ETO organization needs to recover from production profit. Organizations are not paying for this cost every time there is a new request for ETO quotes or orders.

For this study, the lead-time of the product design process is defined as the amount of time required for a design engineer to create the initial design as a quote and execute the Engineering Change (EC) order based on the customers' specifications. The lead-time includes the time to create the initial design as a quote, time to complete the EC tasks, time to investigate the design and time to correct design errors. The definition of lead-time (T_{LT}) includes:

- Time to complete quote (T_Q). This is the required time to develop 3D CAD models for quoting by using information from similar products previously developed. For the traditional design method, the initial design is modified based on a copy of either product configuration A, B, or C. For the KBE/CAD integration design, the master model is re-configured until the virtual product meets the new design requirements. This experiment was executed and recorded by the researcher.

- Time to complete EC tasks (T_{EC}). This is the required time to complete the request for both traditional and KBE/CAD integration design methodologies. The time was collected from the experiment’s subjects. The data was presented and analyzed above. The estimated true mean of time to complete EC tasks was used.
- Time to investigate EC design (T_{ID}). This is the required time to inspect the 3D product design after EC tasks are completed. This time is constant for both Traditional and KBE/CAD integration design methodologies. For this research experiment, T_{ID} was 0.05 hours.
- Time to correct design errors (T_{CE}). This is the required time to redo EC errors. The time is calculated based on the estimated true mean of EC design errors.
    - For the traditional design method, variable X represents the time to complete errors (T_{CE}) since there is an average of 2 design errors. The variable X is unknown and a positive value. For this study, the value of X was set to 0 hours to demonstrate the best case scenario for the traditional design method. This 0 value gives the minimum value for the time difference between the design methods. For actual data, X can only be 0 or larger.
    - For the KBE/CAD integration design method, value of 0 was used since there was an average of 0 design errors.

4.7.1 Lead-time equation

The equation for lead-time (T_{LT}) is shown below:

Lead-time (T_{LT}) = Time to complete quote (T_Q) + Time to complete EC tasks (T_{EC}) + Time to investigate EC design (T_{ID}) + Time to correct design errors (T_{CE})

4.7.2 Time to complete quote (T_Q) data

The time to complete quote (T_Q) is the required time to develop 3D CAD products for quoting by using information from similar products previously developed. The data was collected when data was prepared for the Engineering Change (EC) experiment. The design requirement for quoting information was presented as Revision A of the suction assembly design. This information can be found in the Engineering Change Request document.

Table 4.22 shows the time to complete quote data for the traditional and KBE/CAD integration design methods. Figure 4.17 shows a graphic representation of the time to complete quote for both design methodologies. For the traditional design method, the quote design began with the product configuration B because the both designs share many similarities. For the KBE/CAD integration design, the master model began with the master model and was configured to meet requirements. The time to complete quote for the traditional design was 0.1 hours longer than the KBE/CAD integration design method. By ratio, the KBE/CAD design method was 4 times faster than the traditional design method. The time to complete quote ratio was calculated by dividing the KBE/CAD integration time to complete quote by the traditional time to complete quote.

Table 4.22.

Time to complete quote data for the traditional and the KBE/CAD integration design methods.

Time to complete quote (T_Q)	
Method	Time (hrs)
Traditional	0.13
KBE/CAD	0.03
Time Difference (hrs)	0.10
Ratio (Traditional T_Q/KBE T_Q)	4.00

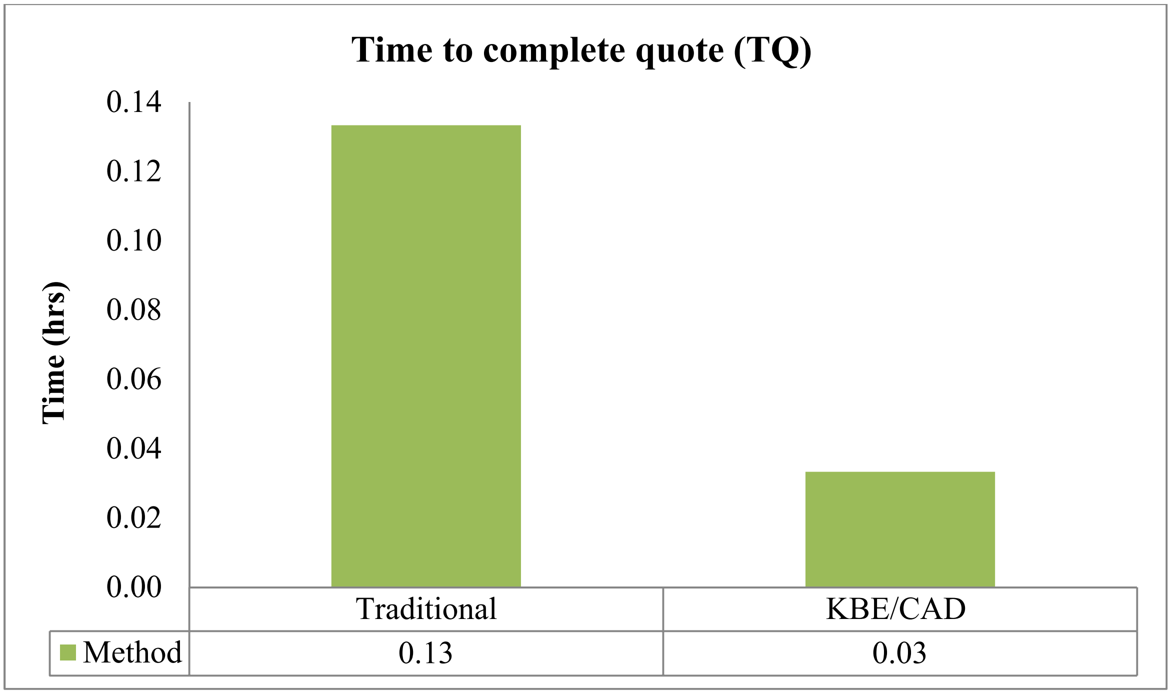


Figure 4.17. The time to complete quote for the traditional and KBE/CAD integration design methods.

4.7.3 Lead-time calculation

Table 4.23 shows the calculation of the lead-time (T_{LT}) for the traditional and KBE/CAD integration design methodologies. Figure 4.18 shows graphical representation for the lead-time (T_{LT}) for both design methodologies. For the traditional design, the lead-time (T_{LT}) was 0.81+X hours, with X being a positive value. For KBE/CAD integration design, the lead-time (T_{LT}) was 0.21 hours. With the traditional design time to correct errors (T_{CE}) of X value equal to 0 hour, the minimum value of lead-time difference was 0.60 hours. The KBE/CAD integration design method was at least 0.60 hrs faster than the traditional design method. By ratio, the KBE/CAD integration design was at least 3.81 times faster than the traditional design method. The lead-time ratio was calculated by dividing the KBE/CAD integration design lead-time by the traditional design lead-time.

Table 4.23.

Lead-time (TLT) calculation for the traditional and the KBE/CAD integration design methods.

	Traditional (hrs)	**KBE/CAD (hrs)**	**Differences (hrs)**	**Differences (Ratio)**
T_{QT}	0.13	0.03	0.10	4.03
T_{EC}	0.63	0.13	0.50	4.85
T_{ID}	0.05	0.05	0.00	1.00
T_{CE}	X	0.00	X	0.00
T_{LT}	0.81 + X	0.21	0.60 + X	(0.81+X)/0.21

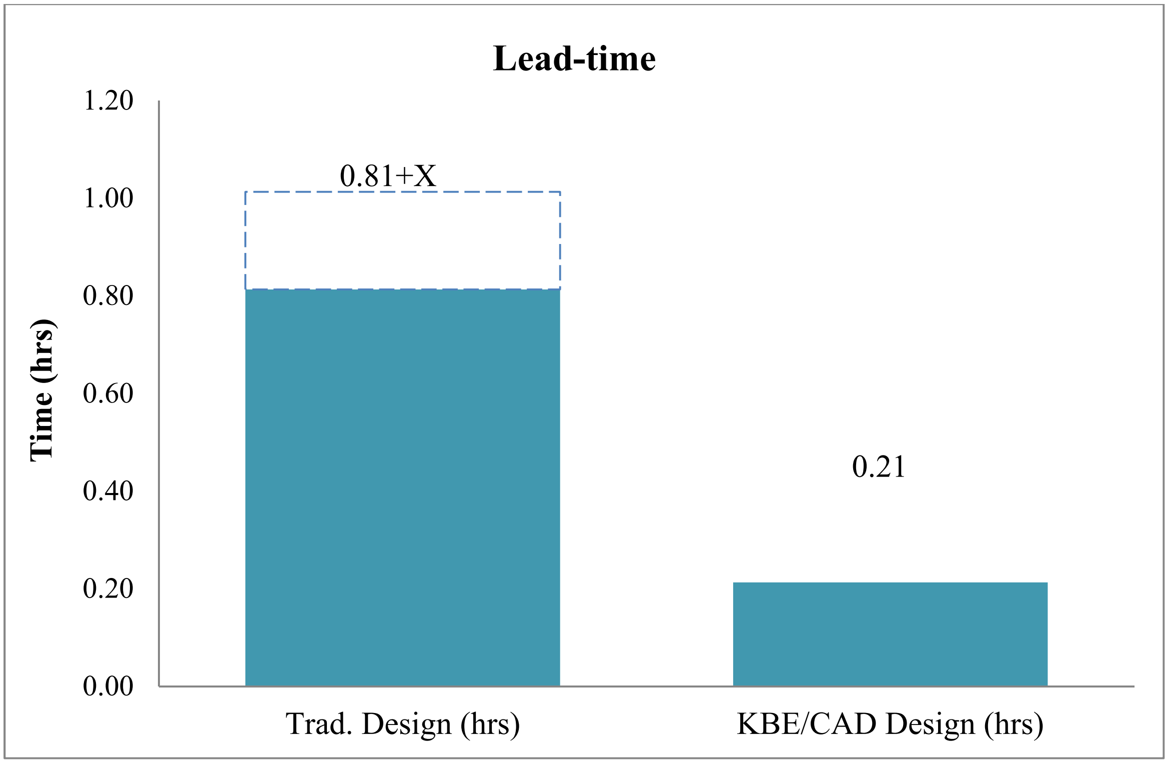


Figure 4.18. Lead-time (T_{LT}) for traditional and the KBE/CAD integration design methods.

4.8 Analyzing investment time

For this study, the investment time of the product design process was the time required to develop the preliminary 3D CAD product data for both traditional and KBE/CAD integration design methods and the time required for maintenance. This included both the development time and maintenance time. For the development time, the data was presented from chapter 3. The KBE/CAD automated model was assumed to be used for a 5 year period. During this period the overall maintenance was assumed to be 20% of development cost (Galorath, 2011). The equation for investment time (T_{IV}) is shown below:

Investment time (T_{IV}) = Development time (T_{DV}) + Maintenance time (T_M)

Table 4.24 shows the calculation of the investment time (T_{IV}) for the traditional and KBE/CAD integration design methodologies. Figure 4.19 shows graphical representation for the investment time (T_{IV}) for both design methodologies. The investment time was 19.2 hours for the traditional design and 59.36 hours for the KBE/CAD integration design. The investment time for KBE/CAD integration design was 40.16 hours longer than the traditional design method and was 3.09 times longer in ratio. The investment time ratio was calculated by dividing the traditional design investment time by the KBE/CAD integration design investment time.

Table 4.24.
Investment time (T_{IV}) calculation for the Traditional and the KBE/CAD integration design methods.

	Traditional (hrs)	**KBE/CAD (hrs)**	**Differences (hrs)**	**Differences (Ratio)**
T_{DV}	16.00	49.47	-33.47	3.09
T_{M}	3.20	9.89	-6.69	3.09
T_{IV}	19.20	59.36	-40.16	3.09

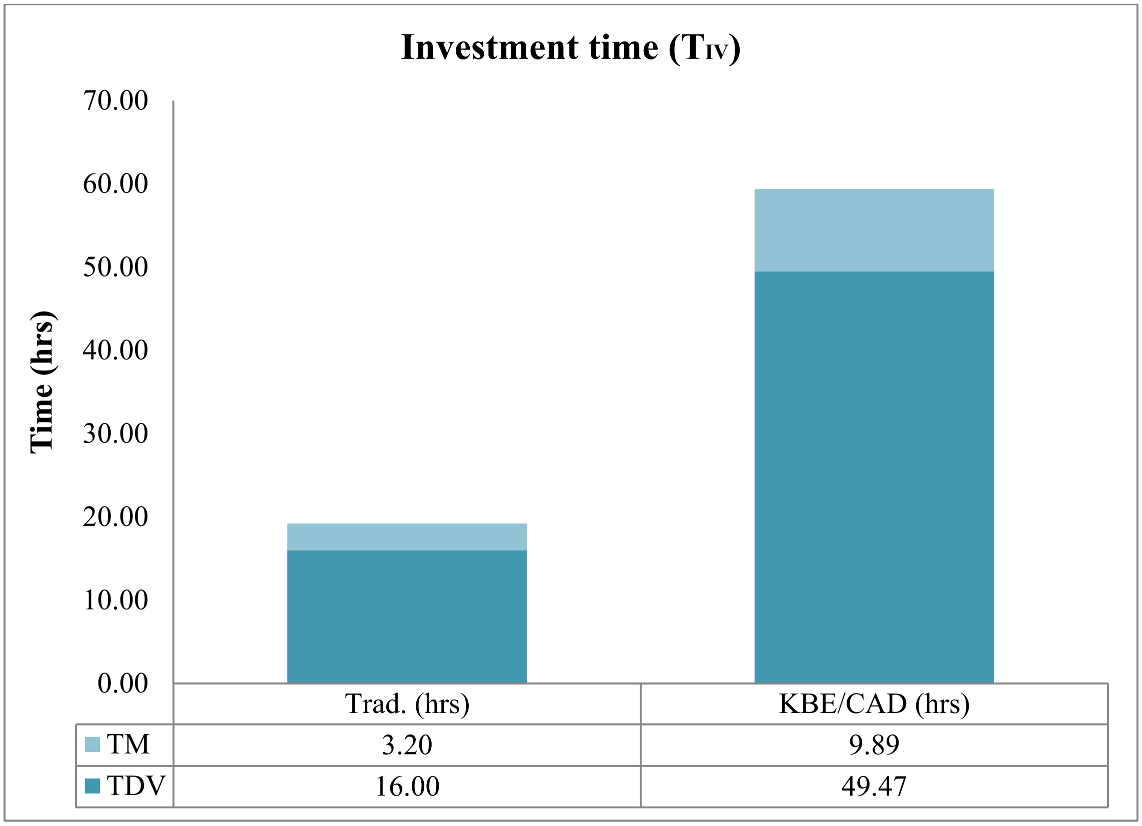


Figure 4.19. The Investment time (T_{IV}) for traditional and KBE/CAD integration design methods.

4.9 Analyzing recovery time gap between the investment time and the lead-time

Table 4.25 shows the calculation of the recovery gap between time difference of the investment time and lead-time for the traditional and KBE/CAD integration design methodologies. Figure 4.20 shows graphical representation of the recovery gap between time difference of investment and lead-time for both design methodologies. The data information included:

- The T_{IV} Dff is the investment time difference between the design methodologies that are analyzed in section 4.8.

- The T_{LV} Dff is the lead-time differences between the design methodologies that are analyzed in section 4.7.
- The recovery gap is the time difference between T_{IV} Dff and T_{LV} Dff. The equation of the value is T_{IV} Dff - T_{LT} Dff.
- The recovery ratio is the time ration between T_{IV} Dff and T_{LV} Dff. The equation of the value is T_{IV} Dff /T_{LT} Dff.

Table 4.25.
Recovery gap between time difference of the investment time and the lead-time for the traditional and KBE/CAD integration design methods.

	Time recovery
T_{IV} Dff	40.16
T_{LT} Dff	0.60 + X
Recovery Gap	39.56 + X
Recovery Ratio	40.16/(0.60+X)

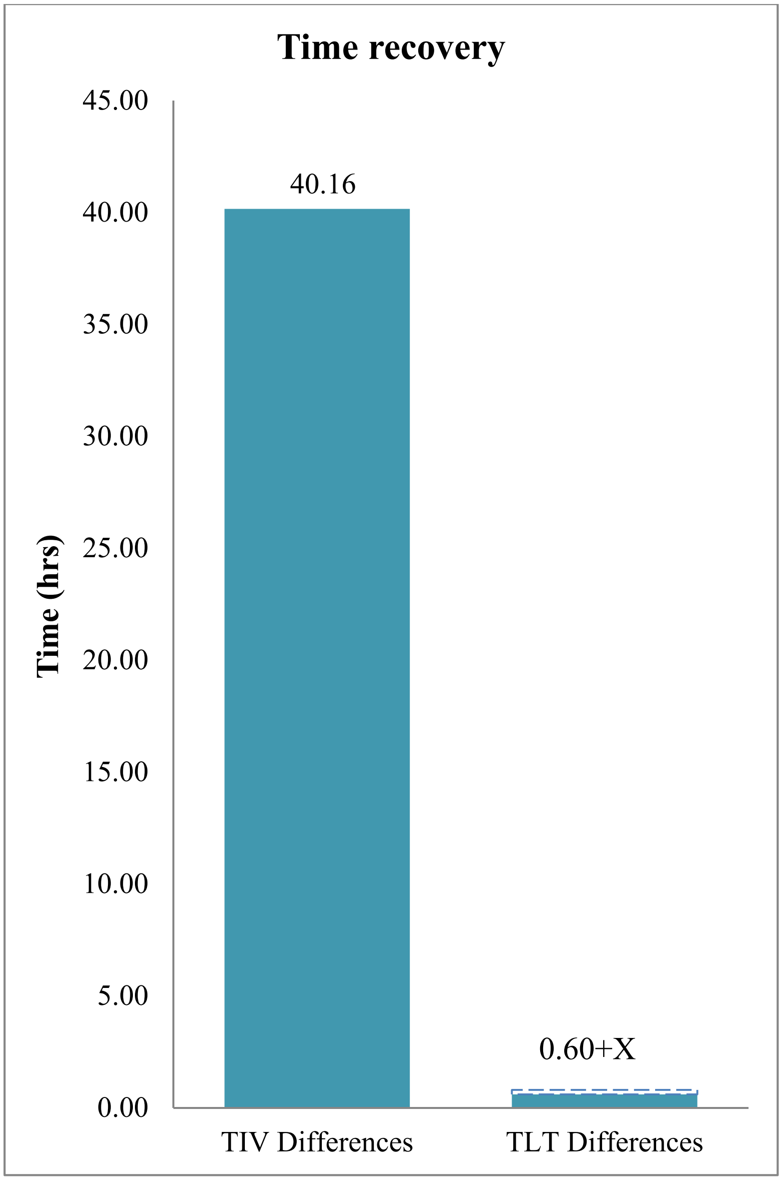


Figure 4.20. The investment time (T_{IV}) for the traditional and the KBE/CAD integration design methods.

The value of T_{LT} Dff indicated KBE/CAD integration design lead-time was 0.60+X hours faster than the traditional design lead-time. With the best case scenario for the traditional design, the time to correct errors (T_{CE}) the value of X equals 0, KBE/CAD integration design lead-time was at least 0.60 hours faster and by ratio, 3.81 times faster. The value for T_{IV} Dff indicates KBE/CAD integration design investment time was 40.16

hours longer than the traditional design investment time and it was 3.09 times longer in ratio.

For the KBE/CAD integration design method to be more efficient than the Traditional design method, the lead-time savings of the KBE/CAD integration design method must show a return of more than the recovery gap value of 39.56 + X hours. With the best case scenario for the traditional design time to correct errors (T_{CE}) the value of X equals 0, the lead-time saving of the KBE/CAD integration design method was a ratio of 1/67. This indicates ETO organizations need to perform 67 Engineering Change orders to balance the investment time and lead-time savings. Any EC order after the 67th time would be profitable.

Table 4.26 shows the ETO project time line by the investment time and lead-time based on number of ECs request for the traditional and KBE/CAD integration design methodologies. Figure 4.21 shows the graphical representation of the ETO project time line for both design methods. The area difference of investment time between the design methods was equal the area difference at the 67th ECs lead-time between the design methods. This was the point in time ETO organizations recover the KBE/CAD investment. From the point of 67th EC request forward, the area difference of ECs lead-time between the design methods were time savings ETO organizations get by using the KBE/CAD integration design method over the traditional design method. This time saving area was the return on investment.

Table 4.26.

The ETO project time line by the investment time and lead-time based on number of ECs requests for the traditional and the KBE/CAD integration design methods.

Number of ECs	**Investment time (hrs)**	**0th**	**67th**	**180th**	**240th**
Traditional Lead-time (hrs)	-19.2	0	54.27	91.53	140.13
KBE/CAD Lead-time (hrs)	-59.36	0	14.07	23.73	36.33

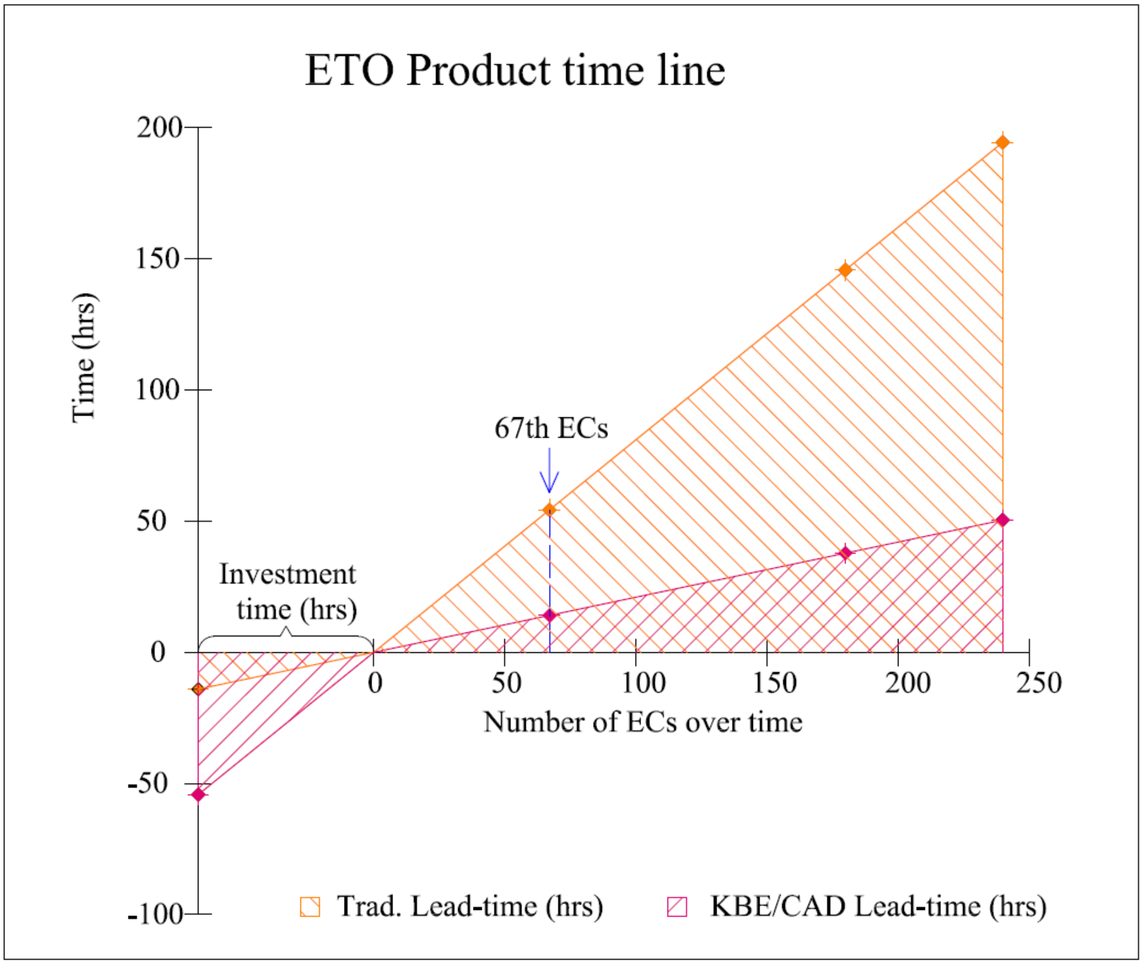


Figure 4.21. The ETO project time line for the traditional and KBE/CAD integration design methods.

In 2012, The Manufacturers Alliance for Productivity and Innovation (MAPI) organization published a report on how many Engineering Change orders were processed and how long this process would take from a variety of industries and product complexities. The MAPI report found the monthly average was 34 EC orders for minor changes, 24 EC orders for medium changes and 3 EC orders for large changes. On average, there were 61 EC orders per month. The annual EC orders were 732 (Manufacturers Alliance for Productivity and Innovation, 2012). However, the MAPI report did not indicate if the EC average numbers were based on one or multiple products or projects. Although the EC annual orders of 732 could not be used to estimate the amount of time ETO organizations need to recover investment time, this annual number of 732 EC orders could indicate that ETO organizations would likely perform more than 67 EC orders per year.

Depending on the number of EC orders the organization will get per ETO project or product, KBE/CAD integration design would vary the initial length of time to recover the investment time. However, when this time had been recouped, the KBE/CAD integration is a fast and accurate design methodology for an ETO product environment.

4.10 Investment decision between the KBE/CAD integration and the traditional design methodologies for ETO product situation

Based on literature research and analyzed data, this section evaluates if the KBE/CAD integration design method is more efficient in the ETO product situation than the traditional design method. The major problems ETO organizations had with the traditional design methods are recalled from chapter 2. The KBE/CAD integration design method was analyzed in this context.

The annual ETO market showed requests for customization from 50 to 60 customers at each firm annually. For each customer, ETO companies must prepare product information. Although 50 to 60 customers request quotes, only 15% of these quotations lead to an actual order. The major challenge was to provide product information based on performance, estimated prices, delivery schedule, etc. (Bertrand & Muntslag, 1993). From the result of this study, the KBE/CAD integration design method showed product design lead-time reduction of at least 3.81 times the traditional time with 100% information accuracy. In addition, since the KBE/CAD integration system was scripted with engineering knowledge, ETO organizations would able to produce multiple design scenarios of the product specification in a short period of time for better and more accurate quotations. The results might expand the opportunities for more ETO orders and earn more trust from ETO customers. By getting more ETO orders, organizations could expand profit margins and close the recovery gap of KBE/CAD integration design investment cost.

The business model of ETO is distinct from other production models due to the upstream Customer Order Decoupling Point (CODP). During the ETO project, customers have direct control over the product specifications and are heavily involved at the beginning of the product design activity (Qin & Geng, 2012, 2013). Because of this specific relationship between the ETO customers and the project, the major difficulty of the ETO environment was the uncertainty of customer requirements during the product development phase. Often ETO companies must rely on their own expertise in the field and estimates from a similar design. After the initial design estimate, the product goes through multiple design changes that require labor intensive activities especially for 3D

CAD products (Rahim & Baksh, 2003). With the traditional design method, ETO organizations struggle to ensure quality of the product design and downstream process of the project itself. With the KBE/CAD integration design method, the engineering knowledge is captured and reused with rules, relations, and facts that will ensure product quality and accuracy throughout repetitive design changes. This study results showed KBE/CAD integration design provide accurate designs and faster response times as well as the ability to provide more design scenarios with no additional time. In addition, the more Engineering Change processes that ETO products went through, the sooner organizations could close the recovery gap of the KBE/CAD integration design investment cost. This study found at the minimum time difference between the designs methods, after 67 EC orders, organizations would recover the time investment and further EC orders would result in profit from reduced project lead-times.

During the ETO project, the product design department was not the only function that was responsible for the job. Across the organization, many functions are involved such as sales, manufacturing, field service and engineering. During certain periods of the project, these functions would need product information from the product design experts. This could cause longer lead-time, incorrect or misused information that would decrease sales as well as competitive advantage (Barker et al., 1989; Fleischanderl et al., 1998; Forza & Salvador, 2002; Heatley, Agarwal, & Tanniru, 1995). By developing the KBE/CAD integration system, ETO organization could capture the engineering knowledge from the experts for less experienced users. The study results showed the traditional design method requires some level of CAD education and experience to understand the product information. The correlation between the EC design errors for the traditional design method and the user's level of CAD education and experiment was about -0.25 with a 95% chance of negative linear relationship. For the KBE/CAD integration method, there was no requirement of CAD education and experience to interact with the virtual representation of the product. There were consistently zero design error from the KBE/CAD integration design. By implementing the KBE/CAD integration design application, organizations would allow all functions to have direct interaction with the product system with minimal training required. This could serve as an alternative resource of expert information and reduce the burden of interacting with the product design functions. As a result, multiple functions across the organizations would perform a better job in a shorter time while learning more about the company products.

The research indicated that ETO revenue was depended heavily on high profit margins rather than unit sales volume. The key to business was to establish a partnership between the customers and the ETO manufacture to provide effective solutions to the ambiguous problems of the individual customer (Rahim & Baksh, 2003). ETO organizations must be able to show their competence and expertise through a well-defined product solution. With an accurate and fast response rate from KBE/CAD integration design method, organizations could build a better reputation and confidence throughout the ETO project. In addition, the higher profit margin from each ETO order could minimize the time to recover the investment cost of the KBE/CAD integration design method.

In conclusion, this research experiment has found that the KBE/CAD integration design method provided 100% design accuracy with at least 3.8 times shorter lead-time than the traditional design method. There was no relationship found between CAD experience and design error. The KBE/CAD integration design captured the engineering knowledge of the expert and made it available to experienced users. The recovery between investment time and lead-time savings was 67 EC requests or less. The KBE/CAD integration design approach was a more efficient design approach for the Engineering-to-Order product situation.

4.11 Summary

This chapter presented the data collected from the experiment and analyzed differences of time to complete EC task, differences of EC design errors, lead-time and investment time. The chapter evaluated the training materials that were used during the experiment to ensure the users were prepared for their tasks. Correlation relationships were examined between the time to complete EC tasks and EC design errors with the user’s level of CAD education and experience. Investment decision was discussed taking in consideration of the research results and ETO product situation. The next chapter will review the purpose of the research experiment and conclude the research findings.

CHAPTER 5. DISCUSSION AND CONCLUSION

This section presents the results of the research experiment and provides recommendation for future work. The research hypotheses are discussed based on data analyzed results to answer the research question. Recommendations for future research are documented.

5.1 Reduction of lead-time discussion

The first focus of this study was to examine if there is difference in lead-time of the product design process between the traditional and KBE/CAD integration design methods and if this difference is positive. The null and alternate hypotheses are:

- Ho1: There is no change in the reduction of the lead-time between the design methodologies in ETO environments.
- Ha1: There is a positive change in the reduction of the lead-time between the design methodologies in ETO environment.

During the experiment, the definition of lead-time was re-evaluated. The lead-time of the product design process was redefined as the amount of time required for a design engineer to create the initial design as a quote and execute the Engineering Change (EC) order based on the customer specifications. With the reduction of lead-time, the ETO organizations would able to gain more control over the production and delivery schedule and make more effective use of its time.

In this study, the lead-time was made up of time to complete quote, time to complete EC tasks, time to investigate EC time, and time to correct design errors. The data was collected and statistically analyzed in chapter 4. The results of this study showed the KBE/CAD integration design method is more effective in reducing lead-time than the traditional design method by at least 0.60 hrs. By ratio, KBE/CAD integration design method was 3.81 times faster. However, the results of this study also showed the investment time of the KBE/CAD integration design method was 3.09 times longer than the traditional design method. The time differences of the investment process could be recovered by utilizing the lead-time saving of the KBE/CAD integration design method during ETO business processes.

5.2 Reduction of design errors discussion

The second focus of this study was to examine if there is any difference in design error reduction during product design process between the traditional and KBE/CAD integration design methods and if this difference is positive. The null and alternate hypotheses are:

- Ho2: There is no change in the reduction of the design errors between the design methodologies in the ETO environment.
- Ha2: There is a positive change in the reduction of the design errors between the design methodologies in the ETO environment.

The reduction of design errors is important to ETO organizations to ensure product quality throughout the production process. The further downstream the design errors enter the processes, the more complex and costly they are to fix. The EC design errors data was collected and statistically analyzed. The results of this study showed the KBE/CAD integration design method was more effective than the traditional design method by reducing design errors to 0. The KBE/CAD integration design method enabled 100% design accuracy. This study also investigated the relationship between the design methods and the user's level of CAD education and experience. The results of this study showed there was no dependency between the KBE/CAD design method and the user's level of CAD education and experience for design errors. There was an improvement between dependencies of the traditional design method and user level of the CAD education and experience relationship. The KBE/CAD design method was open to a wider range of users while ensuring design accuracy.

5.3 Research question discussion

The research question of this experiment is "Is the Knowledge-Based Engineering (KBE) and Computer Aided Design (CAD) integration design approach more efficient for the reduction of lead time and design errors than the traditional method for Engineering-to-Order (ETO) product situations?"

Based on the data results and discussion of this study, the KBE/CAD integration design approach was more efficient for the reduction of lead-time and design errors than the traditional method for the ETO product situations. The KBE/CAD integration approach was proven to be more accurate and faster than the traditional method. By implementing this approach, organizations would able to control production time and quality during the early process of ETO product development and to prevent unpredictable production planning for downstream processes.

5.3.1 Benefit of lead-time and design errors reduction to the ETO organizations

Lead-time and design qualities are important aspects for the production process. This study has proven the KBE/CAD integration design is the innovative way to shorten the design lead-time while improving product quality. The people who would benefit from the integrated design approach are project managers, customers as well as other related functions within the ETO organizations such as marketing, manufacturing, etc.

The projects managers would get direct tradeoff between lead-time, data quality, and cost. The KBE/CAD integration design method can cover a high percentage of design scenarios and take a small fraction of time to configure them accurately. The project managers can be confident with planning and scheduling either for quoting information or actual Engineering Change requests. This lead-time saving would go towards the project cost revenue while opening up labor hours for more productive work. In addition, being able to produce the same product, with a shorter lead-time, while maintaining data quality would give the project manager increased competitiveness.

The ETO customers would benefit from reduced time to consumption and improved to cash flow. Different from other consumers, the ETO customers often have specific need to customize their orders either to use directly in their production process or as a component of the finished product (Mäkipää, Paunu, & Ingalsuo, 2012). Thus the ETO customers are looking for a solution to their existing problems. The KBE/CAD integration design ability to shorten the lead-time while maintaining design quality would bring the ETO customers closer to the time of consumption and reduce unproductive time. In addition, shorter lead-time is directly related to shorten time for the ETO customers to have their deposit money on hold. To have short time to cash flows can mean many things to the ETO customer, such as more cash availability, lowering the need to borrow and/or lower interest on loans.

For other functions related to the ETO projects, such as marketing and manufacturing, the KBE/CAD integration design not only reduces lead-time but is also key to getting information about the product. Marketing and manufacturing functions are able to interact with the ETO product to get the information they need instantly. They would have a chance to understand more about the ETO products and avoid long wait time from the production design department.

5.3.2 Benefit of this research experiment to ETO and KBE area of research and development

Currently there is limited research on the topic of Engineering to Order (ETO) product and/or Knowledge Based Engineering (KBE). Most related literatures reported some percentage or number of lead-time, cost, and design errors reduction from implementing the automatic configurators in the industrial setting (Forza & Salvador, 2002; Hong et al.,2008; Hvam L., 2006; Hvam, Pape, & Nielsen, 2006; Jiao & Zhang, 2005). However, little or no quantitative data were provided in detail of how the statistical numbers were calculated for the report. In addition, these automatic configurators were initiated from the IT or KBE specialist's perspective who uses generic programming and the investment cost of product development were not taken into account.

To fill the research gap, this research experiment provided quantitative study concerning the KBE technology that was initiated from the engineering perspective. The study provided qualitative data of the time required to invest in development, lead-time required to complete Engineering Change tasks, design errors and user level of CAD experience. This data showed statistical evidence that KBE/CAD integration technology is improving the ETO product situation and can be used as leverage when it comes to investment decision. The ETO organizations can relate their ETO product and its complexity to the product that was used in the study in order to estimate benefits.

5.3.3 Overall view of the KBE/CAD integration and the Traditional design methodologies comparison

Generally the KBE/CAD integration design method is an automated design concept that might be mistaken as costly in time and effort to develop as application software. This is not necessarily true. There are several aspects that come across during this research study.

The KBE/CAD integration design method used the KBE functions and features that are embedded inside the CAD software and does not require additional software license to run the programming function. These KBE/CAD integrated functions and features are included with the CAD package. In addition, the KBE/CAD integrated technology has a lower cost for maintenance.

The KBE/CAD integration design methodology is a combination of low level programming and best practices of CAD modeling procedure. In terms of development techniques, the KBE/CAD integration design method is not very different from the traditional design methodology but the improvement was different. The time required for the development process of KBE/CAD integration design method can be recovered in a relatively small number of uses. In addition, the pool of users is open to a wider range of less experience CAD users.

In a product situation, such as ETO, where there is a need for numerous configuration changes in a short period of time, using KBE/CAD integration technology to automate design configuration would allow the ETO companies to provide accurate information faster for quoting, prototyping design scenarios, or completing Engineering Change requests. The ETO companies using the KBE/CAD integration would have a competitive advantage over others. Automating configuration design with the KBE/CAD integration technology is definitely worth the investment for the ETO product situation.

5.3.4 KBE/CAD integration design method investment consideration

Although KBE/CAD integration design enables enormous benefit to lead-time and design errors, there are considerations that ETO organizations must take into account for investment decisions:

- The ETO product configuration design must be able to cover a high percentage of product design customization scenarios. For this study, the KBE/CAD master model of the product was designed to cover 80% of customization scenarios.
- To make KBE/CAD design method profitable, the ETO business must be a larger portion of the organization’s business. If ETO is only a small portion of the business with only a few orders a year, the required time to recover from KBE/CAD investment might be longer than expected. The profit margin might be too low to consider this investment.

- The availability of labor hours to invest in product development must be considered.
- A Product Data Management (PDM) system was not used for this research experiment.

5.4 Recommendation for future research

Although the research experiment provided effective results to address the research problem, additional experiments can improve research findings. Recommendations for future research are as follows:

- Provide a better solution to prepare subjects for the experiment. The training subjects have to go through for the experiment includes product system training, traditional training and KBE/CAD training. From the participants feedback, the presented information is relevant but complex and difficult to absorb or assimilate. Providing more effective training materials would help the subjects perform their best.
- Implement the experiment with an actual company in the ETO industry. If permission could be obtained to experiment with an actual product in the ETO industrial setting, the study would discover information that current research is missing. The data collected would have industrial value, and could be used as measurement standard for ETO study. The project time length could be longer. Research focus can expand to more dimensions such as cost and effort.
- Investigate whether industrial companies would adopt the KBE/CAD integration method and continue to implement it. By presenting the study to ETO companies,

survey information could be collected to establish whether companies would implement the KBE/CAD integration design method, as well as determine what their concerns and expectations are. Furthermore, for ETO companies that have already implemented the KBE/CAD integration design method, a future study could investigate if the company continues using the applications for the ETO product environment or returns to the traditional method and what are the reasons behind the return.

- Investigate the level of training required to prepare a design engineer to be a KBE/CAD integration developer. Since research indicates KBE/CAD integration is a method involving low level programming and scripting, it is important to examine minimum qualifications, user background and the amount that needs to be invested in training.
- Implementing the KBE/CAD integration design method within PDM environment. By controlling configuration with rules, relations, and facts from an application programming interface, it is important to understand how to control the data in a PDM system. The KBE/CAD design method might require differences in PDM implementation compared to traditional design method requirements.

5.5 Conclusion

The research experiment was conducted at Purdue University during semesters of Fall 2014 and Spring 2015 with additional research credits from the independent study section. There were 86 subjects that participated resulting in a data set of 62 that were usuable. The data analysis showed there was positive improvement in the reduction of lead-time and design errors by using the KBE/CAD integration design approach over the traditional method for the ETO product situations. Research limitations and considerations were taken into account and documented for future research.

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APPENDICES

Appendix A

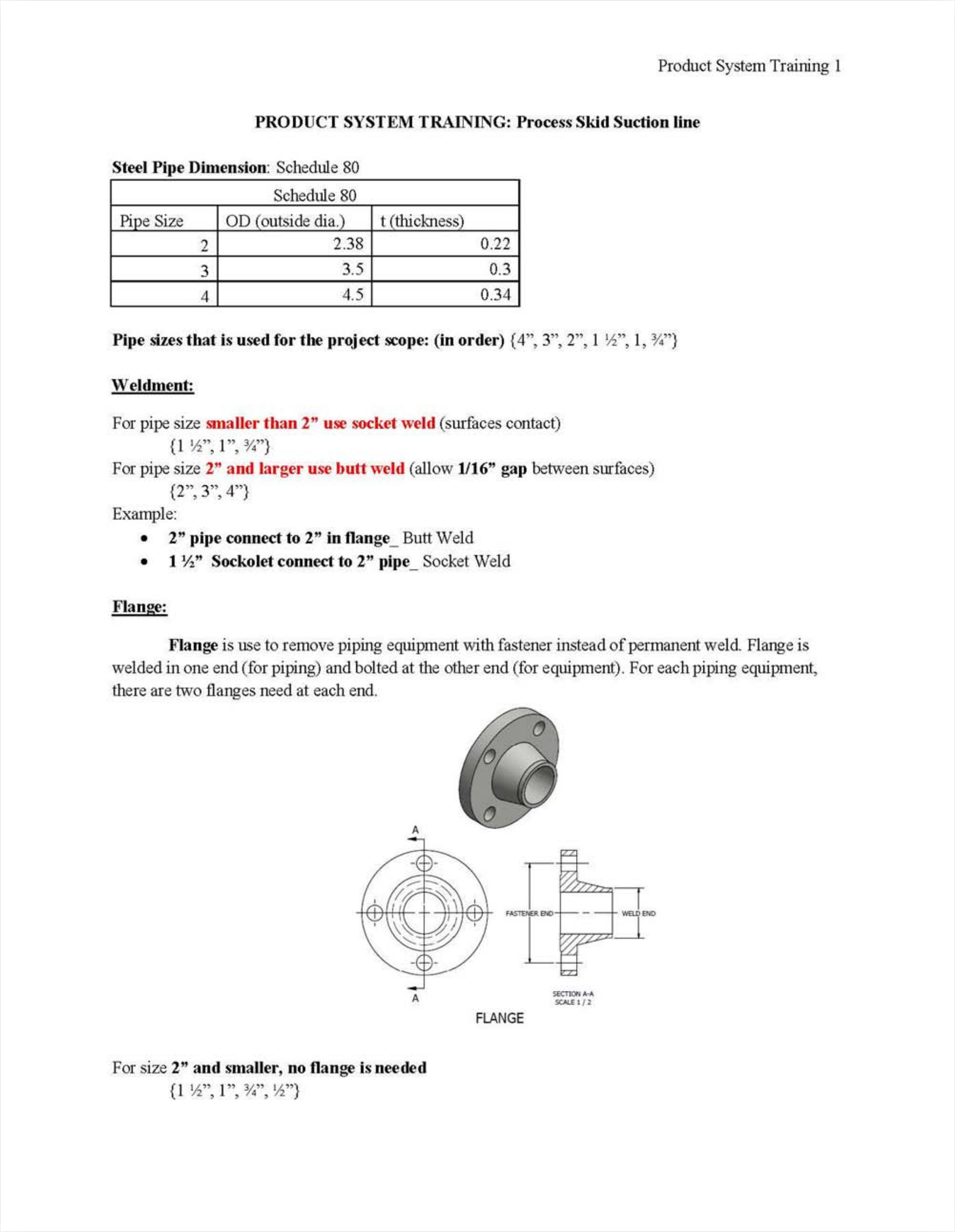
Table A.1 *Typical ETO characteristics*

Unit of analysis	Typical characteristics	Reference
Products	Complex Deep product structure (many components) Low volume on product level, higher on sub-assembly and component level Mix of standardized and customized components High degree of customization-"one of a kind products" High product variety Long lead times Frequent changes	(Bertrand & Muntslag, 1993; Hicks, McGovern, & Earl, 2000; Hicks, McGovern, & Earl, 2001; Rahim, A. R. A., 2003; Stavrulaki, E., 2010)
Processes	Business processes divided into three stages: marketing, tendering and contract execution Temporariness, uniqueness and multifuctionality Focus on flexibility General purpose equipment Non-routine work processes Job shops/projects	(Caron & Fiore, 1995; Hicks, McGovern, & Earl, 2000; Rahim, A. R. A., 2003; Stavrulaki, E., 2010)
Markets	Uncertainty in demand and product mix External flexibility needed in handling the uncertainty	(Bertrand & Muntslag, 1993; Gosling & Naim, 2009)
Uncertainty and risk	Three types of risk: technical risk, time risk and financial risk	(Bertrand & Muntslag, 1993; Muntslag D. R., 1994)
Challenges	Long lead times Uncertain delivery date Handling change orders Production planning and control Product quality	(Danese & Romano, 2004; Hicks & Braiden, 2000; Krajewski, L., 2005; Little, Rollins, Peck, & Porter, 2000; Pandit & Zhu, 2007; Terwiesch & Loch, 1999)

Conflicts in manufacturing/marketing schedules

Material waste

Appendix B Training Materials



PRODUCT SYSTEM TRAINING: Process Skid Suction line

Steel Pipe Dimension: Schedule 80

Schedule 80		
Pipe Size	OD (outside dia.)	t (thickness)
2	2.38	0.22
3	3.5	0.3
4	4.5	0.34

Pipe sizes that is used for the project scope: (in order) {4", 3", 2", 1 ½", 1, ¾"}

Weldment:

For pipe size **smaller than 2" use socket weld** (surfaces contact)
{1 ½", 1", ¾"}
For pipe size **2" and larger use butt weld** (allow **1/16" gap** between surfaces)
{2", 3", 4"}
Example:

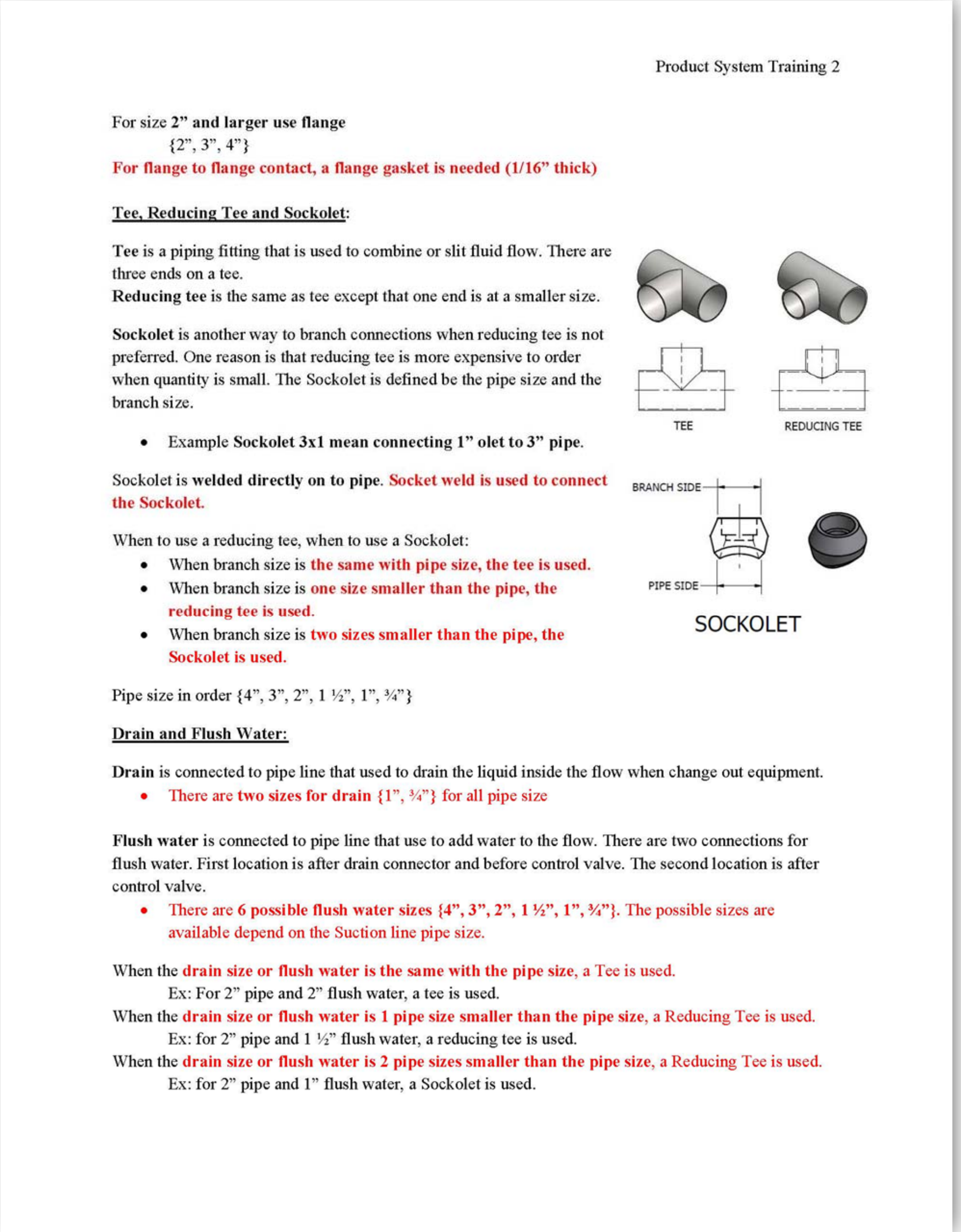
- **2" pipe connect to 2" in flange**_ Butt Weld
- **1 ½" Sockolet connect to 2" pipe**_ Socket Weld

Flange:

Flange is use to remove piping equipment with fastener instead of permanent weld. Flange is welded in one end (for piping) and bolted at the other end (for equipment). For each piping equipment, there are two flanges need at each end.

FLANGE

For size **2" and smaller, no flange is needed**
{1 ½", 1", ¾", ½"}



For size **2" and larger use flange**
{2", 3", 4"}
For flange to flange contact, a flange gasket is needed (1/16" thick)

Tee, Reducing Tee and Sockolet:

Tee is a piping fitting that is used to combine or slit fluid flow. There are three ends on a tee.
Reducing tee is the same as tee except that one end is at a smaller size.

Sockolet is another way to branch connections when reducing tee is not preferred. One reason is that reducing tee is more expensive to order when quantity is small. The Sockolet is defined be the pipe size and the branch size.

- Example **Sockolet 3x1 mean connecting 1" olet to 3" pipe**.

Sockolet is **welded directly on to pipe**. **Socket weld is used to connect the Sockolet.**

SOCKOLET

When to use a reducing tee, when to use a Sockolet:

- When branch size is **the same with pipe size, the tee is used.**
- When branch size is **one size smaller than the pipe, the reducing tee is used**.
- When branch size is **two sizes smaller than the pipe, the Sockolet is used.**

Pipe size in order {4", 3", 2", 1 ½", 1", ¾"}

Drain and Flush Water:

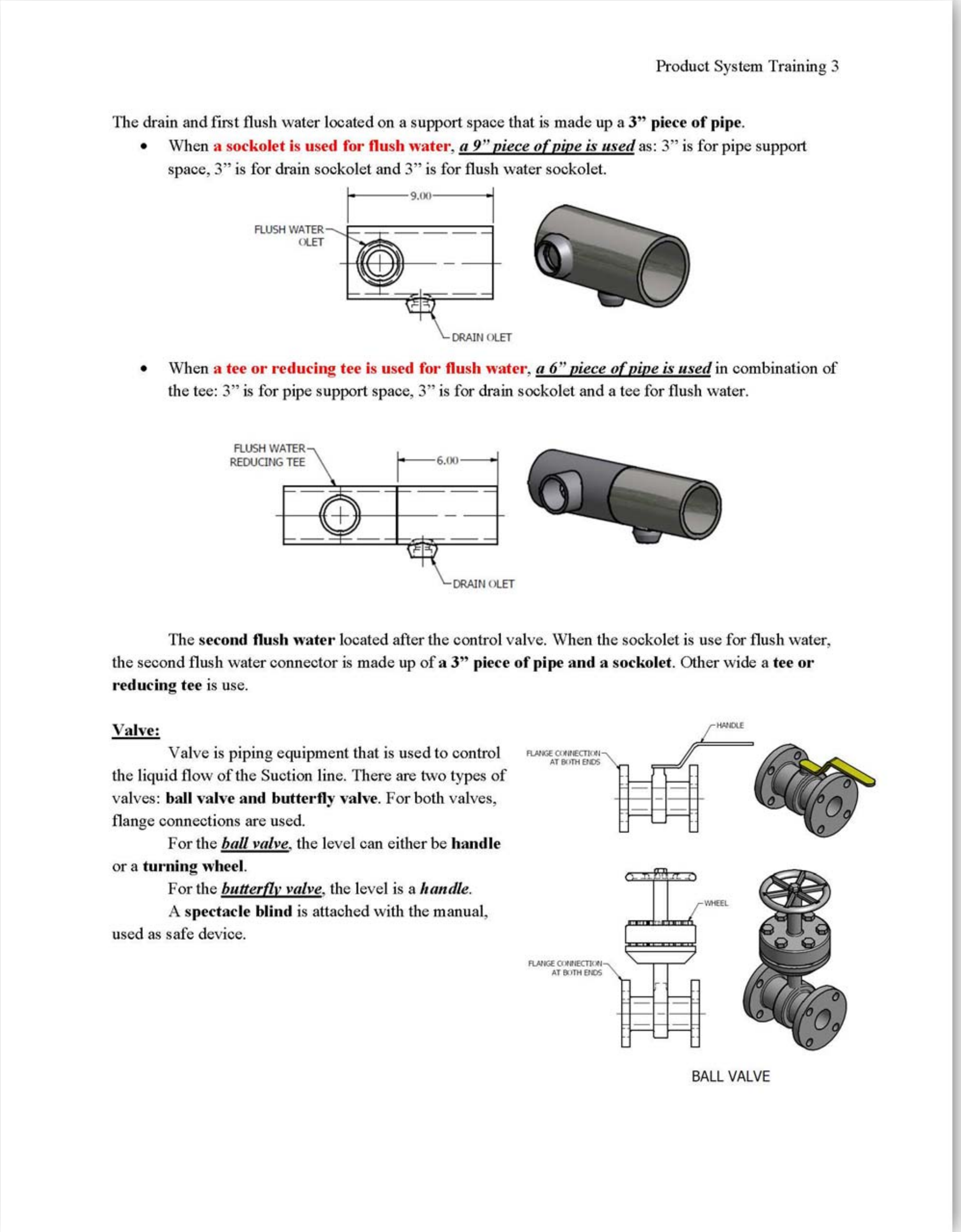
Drain is connected to pipe line that used to drain the liquid inside the flow when change out equipment.

- There are **two sizes for drain** {1", ¾"} for all pipe size

Flush water is connected to pipe line that use to add water to the flow. There are two connections for flush water. First location is after drain connector and before control valve. The second location is after control valve.

- There are **6 possible flush water sizes {4", 3", 2", 1 ½", 1", ¾"}**. The possible sizes are available depend on the Suction line pipe size.

When the **drain size or flush water is the same with the pipe size**, a Tee is used.
Ex: For 2" pipe and 2" flush water, a tee is used.
When the **drain size or flush water is 1 pipe size smaller than the pipe size**, a Reducing Tee is used.
Ex: for 2" pipe and 1 ½" flush water, a reducing tee is used.
When the **drain size or flush water is 2 pipe sizes smaller than the pipe size**, a Reducing Tee is used.
Ex: for 2" pipe and 1" flush water, a Sockolet is used.



The drain and first flush water located on a support space that is made up a **3” piece of pipe**.

- When **a sockolet is used for flush water**, ***a 9” piece of pipe is used*** as: 3” is for pipe support space, 3” is for drain sockolet and 3” is for flush water sockolet.

- When **a tee or reducing tee is used for flush water**, ***a 6” piece of pipe is used*** in combination of the tee: 3” is for pipe support space, 3” is for drain sockolet and a tee for flush water.

The **second flush water** located after the control valve. When the sockolet is use for flush water, the second flush water connector is made up of **a 3” piece of pipe and a sockolet**. Other wide a **tee or reducing tee** is use.

Valve:

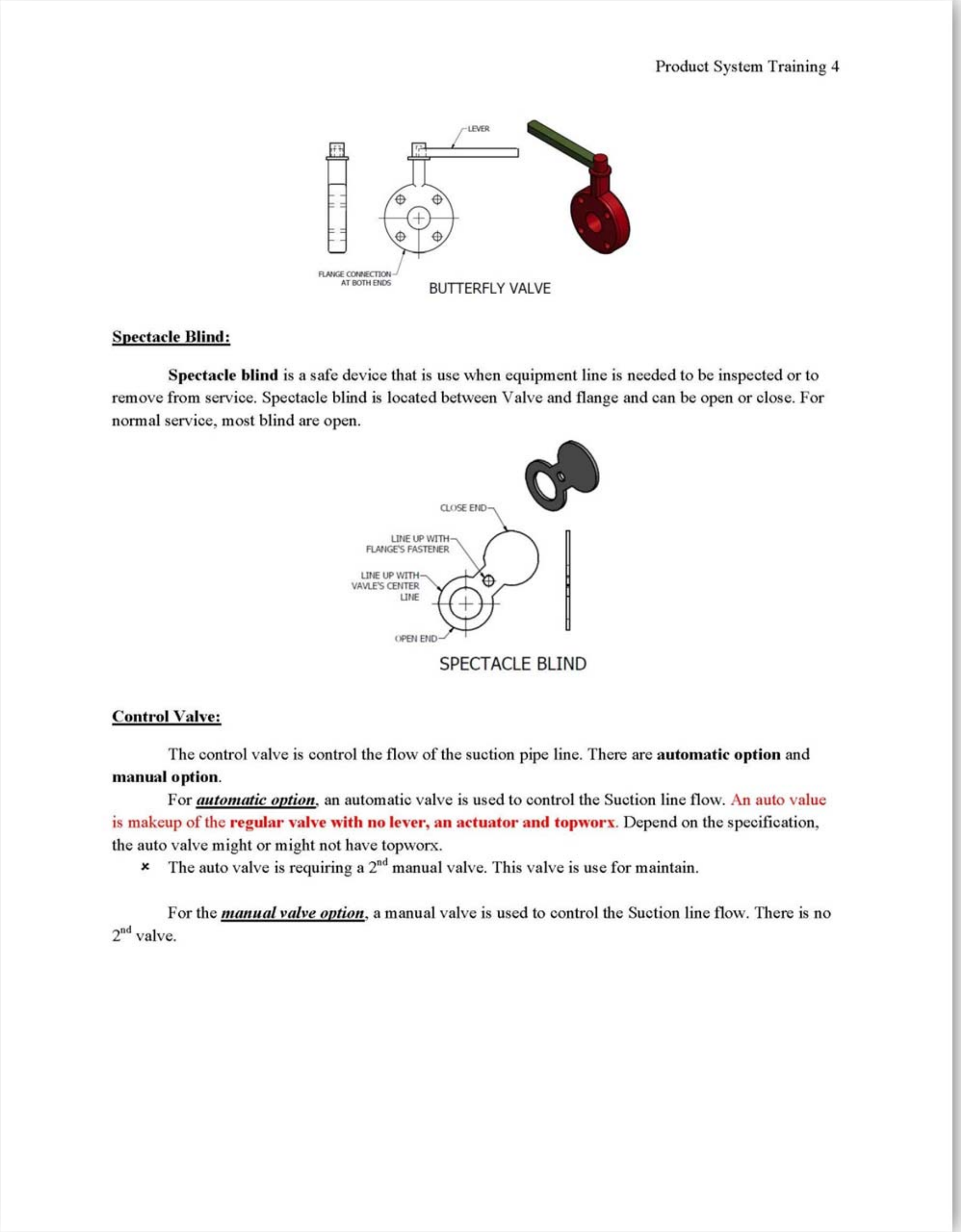
Valve is piping equipment that is used to control the liquid flow of the Suction line. There are two types of valves: **ball valve and butterfly valve**. For both valves, flange connections are used.

For the ***ball valve***, the level can either be **handle** or a **turning wheel**.

For the ***butterfly valve***, the level is a ***handle***.

A **spectacle blind** is attached with the manual, used as safe device.

BALL VALVE



BUTTERFLY VALVE

Spectacle Blind:

Spectacle blind is a safe device that is use when equipment line is needed to be inspected or to remove from service. Spectacle blind is located between Valve and flange and can be open or close. For normal service, most blind are open.

SPECTACLE BLIND

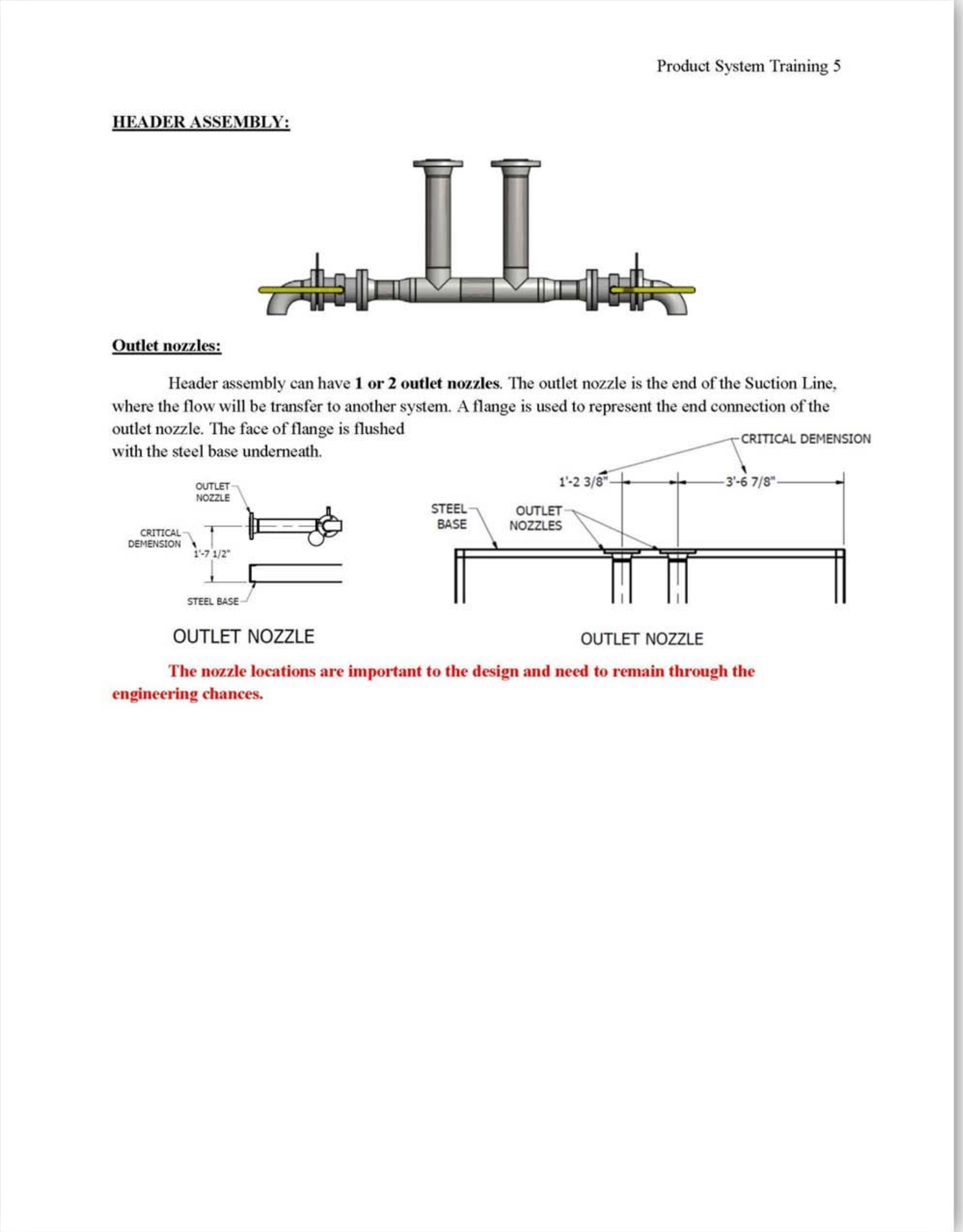
Control Valve:

The control valve is control the flow of the suction pipe line. There are **automatic option** and **manual option**.

For ***automatic option***, an automatic valve is used to control the Suction line flow. An auto value is makeup of the **regular valve with no lever, an actuator and topworx**. Depend on the specification, the auto valve might or might not have topworx.

- The auto valve is requiring a 2nd manual valve. This valve is use for maintain.

For the ***manual valve option***, a manual valve is used to control the Suction line flow. There is no 2nd valve.



HEADER ASSEMBLY:

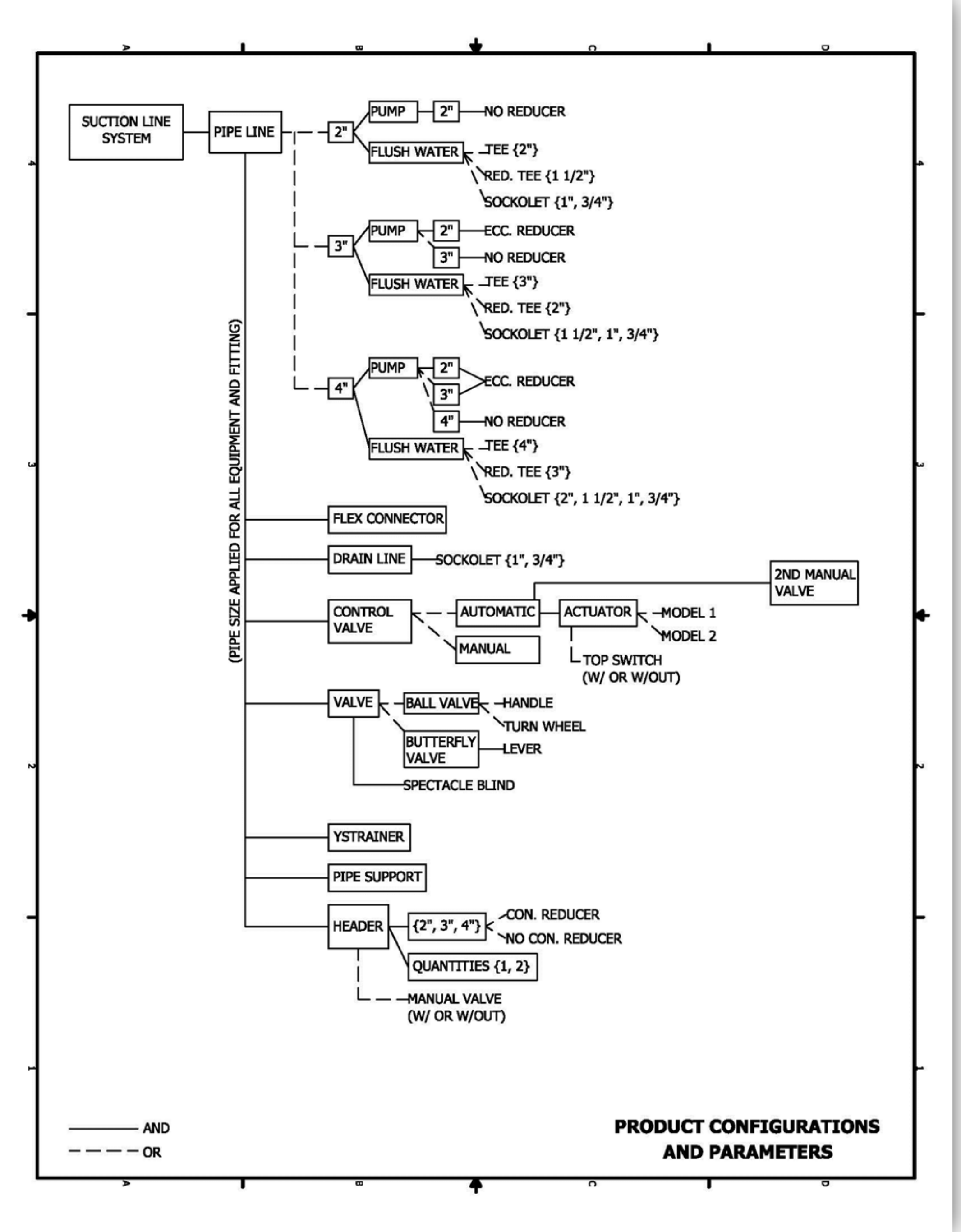
Outlet nozzles:

Header assembly can have **1 or 2 outlet nozzles**. The outlet nozzle is the end of the Suction Line, where the flow will be transfer to another system. A flange is used to represent the end connection of the outlet nozzle. The face of flange is flushed with the steel base underneath.

OUTLET NOZZLE

OUTLET NOZZLE

The nozzle locations are important to the design and need to remain through the engineering chances.


SUCTION LINE SYSTEM
PIPE LINE
(PIPE SIZE APPLIED FOR ALL EQUIPMENT AND FITTING)
2"
PUMP
2"
NO REDUCER
FLUSH WATER
TEE {2"}
RED. TEE {1 1/2"}
SOCKOLET {1", 3/4"}
3"
PUMP
2"
ECC. REDUCER
3"
NO REDUCER
FLUSH WATER
TEE {3"}
RED. TEE {2"}
SOCKOLET {1 1/2", 1", 3/4"}
4"
PUMP
2"
3"
ECC. REDUCER
4"
NO REDUCER
FLUSH WATER
TEE {4"}
RED. TEE {3"}
SOCKOLET {2", 1 1/2", 1", 3/4"}
FLEX CONNECTOR
DRAIN LINE
SOCKOLET {1", 3/4"}
CONTROL VALVE
AUTOMATIC
ACTUATOR
MODEL 1
MODEL 2
TOP SWITCH (W/ OR W/OUT)
2ND MANUAL VALVE
MANUAL
VALVE
BALL VALVE
HANDLE
TURN WHEEL
BUTTERFLY VALVE
LEVER
SPECTACLE BLIND
YSTRAINER
PIPE SUPPORT
HEADER
{2", 3", 4"}
CON. REDUCER
NO CON. REDUCER
QUANTITIES {1, 2}
MANUAL VALVE (W/ OR W/OUT)
AND
OR
PRODUCT CONFIGURATIONS AND PARAMETERS

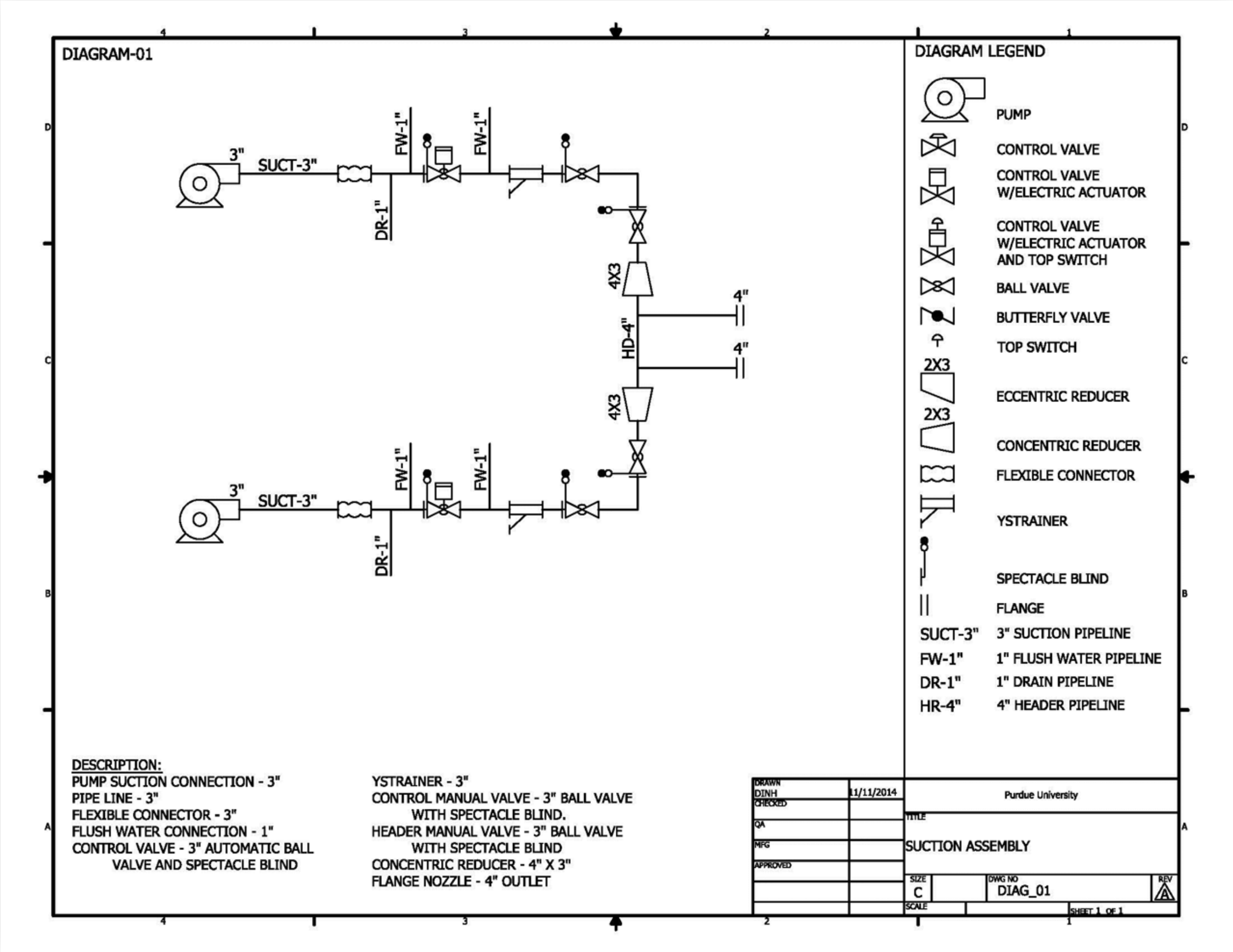
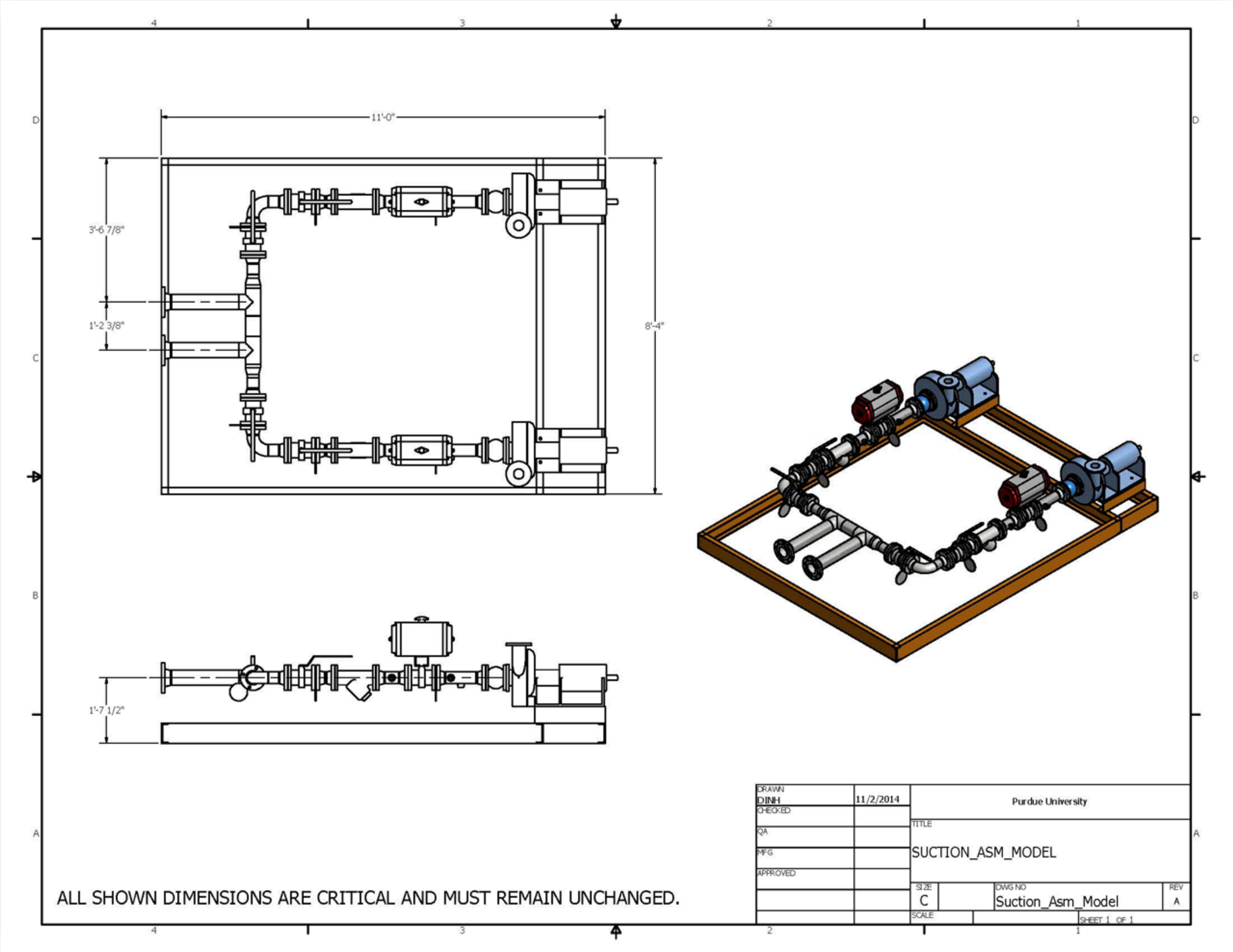
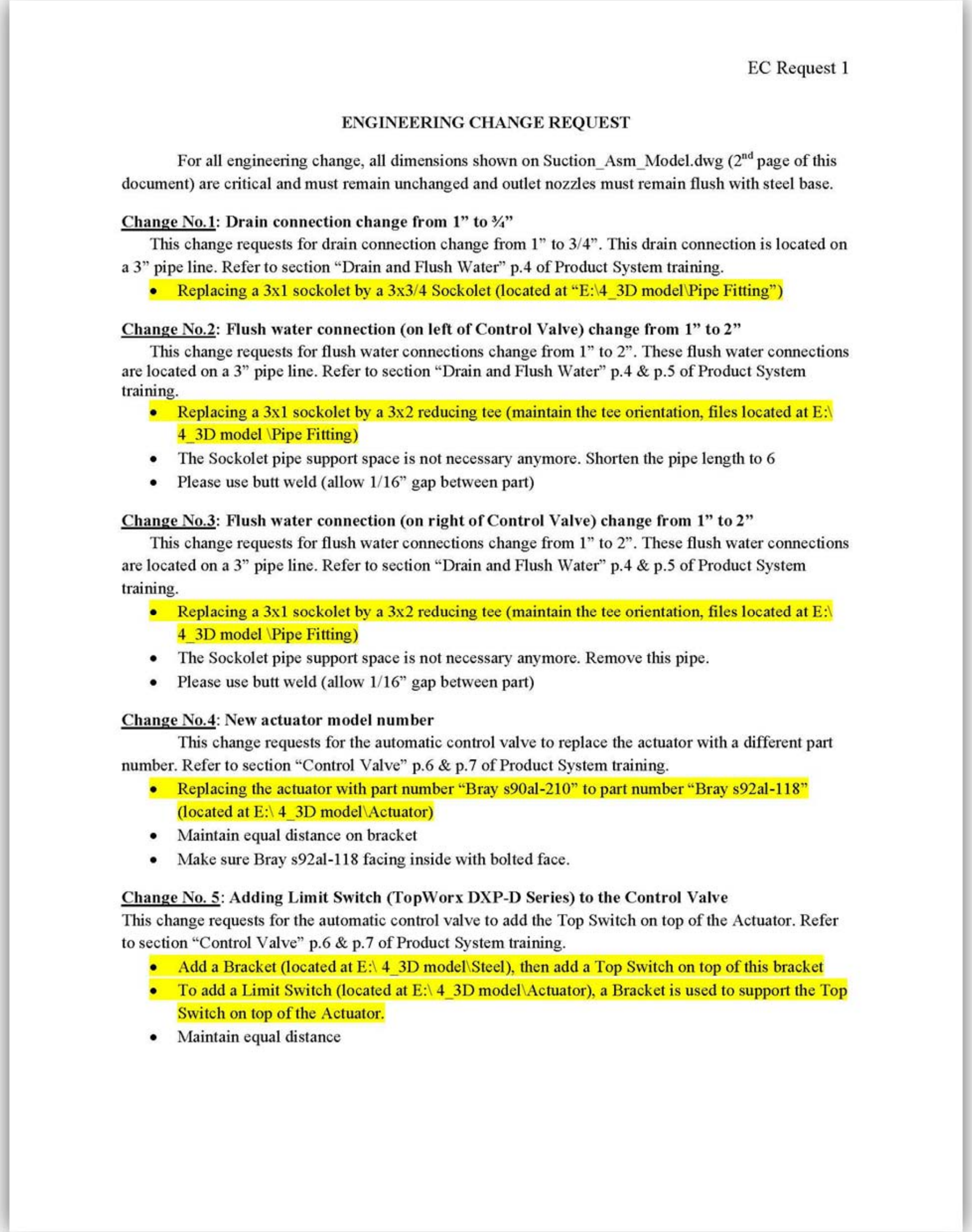


DIAGRAM-01
3"
SUCT-3"
DR-1"
FW-1"
FW-1"
4X3
HD-4"
4X3
4"
4"
3"
SUCT-3"
DR-1"
FW-1"
FW-1"
DESCRIPTION:
PUMP SUCTION CONNECTION - 3"
PIPE LINE - 3"
FLEXIBLE CONNECTOR - 3"
FLUSH WATER CONNECTION - 1"
CONTROL VALVE - 3" AUTOMATIC BALL VALVE AND SPECTACLE BLIND
YSTRAINER - 3"
CONTROL MANUAL VALVE - 3" BALL VALVE WITH SPECTACLE BLIND.
HEADER MANUAL VALVE - 3" BALL VALVE WITH SPECTACLE BLIND
CONCENTRIC REDUCER - 4" X 3"
FLANGE NOZZLE - 4" OUTLET
DIAGRAM LEGEND
PUMP
CONTROL VALVE
CONTROL VALVE W/ELECTRIC ACTUATOR
CONTROL VALVE W/ELECTRIC ACTUATOR AND TOP SWITCH
BALL VALVE
BUTTERFLY VALVE
TOP SWITCH
2X3
ECCENTRIC REDUCER
2X3
CONCENTRIC REDUCER
FLEXIBLE CONNECTOR
YSTRAINER
SPECTACLE BLIND
FLANGE
SUCT-3" 3" SUCTION PIPELINE
FW-1" 1" FLUSH WATER PIPELINE
DR-1" 1" DRAIN PIPELINE
HR-4" 4" HEADER PIPELINE
DRAWN
DINH
11/11/2014
CHECKED
QA
MFG
APPROVED
Purdue University
TITLE
SUCTION ASSEMBLY
SIZE
C
DWG NO
DIAG_01
REV
A
SCALE
SHEET 1 OF 1


11'-0"
3'-6 7/8"
1'-2 3/8"
8'-4"
1'-7 1/2"
ALL SHOWN DIMENSIONS ARE CRITICAL AND MUST REMAIN UNCHANGED.
DRAWN
DINH
11/2/2014
CHECKED
QA
MFG
APPROVED
Purdue University
TITLE
SUCTION_ASM_MODEL
SIZE
C
DWG NO
Suction_Asm_Model
REV
A
SCALE
SHEET 1 OF 1

Appendix C Engineering Change Order



EC Request 1

ENGINEERING CHANGE REQUEST

For all engineering change, all dimensions shown on Suction_Asm_Model.dwg (2nd page of this document) are critical and must remain unchanged and outlet nozzles must remain flush with steel base.

Change No.1: Drain connection change from 1" to ¾"

This change requests for drain connection change from 1" to 3/4". This drain connection is located on a 3" pipe line. Refer to section "Drain and Flush Water" p.4 of Product System training.

- Replacing a 3x1 sockolet by a 3x3/4 Sockolet (located at "E:\4_3D model\Pipe Fitting")

Change No.2: Flush water connection (on left of Control Valve) change from 1" to 2"

This change requests for flush water connections change from 1" to 2". These flush water connections are located on a 3" pipe line. Refer to section "Drain and Flush Water" p.4 & p.5 of Product System training.

- Replacing a 3x1 sockolet by a 3x2 reducing tee (maintain the tee orientation, files located at E:\ 4_3D model \Pipe Fitting)
- The Sockolet pipe support space is not necessary anymore. Shorten the pipe length to 6
- Please use butt weld (allow 1/16" gap between part)

Change No.3: Flush water connection (on right of Control Valve) change from 1" to 2"

This change requests for flush water connections change from 1" to 2". These flush water connections are located on a 3" pipe line. Refer to section "Drain and Flush Water" p.4 & p.5 of Product System training.

- Replacing a 3x1 sockolet by a 3x2 reducing tee (maintain the tee orientation, files located at E:\ 4_3D model \Pipe Fitting)
- The Sockolet pipe support space is not necessary anymore. Remove this pipe.
- Please use butt weld (allow 1/16" gap between part)

Change No.4: New actuator model number

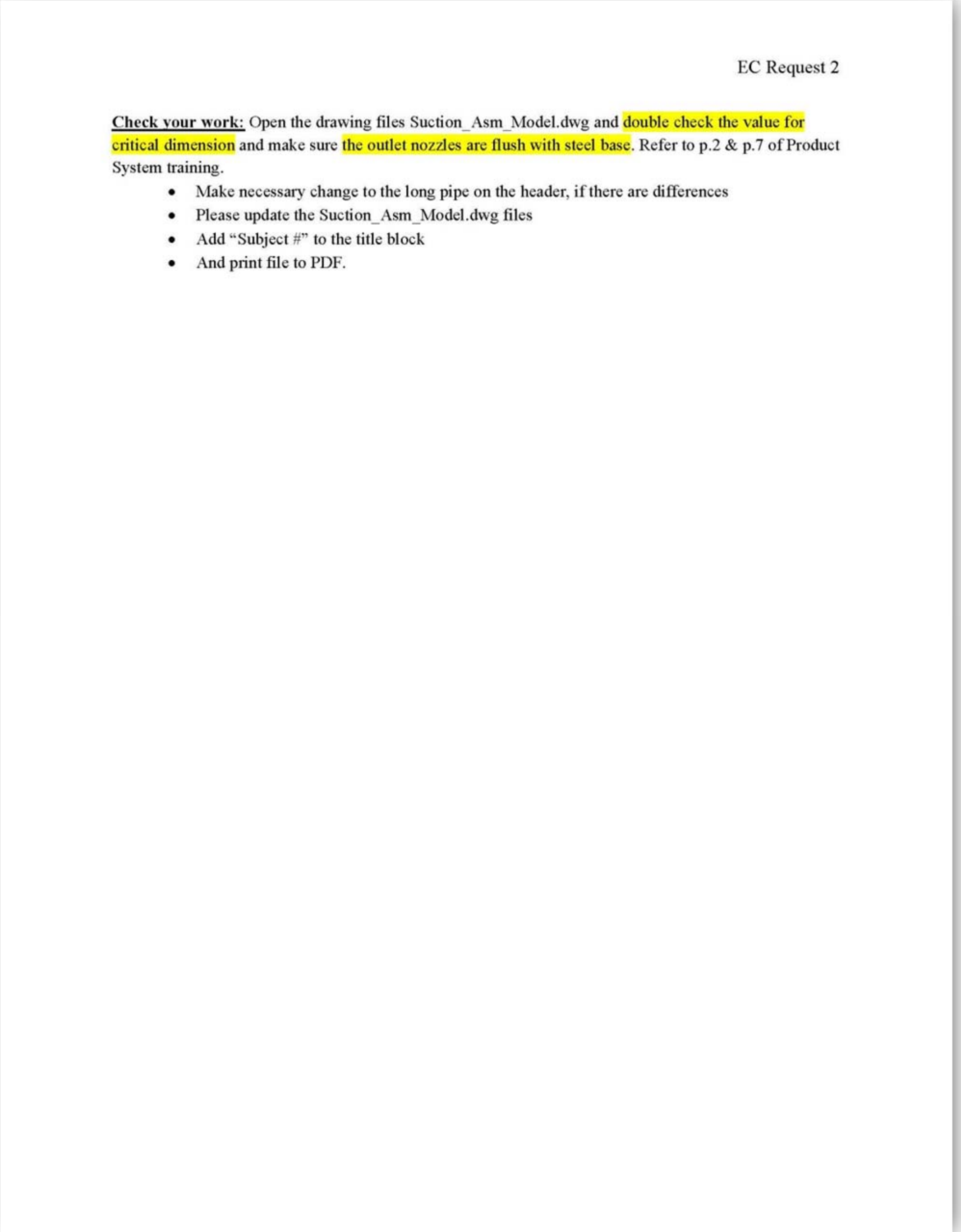
This change requests for the automatic control valve to replace the actuator with a different part number. Refer to section "Control Valve" p.6 & p.7 of Product System training.

- Replacing the actuator with part number "Bray s90al-210" to part number "Bray s92al-118" (located at E:\ 4_3D model\Actuator)
- Maintain equal distance on bracket
- Make sure Bray s92al-118 facing inside with bolted face.

Change No. 5: Adding Limit Switch (TopWorx DXP-D Series) to the Control Valve

This change requests for the automatic control valve to add the Top Switch on top of the Actuator. Refer to section "Control Valve" p.6 & p.7 of Product System training.

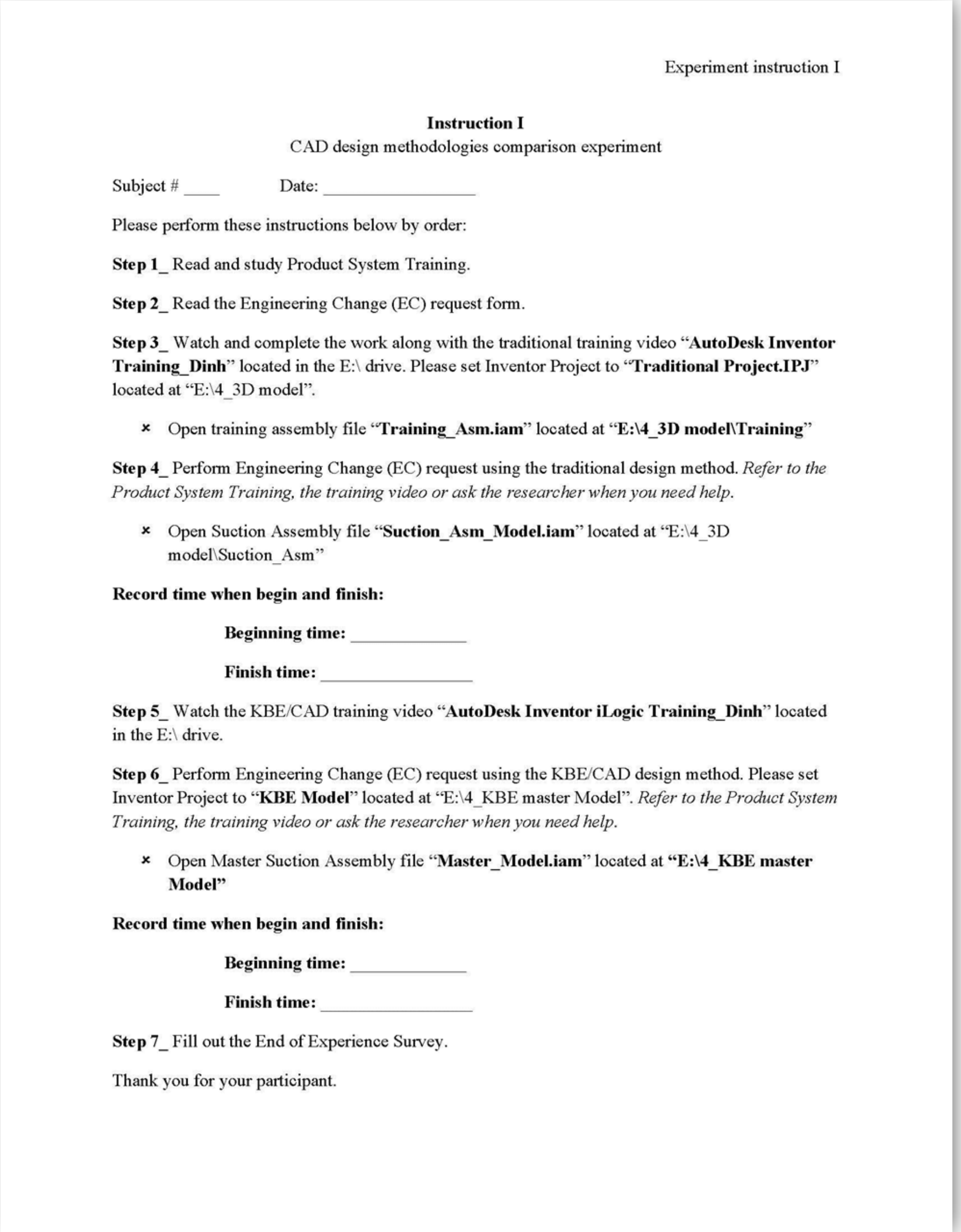
- Add a Bracket (located at E:\ 4_3D model\Steel), then add a Top Switch on top of this bracket
- To add a Limit Switch (located at E:\ 4_3D model\Actuator), a Bracket is used to support the Top Switch on top of the Actuator.
- Maintain equal distance



EC Request 2

Check your work: Open the drawing files Suction_Asm_Model.dwg and double check the value for critical dimension and make sure the outlet nozzles are flush with steel base. Refer to p.2 & p.7 of Product System training.

- Make necessary change to the long pipe on the header, if there are differences
- Please update the Suction_Asm_Model.dwg files
- Add “Subject #” to the title block
- And print file to PDF.



Experiment instruction I

Instruction I
CAD design methodologies comparison experiment

Subject # ____ Date: _________________

Please perform these instructions below by order:

Step 1_ Read and study Product System Training.

Step 2_ Read the Engineering Change (EC) request form.

Step 3_ Watch and complete the work along with the traditional training video "**AutoDesk Inventor Training_Dinh**" located in the E:\ drive. Please set Inventor Project to "**Traditional Project.IPJ**" located at "E:\4_3D model".

- Open training assembly file "**Training_Asm.iam**" located at "**E:\4_3D model\Training**"

Step 4_ Perform Engineering Change (EC) request using the traditional design method. *Refer to the Product System Training, the training video or ask the researcher when you need help.*

- Open Suction Assembly file "**Suction_Asm_Model.iam**" located at "E:\4_3D model\Suction_Asm"

Record time when begin and finish:

Beginning time: _____________

Finish time: _________________

Step 5_ Watch the KBE/CAD training video "**AutoDesk Inventor iLogic Training_Dinh**" located in the E:\ drive.

Step 6_ Perform Engineering Change (EC) request using the KBE/CAD design method. Please set Inventor Project to "**KBE Model**" located at "E:\4_KBE master Model". *Refer to the Product System Training, the training video or ask the researcher when you need help.*

- Open Master Suction Assembly file "**Master_Model.iam**" located at **"E:\4_KBE master Model"**

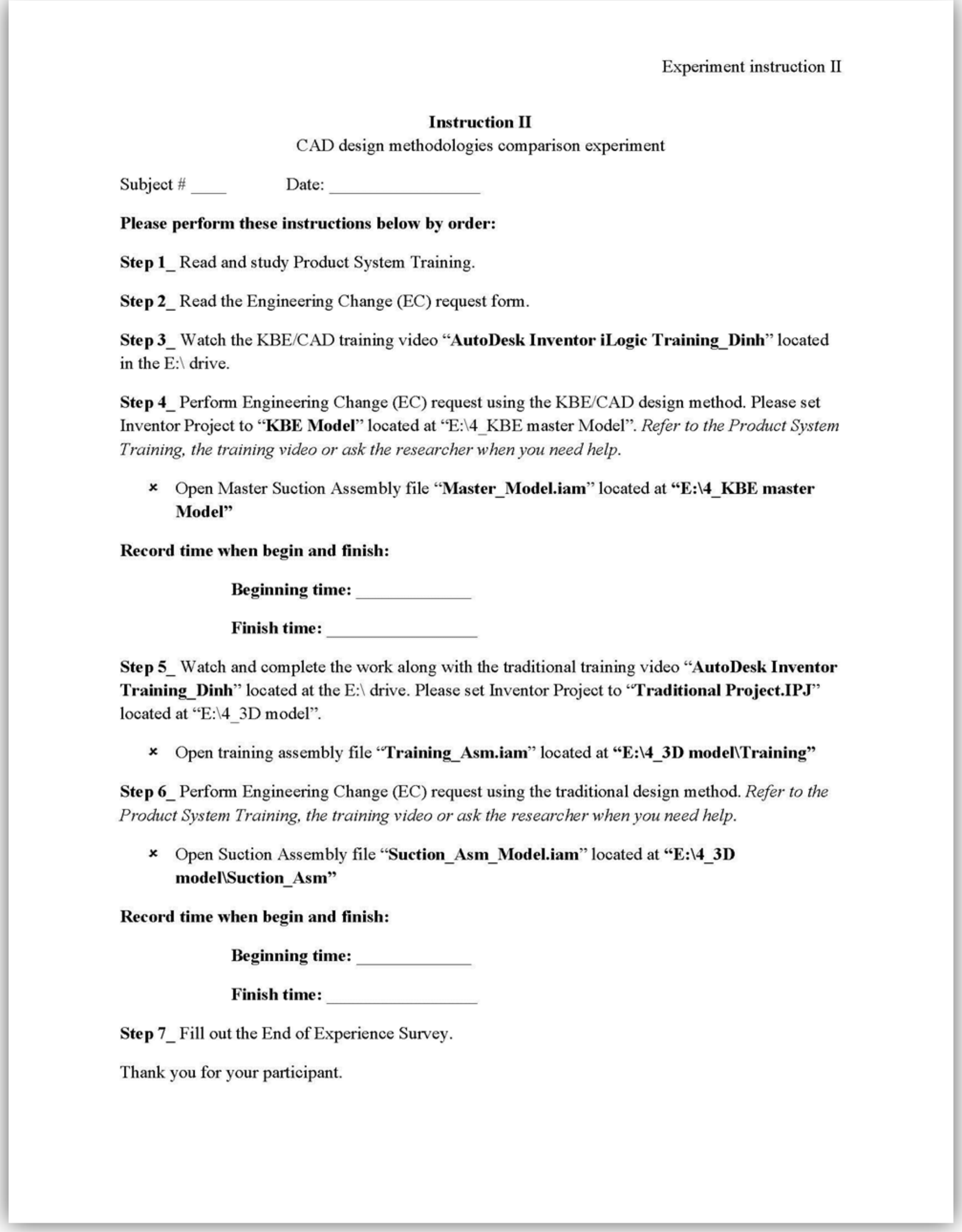
Record time when begin and finish:

Beginning time: _____________

Finish time: _________________

Step 7_ Fill out the End of Experience Survey.

Thank you for your participant.



Experiment instruction II

Instruction II

CAD design methodologies comparison experiment

Subject # ____ Date: _________________

Please perform these instructions below by order:

Step 1_ Read and study Product System Training.

Step 2_ Read the Engineering Change (EC) request form.

Step 3_ Watch the KBE/CAD training video "**AutoDesk Inventor iLogic Training_Dinh**" located in the E:\ drive.

Step 4_ Perform Engineering Change (EC) request using the KBE/CAD design method. Please set Inventor Project to "**KBE Model**" located at "E:\4_KBE master Model". *Refer to the Product System Training, the training video or ask the researcher when you need help.*

- Open Master Suction Assembly file "**Master_Model.iam**" located at **"E:\4_KBE master Model"**

Record time when begin and finish:

Beginning time: _____________

Finish time: _________________

Step 5_ Watch and complete the work along with the traditional training video "**AutoDesk Inventor Training_Dinh**" located at the E:\ drive. Please set Inventor Project to "**Traditional Project.IPJ**" located at "E:\4_3D model".

- Open training assembly file "**Training_Asm.iam**" located at **"E:\4_3D model\Training"**

Step 6_ Perform Engineering Change (EC) request using the traditional design method. *Refer to the Product System Training, the training video or ask the researcher when you need help.*

- Open Suction Assembly file "**Suction_Asm_Model.iam**" located at **"E:\4_3D model\Suction_Asm"**

Record time when begin and finish:

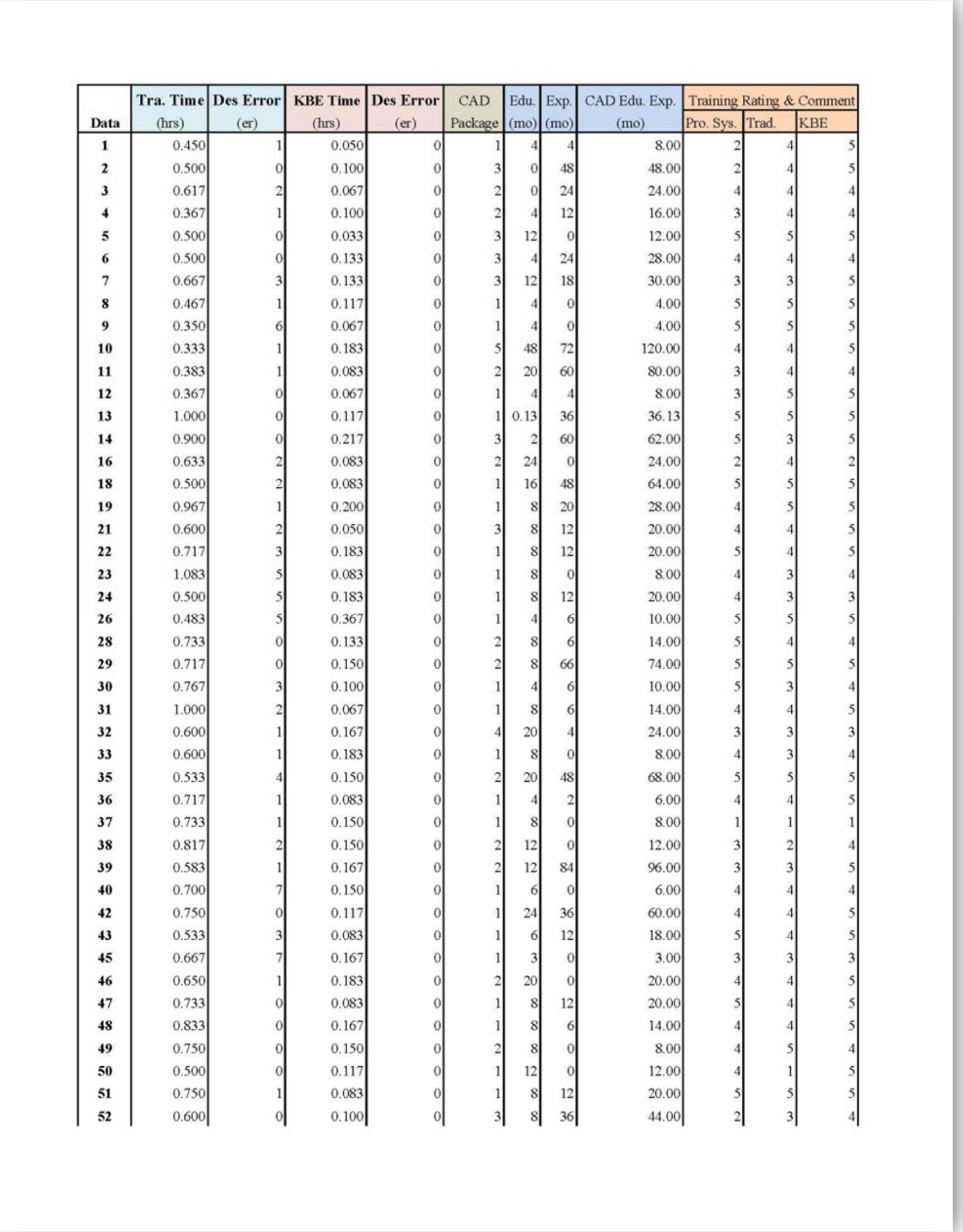
Beginning time: _____________

Finish time: _________________

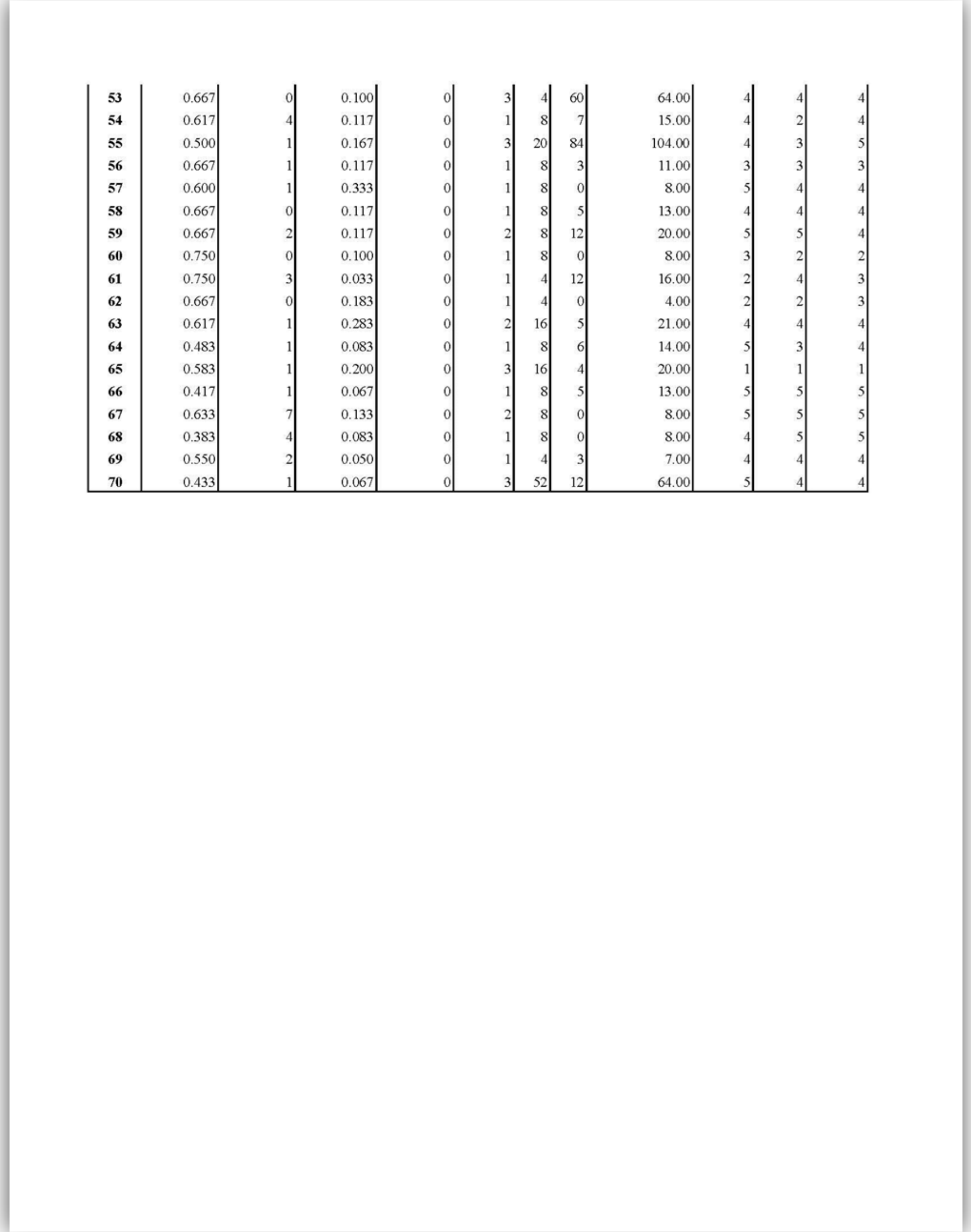
Step 7_ Fill out the End of Experience Survey.

Thank you for your participant.

Appendix D Data for Analyses



Data	Tra. Time (hrs)	Des Error (er)	KBE Time (hrs)	Des Error (er)	CAD Package	Edu. (mo)	Exp. (mo)	CAD Edu. Exp. (mo)	Training Rating & Comment		
									Pro. Sys.	Trad.	KBE
1	0.450	1	0.050	0	1	4	4	8.00	2	4	5
2	0.500	0	0.100	0	3	0	48	48.00	2	4	5
3	0.617	2	0.067	0	2	0	24	24.00	4	4	4
4	0.367	1	0.100	0	2	4	12	16.00	3	4	4
5	0.500	0	0.033	0	3	12	0	12.00	5	5	5
6	0.500	0	0.133	0	3	4	24	28.00	4	4	4
7	0.667	3	0.133	0	3	12	18	30.00	3	3	5
8	0.467	1	0.117	0	1	4	0	4.00	5	5	5
9	0.350	6	0.067	0	1	4	0	4.00	5	5	5
10	0.333	1	0.183	0	5	48	72	120.00	4	4	5
11	0.383	1	0.083	0	2	20	60	80.00	3	4	4
12	0.367	0	0.067	0	1	4	4	8.00	3	5	5
13	1.000	0	0.117	0	1	0.13	36	36.13	5	5	5
14	0.900	0	0.217	0	3	2	60	62.00	5	3	5
16	0.633	2	0.083	0	2	24	0	24.00	2	4	2
18	0.500	2	0.083	0	1	16	48	64.00	5	5	5
19	0.967	1	0.200	0	1	8	20	28.00	4	5	5
21	0.600	2	0.050	0	3	8	12	20.00	4	4	5
22	0.717	3	0.183	0	1	8	12	20.00	5	4	5
23	1.083	5	0.083	0	1	8	0	8.00	4	3	4
24	0.500	5	0.183	0	1	8	12	20.00	4	3	3
26	0.483	5	0.367	0	1	4	6	10.00	5	5	5
28	0.733	0	0.133	0	2	8	6	14.00	5	4	4
29	0.717	0	0.150	0	2	8	66	74.00	5	5	5
30	0.767	3	0.100	0	1	4	6	10.00	5	3	4
31	1.000	2	0.067	0	1	8	6	14.00	4	4	5
32	0.600	1	0.167	0	4	20	4	24.00	3	3	3
33	0.600	1	0.183	0	1	8	0	8.00	4	3	4
35	0.533	4	0.150	0	2	20	48	68.00	5	5	5
36	0.717	1	0.083	0	1	4	2	6.00	4	4	5
37	0.733	1	0.150	0	1	8	0	8.00	1	1	1
38	0.817	2	0.150	0	2	12	0	12.00	3	2	4
39	0.583	1	0.167	0	2	12	84	96.00	3	3	5
40	0.700	7	0.150	0	1	6	0	6.00	4	4	4
42	0.750	0	0.117	0	1	24	36	60.00	4	4	5
43	0.533	3	0.083	0	1	6	12	18.00	5	4	5
45	0.667	7	0.167	0	1	3	0	3.00	3	3	3
46	0.650	1	0.183	0	2	20	0	20.00	4	4	5
47	0.733	0	0.083	0	1	8	12	20.00	5	4	5
48	0.833	0	0.167	0	1	8	6	14.00	4	4	5
49	0.750	0	0.150	0	2	8	0	8.00	4	5	4
50	0.500	0	0.117	0	1	12	0	12.00	4	1	5
51	0.750	1	0.083	0	1	8	12	20.00	5	5	5
52	0.600	0	0.100	0	3	8	36	44.00	2	3	4



53	0.667	0	0.100	0	3	4	60	64.00	4	4	4
54	0.617	4	0.117	0	1	8	7	15.00	4	2	4
55	0.500	1	0.167	0	3	20	84	104.00	4	3	5
56	0.667	1	0.117	0	1	8	3	11.00	3	3	3
57	0.600	1	0.333	0	1	8	0	8.00	5	4	4
58	0.667	0	0.117	0	1	8	5	13.00	4	4	4
59	0.667	2	0.117	0	2	8	12	20.00	5	5	4
60	0.750	0	0.100	0	1	8	0	8.00	3	2	2
61	0.750	3	0.033	0	1	4	12	16.00	2	4	3
62	0.667	0	0.183	0	1	4	0	4.00	2	2	3
63	0.617	1	0.283	0	2	16	5	21.00	4	4	4
64	0.483	1	0.083	0	1	8	6	14.00	5	3	4
65	0.583	1	0.200	0	3	16	4	20.00	1	1	1
66	0.417	1	0.067	0	1	8	5	13.00	5	5	5
67	0.633	7	0.133	0	2	8	0	8.00	5	5	5
68	0.383	4	0.083	0	1	8	0	8.00	4	5	5
69	0.550	2	0.050	0	1	4	3	7.00	4	4	4
70	0.433	1	0.067	0	3	52	12	64.00	5	4	4