An Application of Lean Thinking to the Furniture Engineering Process

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(Abstract)

Efficient engineering processes are critically important for furniture manufacturers. Engineering impacts the production cost, design quality, product lead time, and customer satisfaction. This research presents a systematic approach to analyze a furniture engineering process through a case study. The research was conducted through a case study in a furniture plant located in China, producing American style furniture products. The first stage was to investigate the company's current engineering process, identify non value-added activities, and analyze the engineering performance based on selected Key Performance Indicators (KPIs) such as lead time, document error rate, and engineering throughput. A survey questionnaire was sent out to the engineering group to determine the current engineering efficiency.

Results show that "product complexity" and "engineer competency" are the two most influential factors that impact engineering lead time and quality. In the second stage, value stream mapping was used to analyze an upholstery furniture engineering process. The approach encompasses an analysis of the current state of the engineering process and the proposal of a lean future state value stream map (VSM).

Results from the current state VSM show, that the value-added ratio of the current engineering process is only 26%. Several engineering steps present deficiency such as the processes of creating drawings, compile mass production documents, check and sign-off engineering documents, create CNC programs, and generate packaging files. Based on current state VSM analysis, the researcher focused on transforming these processes to eliminate waste and to propose the best practices for the future state VSM.

From this research, it shows that current processes include a large amount of non-value adding activities such as waiting, extra processing, rework, excess motion, transportation, underutilized people, and inefficient information. These non-value adding activities are interfering with engineers' ability to prepare engineering documents for downstream jobs and affecting the overall manufacturing process. The VSM is effective to provide the visual control over the engineering process for implementing lean transformations.

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Preface

This thesis consists of five sections. Chapter one starts with introduction, motivation, justification of this research. Chapter two reviews the literature on lean thinking, engineering processes, and the lean implementations of the wood furniture industry. Chapter three discusses the general methods for the research including questionnaire design, travel plan, data collection, data analysis, results, and conclusion. Chapter four discusses the results obtained from the survey questionnaire applied in the engineering group of the case study company. Chapter five conducts a value stream mapping (VSM) lean transformation to streamline an upholstery engineering process.

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CHAPTER 1 INTRODUCTION

1.1 Introduction

Presently, furniture manufacturers have been searching for effective Lean Thinking principles to reduce cost, improve quality, and shorten time-to-market to increase their competitive advantage in the market place. Schuler and Buehlmann (2003) indicate that lean manufacturing is an essential element for the strategic renewal of a business model for the U.S. furniture industry. Another investigation of 145 wood products companies in the US, Cumbo, Kline, and Bumgardner (2006) indicates that a majority (55%) of these companies had been implementing lean manufacturing at the time of the study. The research concluded that 56% of cabinets makers, 71% of upholstered and 53% non-upholstered furniture manufacturers indicated they were implementing lean manufacturing. Quesada-Pineda and Gazo (2007) report that lean manufacturing practices, like pull system scheduling, are positively related to the performance of furniture manufacturing companies.

Lean principles encompass systematic approaches for both administration (Beau Keyte and Locher, 2004) and manufacturing level processes (Rother and Shook, 1998). Lean administration initiatives help people eliminate waste and improve work efficiency in nonproduction areas such as accounting (Maskell and Baggaley, 2003), engineering (Middleton, Flaxel, and Cookson, 2005; Haque, 2003; Freire and Alarcón, 2002) and service (Bowen and Youngdahl, 1998), while lean manufacturing performs a lean transformation for the production process improvement such as automobile manufacturing (Womack, Jones, and Roos, 1990), aerospace production (Murman and Allen, 2002), or the PC fabrication process (Ben Naylor, Naim, and Berry, 1999).

In the secondary wood products industry, research has been conducted in the use of lean tools and methods to eliminate waste and improve production efficiency in manufacturing processes (Hunter, 2008; Motsenbocker et al., 2005; Hunter, Bullard, and Steele, 2004). However, little attention is given in the application of lean to nonproduction areas such as design, new product development (NPD), engineering, and product development (PD) (Baines et al., 2006). Since over 70% of production costs are determined at the product design stage (Boothroyd, Dewhurst, and Knight, 2001), lean strategies in the product development process will give manufacturers more opportunity to achieve further improvements and enhance performance.

Like other manufacturing industries, the role engineering plays is important within product development in the wood furniture industry as it realizes design concepts, facilitates mass production and mass customization (Lihra, Buehlmann, and Beauregard, 2008). However, many furniture manufacturers do not have an efficient engineering process (Huang and Mak, 1998). As a result, problems are manifested in longer processing times of drawings which lead to production delays, an increase in engineering errors that affect product quality, higher costs, and excessive changes of design and waste. These problems negatively impact the engineering efficiency and affect the overall manufacturing processes in the downstream.

Therefore, applying lean thinking to the engineering process would greatly benefit furniture manufacturers in today's competitive market place. This research incorporates two parts in introducing lean thinking to the furniture engineering process. The first part is the analytical research of a furniture engineering process in a case study company. The second part encompasses an in-depth analysis of the engineering value stream and utilizes the value stream mapping (VSM) method to implement a lean application within the engineering department for that company.

1.2 Motivation

Engineering is an important stage in the product life-cycle because it determines the manufacturability of products and their production costs. In **Figure 1.1**, as the product is designed, there is just 8% of the budget (incurred cost) spent, but 80% cost of the product (permitted cost) is determined (Anderson, 1990). Also, Boothroyd, Dewhurst, and Knight (2001) stated that over 70% production cost is determined in the product design stage. Further, Ehrlenspiel et al. (2007) indicated that the decision made within the product development stage has a great impact on cost through the product life-cycle. Thus a lean and effective engineering process is important to the furniture manufacturers to control the product costs in the product life-cycle.

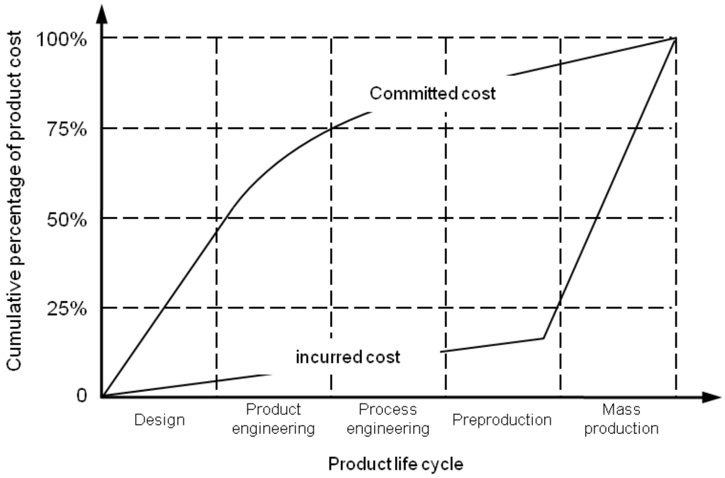


Figure 1.1 Product cost versus time

Product quality is another internal factor for conducting this research. Morgan and Liker (2006) described the engineering process as *"raw material consists of information – customer needs, past product characteristics, competitive product data, engineering principles, and other inputs that are transformed through the product development process into the complete engineering of a product that will be built by manufacturing."* Research on engineering process for optimizing product quality has been reported (Freire and Alarcón, 2002; Loch and Terwiesch, 1999; Thomas Culbreth, Miller, and O'Grady, 1996). Thus, the lean engineering process is essential to ensure the quality of products.

Researchers have expressed the necessity to conduct research on furniture engineering. Schuler and Buehlmann (2003) indicated that future successful furniture manufacturers have to figure out how to provide special services to their customers in the fields of designing and engineering of their products. Lihra, Buehlmann, and Beauregard (2008) also described engineering as an important process in the value stream to help furniture manufacturers realize mass customization. Quesada-Pineda and Gazo (2007) indicated that product design and engineering is a key performance measure for the wood furniture industry.

However, there is no systematic approach in the furniture industry to measure the internal engineering processes like designing, reviewing, checking, and releasing to accommodate the production deadlines.

1.3 Justification

The primary focus of this research is to identify the function of engineering to determine product lead time, quality, and cost in the wood furniture industry. The secondary focus of this research is to use the value stream mapping method to analyze the current state of a furniture engineering process and to use lean principles to design future state value stream mapping based on proposed improvements.

The furniture industry is dependent on raw materials and labor which are the major elements comprising production costs. However, design and engineering process are critical steps in determining the production cost because inappropriate design will lead to unnecessary waste and effort in the late manufacturing process. Furthermore, product quality is also specified at the design stage (Thomas Culbreth, Miller, and O'Grady, 1996). Thus, furniture manufacturers are obligated to build and explore more radical changes to the process of product design and engineering.

Currently, the furniture industry is transitioning from mass production to mass customization (Lihra, Buehlmann, and Beauregard, 2008). The product complexity and frequency of new introductions makes it difficult for product engineering to catch up with the production pace, which tends to cause shipment delays, inferior quality, and excessive costs. An efficient engineering process will allow the furniture manufacturers to have more flexibility and control in delivering desired products and services to the customer. As Karlsson and Ahlstrom (1996) indicated, lean product development provides the potential to “faster product development with fewer engineering hours, improve manufacturability of products, higher quality products, fewer production start-up problems, and faster to market”. Lean engineering is one of the important functions within lean product development; it exhibits great potential to facilitate and extend the advantages achieved in the manufacturing context.

Although engineering research has been conducted in the furniture industry (Min, Cheng, and Qiao-yun, 2010; Thomas Culbreth, Miller, and O'Grady, 1996), it is still lacking a systematic method to streamline the engineering process. There is no study showing the impact of engineering in the product life-cycle for furniture manufacturers. The relevant research on analyzing two important elements in the furniture engineering system – people and process, has received less attention.

1.4 Problem statement

As 70% of production costs are determined at product design stage (Boothroyd, Dewhurst, and Knight, 2001), lean implementation applied to design and engineering processes should receive more attention than that applied to the production area. It is easy to see that many furniture manufacturers do not have an efficient engineering process. Similar to the situation of most design companies in the other manufacturing businesses, drawing or production documents are controlled merely by the released date without having a quantified method to measure each internal design process such as designing, reviewing, checking, and releasing (Freire and Alarcón, 2002).

Engineering coordinates and interconnects with other administrative functions within a company. As Rother and Harris (2001) described, ramp-to-ramp value stream mapping is supposed to depict this situation where engineering communicates with its internal suppliers and customers. To streamline this value stream, many obstacles need to be overcome first within the process. **Table 2.1** shows nine types of obstacles and its corresponding example in the furniture engineering process:

Table 1.1 Different types of waste in an engineering process

Categories	**Problem (obstacles)**
Overproduction	Excessive orders (drawings) not in need for the downstream process
Correction	• Engineering changes • Engineering design errors • Reprinted drawings
Material movement	• Unnecessary steps to move drawings • Multiple approval steps
Processing	• Constant interruptions while creating drawings • Various copies/formats of drawings
Inventory	• Work-in-progress (WIP) drawings or orders
Waiting	• Waiting of design confirmation from customers • Waiting information from other departments • Downtime of office automation system
Motion	• Walking to copy machine
Underutilized people	• Unevenly distributed workload • Limited authority to engineers
Information flow	• Inefficient office automation system for engineering request • Inefficient communication within departments

Consequently, the above problems lead to longer drawing processing times which result in production delays, high rates of engineering errors affecting product quality, higher production costs and excessive waste caused by the engineering changes.

Therefore, it is important to use visualization tools to identify waste and non-value-added steps in the product development process. Former research of lean implementation in furniture industry was just focused on improving production efficiency and productivity (Espinoza, 2009; Hunter, 2008; Czabke, 2007; Motsenbocker et al., 2005; Hunter, Bullard, and Steele, 2004). Research on lean application of engineering area in the furniture industry has not been studied.

1.5 Goal and objectives

The goal of this research is to apply lean engineering principles to the wood furniture industry in order to increase productivity, eliminate waste, and increase internal customer satisfaction. Specifically, the objectives of this study are:

- Analyze the current engineering performance and key performance indicators through survey questionnaires in the engineering group of the case study company.
- Evaluate current state VSM of furniture engineering processes to identify both value-added and non-value-added engineering activities towards fulfilling customer requirements.
- Future state will be analyzed and evaluated according to process efficiency and Key Performance Indicators (KPIs) found through survey questionnaire and on-site study analysis to provide solutions for how valid and useful the future state would be to the industry.

1.6 Expected output

- Lean engineering model for wood furniture product development and propose best lean engineering process solutions for potential industrial participants.
- Lean engineering tool kits for furniture manufacturers. Identify causes of engineering waste from current state VSM and explore methods (kaizen events) to eliminate waste based on questionnaires and process data analysis to depict future state VSM.
- Implementation plan for improving the engineering process of the case study company.

CHAPTER 2 LITERATURE REVIEW

2.1 Furniture industry

In the 1800s, the US furniture industry enjoyed a boom on the East Coast. After that, the furniture industry experienced three major transitions. The first transition happened in the late 1800s, when Cincinnati replaced the East Coast area as the leading center for furniture production (Oliver, 1966). The second transition happened between 1880 and 1910, when Grand Rapids, Michigan, became the leading production center. However, as resources in Grand Rapids were depleted at the same time as the Great Depression in 1930s, Michigan manufacturers lost their primary advantage and left mass marketing to manufacturers in the southern states such as North Carolina and Virginia, which formed the third transition. Since then, High Point, North Carolina, has developed into the furniture industry center.

The structure of the US wood household furniture industry is highly fragmented (Grushecky et al., 2006; West and Sinclar, 1992). Furniture manufacturers resist consolidation. Upholstery manufacturers do not want work in the case goods business. Mass producers have little association with small cabinet makers. Southern producers rely on southeastern wood species while the northern manufacturers prefer resources close to their locations. The product construction methods are different between the North and the South. The National Association of Furniture Manufacturers (NAFM) represents the small and family-owned businesses, while the Southern Furniture Manufacturers Association (SFMA) represents large family-owned companies in the South (Dugan, 2009).

In the advent of globalization, the US furniture industry is experiencing tumultuous change as major manufacturers are losing ground because of global competition (Drayse, 2008). Southern manufacturers have been facing competitiveness from exporters outside of the US. The imports of non-upholstered wood household furniture increased from 19% in 1992 to 64% market share in 2008 (**Figure 2.1**). The output of US furniture manufacturing increased slowly and employment has fallen sharply in the midst of global competition and economic recession in recent years.

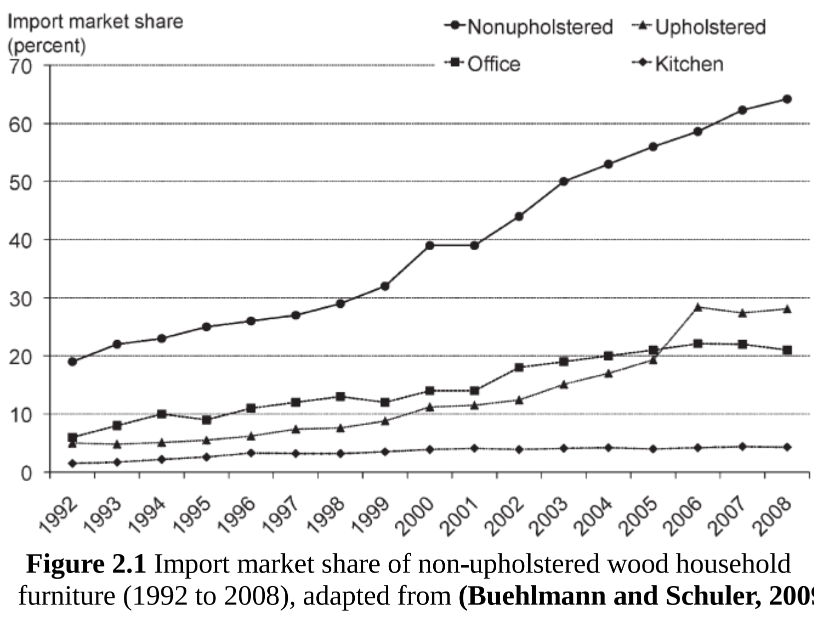


Figure 2.1 Import market share of non-upholstered wood household furniture (1992 to 2008), adapted from **(Buehlmann and Schuler, 2009)**

Furniture manufacturing exhibits complexity in terms of *characteristics of the industry* and *furniture manufacturing process* (Thomas Culbreth, Miller, and O'Grady, 1996):

In regard to complexity of the industry, the following aspects are noted:

- Manufacturers provides large product offerings which results in diverse parts population
- Pressure to frequently introduce new products and redesigns
- Competitive pressure to shorten lead time for quick delivery of products

- Due to the frequent new product introduction, a typical facility has to design large amount of new parts every year

In regard to the perspective of complexity in the manufacturing process, the following characteristics can be identified:

- Many furniture parts present complex geometry instead of rotational or prismatic shapes.
- The variety of wood properties contributes to the difficulties of machining characteristics and processes
- The presence of surface imperfections will affect the value of the final products
- Wood machining process has to take consideration of dimensional variation of wood
- Scrap tends to be generated from the machining processes

The above complexities in the nature of the business, manufacturing process and customization lead to intense competition, high labor cost, and a fragmented market that is creating vulnerability in the industry owing to global competition (Drayse, 2008). Due to the large product offerings and frequent new product introductions, manufacturers have to carry large inventories and frequently introduce new product designs which inevitably increase the production cost and lead time. Also, many manufacturers are reluctant to adopt new technologies which can help upgrade fabrication efficiency and improve product quality (Scott, 2006). The complex manufacturing processes increase the labor cost and generate scraps which impact the manufacturing competitiveness in terms of quality and cost (Vickery, Dröge, and Markland, 1997). These underlying disadvantages in the furniture industry drives the downstream customers such as retailers and distributors look for alternative places to make their products.

Consolidation is considered a solution for the US furniture industry (Drayse, 2008; Quesada and Gazo, 2006). However, the furniture industry is much more fragmented than other manufacturing industries. It is hard to acquire the knowledge of how much market share of each major player has. The competition is fierce within the industry and no one holds a sustainable competitive advantage (Dugan, 2009).

Furthermore, by researching the literature, Vickery, Dröge, and Markland (1997) identified ten manufacturing competitive priorities for the furniture industry which include flexibility in three areas: product (customization), process (mix), and volume. Also included are low production costs, new product introductions, delivery speed and dependability, quality (conformance to specification), product reliability, and design quality (design innovation). The research reveals that manufacturing has primary responsibility for the new product process – design quality and new product introduction. These two items are highly associated with efficient engineering methodologies such as Design for Manufacturability (DFM) (Anderson, 1990) and innovation (Gupta and Wilemon, 1988).

2.2 Engineering design

2.2.1 The role of engineering in a product life-cycle

The importance of design and engineering process toward determining product cost can be found in some of the literature. Anderson (1990) in his book “Design for Manufacturability” mentions that *“By the time a product has been designed, only about 8% of the total product budget has been spent. But by that point, the design has determined 80% of the cost of the product!”* Boothroyd, Dewhurst, and Knight (2001) states that over 70% production costs are determined in the product design stage. Ehrlenspiel et al. (2007) also discusses how significant the decisions made in product development stage may have effects through the product lifecycle.

However, in traditional sequential product development processes, production engineers lack an effective communication conduit with the product engineers. This misses the best opportunity to implement engineering rules and principles, such as Design for Manufacturability (DFM), at an early design stage to optimize design for ease of production and assembly process (Eppinger et al., 1994). Actually, engineering plays an important role to facilitate DFM methodology. Not much research has been conducted on the effectiveness of DFM for addressing manufacturing process and system issues (Boothroyd, Dewhurst, and Knight, 2001; Helander and Nagamachi, 1992; Anderson, 1990). Although few engineering principles show the effectiveness in other industries, the furniture industry has seldom utilized the same methodologies to facilitate design and engineering process (Huang and Mak, 1998).

2.2.2 Process engineering

Furniture product engineering essentially involves the coordination of different departments within the company as well as different partners outside of the company. The information flows are quite important for effective engineering communication within and outside of the company (Allen and Cohen, 1969). An efficient engineering process could facilitate such an effective flow of communication (Freire and Alarcón, 2002). Indeed, furniture engineering is a complex process and potentially hides lots of process improvement opportunities (SÜTÇÜ et al., 2005). Process efficiency is an important metric to reflect process improvement and performance (B. Prasad, 1996). It measures how well a process uses available resources to achieve anticipated results. Prasad (1996) also indicated there is an inverse relationship between process efficiency and a product life cycle lead time. In Prasad's model, he depicted (the Original State of Process Configuration) that as the process efficiency improved the lead time was reduced. The improvement results were impacted by different process configurations such as the lead time results from process renovation configuration was better than lead time results from the process restructuring.

2.2.3 Engineering performance indicators

A significant driver of product development costs and lead time is engineering changes (Loch and Terwiesch, 1999). Engineering changes (ECs) refers to making design changes to an existing product (Barzizza, Caridi, and Cigolini, 2001). It has a significant impact on new product development (NPD) process in terms of NPD success rates, and occurrence of bottleneck activity, since engineering changes management always competes for the same resources as new product development (Li and Moon, 2009).

Engineering changes occur after the engineering drawings are issued and before the product progresses into the production process. However, in **Figure 2.2,** when late stages exist in product life cycle, the more costs occur in production. Diprima identified and categorized three types of engineering changes: immediate, mandatory, and convenience (Diprima, 1982). This classification was based on the degree of urgency. "Immediate" means the EC needs to be implemented now. "Mandatory" means to implement an EC as soon as possible, while "convenient" means to implement EC as conveniently as possible (Diprima, 1982). Furthermore, a new taxonomy of EC was incorporated (Barzizza, Caridi, and Cigolini, 2001). In these classifications, ECs were categorized as "scrap", "rework", and "use-as-is". "Scrap" means serious technical faults and user safety problems exist and need to be solved immediately. "Scrap" will directly affect the work in progress (WIP) inventory since this inventory cannot be applied to other products. "Rework" means EC is required for improvements of pre-change WIP without affecting finished products and components. "Use-as-is" means a product has neither technical faults nor user-safety problems but a product is needed to improve the design. "Scrap" and "rework" are inconsistent to "immediate" in Diprima's classification, while "use-as-is" could be coordinated with either "mandatory" or "convenience" in Diprima's categories.

Loch and Terwiesch (1999) outlined strategies to reduce Engineering Change Orders lead time (in **Table 2.1**):

Table 2.1 Simulation methods and outcomes of reducing ECO lead time

Methods	**Description**	**Outcomes**
Flexible capacity	Optimize utilization (the relationship between capacity available and capacity required)	Effective utilization factor goes down to 88% and helps to decrease the throughput time from 25 hours to 14 hours, a 44% reduction.
Merging tasks	Combine works that were done by separate organizational entities before	Total average throughput time reduces from 28 to 10 hours, a 64% reduction.
Balancing the workload	Identify and bottleneck activity (high utilization) and shift partial jobs to other activity for improvement of overall performance	Total average throughput time for both testing activities reduces from 28 to 12 hours, a 57% reduction.
Pooling	Sharing workloads among engineers	Examples of pooling are not included in the article
Managing batching problems	Reduce the set-up time between activities	Holding the same batch size, utilization reduces to 82%, the throughput time of one activity reduces 60%

ECs include changes for improving production efficiency by optimizing product architecture and fabrication process, as well as the changes for correcting engineering errors and mistakes (Balakrishnan and Chakravarty, 1996). Freire and Alarcón (2002) proposed two performance indicators for tracking both improvement change and the error correcting change in the design process. The indicators are used to diagnose and evaluate the design process in the construction industry (in **Table 2.2**):

Table 2.2 Engineering performance indicators

Indicators	Calculation	Description
Changes in design	Number of changes divided by total number of drawings (or documents)	The indicator helps to deliver the magnitude of changes in projects
Errors/omissions	Number of errors/total number of drawings (documents)	This indicator helps to measure the quality of drawings (or documents) in the design process

From the literature, it can be concluded that engineering changes have significant impacts on product development cost, lead time, and quality. Certain indicators can be used to evaluate the engineering performance relevant to engineering changes.

2.2.4 Lean engineering

Karlsson and Ahlstrom (1996) classified engineering as one of the interrelated techniques in Lean product development. Morgan and Liker (2006) described the engineering process as *"raw material consists of information – customer needs, past product characteristics, competitive product data, engineering principles, and other inputs that are transformed through the product development process into the complete engineering of a product that will be built by manufacturing."*

As people paid more attention to implementing lean manufacturing and mapping manufacturing processes, they overlooked the importance of design and engineering on costs in product life-cycle (Baines et al., 2006).

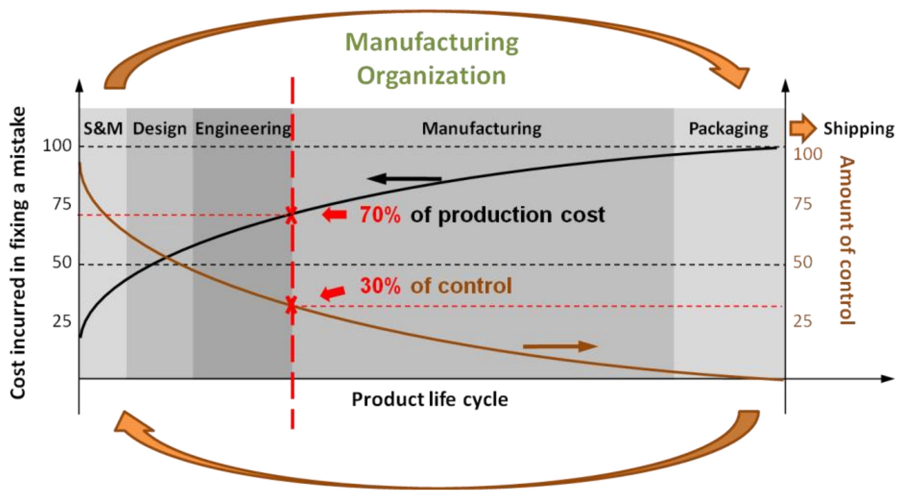


Figure 2.2 Cost incurred to fix mistakes in product life cycle and the corresponding level of control (adapted from Prasad 1996)

Prasad (1996) depicts the trend of the cost to fix a mistake in the product life-cycle (**Figure 2.2**). A problem fixed at the early stages of product life-cycle costs less than detecting and fixing it in the late stages. Also detecting and fixing problems at early stages of the product life-cycle creates more opportunities for improvements. In **Figure 2.2**, engineering is positioned at an early stage of product life cycle which indicates its important role in determining production cost.

Furthermore, lean thinking principles are applied in production area which leads to the concept of "lean manufacturing". However, Womack and Jones (1996a) indicated that lean principles are also suitable for areas outside manufacturing operations. Baines et al. (2006) saw that lean principles have more potential benefits when applied to knowledge-based activities such as design, new product development (NPI), engineering and product development (PD) (**Table 2.4**). Lean engineering research has been conducted in aerospace, automotive, software and construction industry (Middleton, Flaxel, and Cookson, 2005; Liker, 2004; Haque, 2003; Freire and Alarcón, 2002).

Freire and Alarcón (2002) developed a lean design process for a construction project based on lean manufacturing concepts and methods. They proposed four stages to carry out design process improvements:

- Diagnosis and evaluation
- Changes implementation
- Control
- Standardization

The research utilized seven lean tools on five potential improvement areas, which resulted in increased value-added activities, reduced product unit errors, largely decreased waiting time, and enhanced cycle time utilization. Finally, the overall performance of engineering products improved.

Haque (2003) conducted research of lean engineering in aerospace industry. He restated five-step lean principles applied to a manufacturing process (Womack and Jones, 1996; Rother and Shook, 1998) and further redefined each principle in a lean engineering manner. Then he applied three different lean applications (*Kaizen on a design process, Single piece flow in New Product Introduction (NPI), off-line development to speed time to market*) at three different levels – process hierarchy, detailed design, and project management, on three case study companies. He also mentioned the importance of modular design as a lean tool to facilitate product engineering on easing future modification or evolution of products and the reuse of design elements. In a case of illustrating "off-line development of products", modular design showed its effectiveness on reducing lead time by 25 to 50 percent.

Middleton, Flaxel, and Cookson (2005) presented an application of how the lean manufacturing concepts could be transferred to lean implementation of software development. The techniques and principles utilized to streamline the software engineering process include:

- Continuous-flow processing
- Customer defined value
- Design structure matrix (DSM) and flow
- Takt time
- Linked processes
- Standardized procedures
- Eliminate rework
- Balancing loads
- Posting results
- Data driven decisions
- Minimize inventory

By implementing the above techniques, the benefits are identified into the following six aspects (in **Table 2.3**):

Table 2.3 Results of lean software development process

ID	Results
1.	Lean techniques take effect in helping diagram and refine processes to reduce process steps and travel distance, while increasing the value added ratio in the process. For instance, one process which includes 498 steps has been substantially improved.
2.	Informal estimate by senior staff shows that there has been about a 25% productivity gain by implementing lean in the last two years.
3.	By applying a survey to QA engineers, technical writers and business system analysts inside the company, 55% respondents agreed that lean is suitable to software development.
4.	Quality is improved by knowing customer needs through interviews and surveys. The rework time on fixing defects has a 65%-80% decrease.
5.	Visual indicator in the process helps people know how much progress the current output goes towards fulfilling time-related goals. It allows viewer to see whether the number of work units completed over time is reaching a target.
6.	The products developed through lean approach got positive responses from customers at a trade show.

Reinertsen (2005) incorporated how to utilize lean manufacturing methods to deal with the inherent variability in product development process. Five key methods were applied to streamline the product development process; they are queue management, batch size reduction, cadence, rapid local adjustments and waste elimination.

From the literature (**Table 2.4**), it shows that lean principles applied in production environment are applicable to administrative area. Also different industries demonstrated the effectiveness of implementing lean in the administrative processes. Most industries using lean to facilitate the product development and engineering processes are concentrated in aerospace, construction, and software. From the literature, it also shows that the methodologies of lean engineering still are not sufficient, coherent, and sustainable. Proper tools and applications are still missing.

Table 2.4 Literature on lean product development and engineering

Author	Title	Outcomes
Freire and Alarcón 2002	Achieving Lean Design Process: Improvement Methodology	Propose a methodology to achieve a lean design process for the construction industry by applying seven tools for improvement based on five areas – client, administration, project, resources, and information.
Haque 2003	Lean Engineering in the Aerospace Industry	Propose lean principles to three different levels of engineering processes: • Detailed design level • Project management level • Design strategy level
Browning 2003	On Customer Value and Improvement in Product Development Processes	Demonstrate the effectiveness of "maximizing value" as a preferred way to incorporate "lean" in the product development process rather than "minimizing cost and time" as a preferred way to create customer value
Reinertsen 2005	Let It Flow	Propose to apply five key methods of lean manufacturing to address the high inherent variability of product development. The methods encompasses queue management, batch size reduction, cadence, rapid local adjustments, and waste elimination
Middleston et al. 2005	Lean Software Management Case Study: Timberline Inc.	Demonstrate the effective application of lean principles in software engineering.

2.2.5 Concurrent engineering

Concurrent engineering (CE) is an effective methodology used for improving engineering quality and reducing lead time. Sprague, Singh, and Wood (2002) define concurrent engineering as “a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support.” One of the biggest applications of the concurrent engineering approach is the aerospace industry where different functional teams worked in parallel and development process results could be rapidly verified from multiple options (Rush and Roy, 2000). The most phenomenal result of concurrent engineering, compared to the traditional sequential engineering, is the reduction of product development lead time, appreciation of total quality (quality of process, quality of organization, and product quality), increased productivity and decreased costs (costs of rework, scrap, and delays) (Ghodous, Vandorpe, and Biren Prasad, 2000).

The degree of implementing concurrent engineering could be divided into four categories (**Table 2.5**):

Table 2.5 Degree of CE implementation **(O'Grady and Young, 1991)**

Categories	**Description**
One-way (“over the wall”)	• Designs are isolated from other functions then designs send to manufacturing. • No consideration of different product life cycle factors
Stunted two-way	• if necessary, minor changes will be made after designs are complete
Two-way	• Designs are evaluated discretely
Integrated	• Design are evaluated constantly

In the furniture industry, key factors of determining the benefits of CE are product complexity and product life-cycle (Thomas Culbreth, Miller, and O'Grady, 1996). Complexity could be reflected on various style differentiations, part geometries, and materials. Because of complexity, furniture manufacturing tends to have excessive machining operations and relatively long lead times.

Thomas Culbreth, Miller, and O'Grady (1996) illustrated an application of concurrent engineering systems in furniture automation process. The authors utilized constraint networks to represent the constraining impacts of an automation process to realize the flexible automation. Min, Cheng, and Qiao-yun (2010) discussed the use of CE to modeling based on feature modeling and modular design for board-type furniture. The CE system approach allows the company to effectively reduce lead times by improving design for manufacturability. Designers are accessible to global information provided by the CE system which helps determine proper fixture and cutting tool for production, so the potential manufacturing problems and costs are reduced.

2.3 Lean thinking

The Lean Thinking initially received attention in 1990 (Womack, Jones, and Roos, 1990) in the study of manufacturing performance in automobile industry between Western countries and Japanese car makers. They found that the average time for a Japanese manufacturer to produce a car was 20 to 30 percent lower than its Western counterparts. After an investigation of “Toyota Production System (TPS)”, they introduced the concept of “Lean Production”.

Lean Thinking gives us a solution to eliminate *muda*, a Japanese word meaning “waste”. *Muda* incorporates all kinds of human activities that absorb resources without creating value (Womack and Jones, 1996). Ohno (1988) identifies seven types of wastes through the observation of Toyota Production System:

- Overproduction
- Correction
- Material movement
- Processing
- Inventory
- Waiting

- Motion

Prasad (1996) expanded the definition of waste and tapped into engineering area by adding one more candidate to the waste pool – waste of information flow. Waste of information flow refers to "Unnecessary transfer of information between two or more dissimilar systems (computer systems or otherwise)". Some examples of this type of waste described by Prasad include: "conversion from one format to the other", "upload and download of information", "files retrieval and storage", "unnecessary notification or notes", "one-to-many communications instead of posting publicly (many-to-many)", "data security", etc.

By adapting seven types of waste in Ohno's model in production area, Beau Keyte and Locher (2004) developed the model to redefine the waste in administrative area. They also included "Underutilized people" as the eighth waste (**Table 2.6**):

Table 2.6 Waste model in administrative area

Waste Category	Office Examples
1. Overproduction	• Printing paperwork out before it is really needed • Purchasing items before they are needed • Processing paperwork before the next person is ready for it
2. Correction	• Order entry errors • Design errors and engineering change orders • Invoice errors • Employee turnover
3. Material movement	• Excessive email attachments • Multiple hand-offs • Multiple approvals
4. Extra processing	• Re-entering data • Extra copies • Unnecessary or excessive reports • Transactions • Cost accounting • Expediting • Labor reporting • Budget processes • Travel expense reporting • Month-end closing activities
5. Inventory	• Filled in-boxes (electronic and paper) • Office supplies • Sales literature • Batch processing transactions and reports
6. Waiting	• System downtime • System response time • Approvals from others • Information from customers
7. Excess motion	• Walking to/from copier • Central filing • Fax machine • Other offices
8. Underutilized people	• Limited employee authority and responsibility for basic tasks • Management command and control • Inadequate business tools available

Womack and Jones (1996a) incorporate five lean principles to eliminate waste for a process:

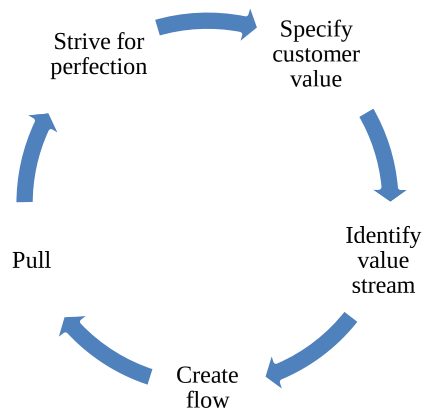


Figure 2.3 The five lean principles

In **Figure 2.3**, "Specify value" means to specify the value that is defined by the customer, but not by the engineers or any other people within an organization. "Identify the value stream" means figuring out all the processes to deliver a product or service to customers. "Flow" means to create continuous value-creating steps flow and reduce batch sizes for a single-task process. "Pull" means pull the value from customer. Every process along the value stream should be aligned with customer needs and adjusted accordingly to satisfy customer needs when it is needed. "Pursue Perfection" means lean principles endlessly strive for perfection, avoiding unnecessary waste and errors in the processes and implementing continuous improvements.

The goal of Lean Thinking is to use least resources and time to deliver desired customer value through a continuous flowing value stream (Hoppmann, 2009). A value stream is the flow of information and materials to produce customer value (Tapping and Shuker, 2003). "Value" means to create something for which customer are willing to pay. "Stream" is a sequential flow of processes creating information and materials and delivering them to customers. Within value stream are value-added and non-value-added activities which are used to transform information and materials to customer needs. It also includes communication between the supplier chain, the network of processes and operations, as well as channels of channels of information and materials flow.

Since value stream incorporates the main flows required to bring a product to a customer, it helps to visualize both production flows – Lean Manufacturing (Rother and Shook, 1998), and design flows – Lean Engineering (Haque, 2003; Freire and Alarcón, 2002). In manufacturing, Value Stream Mapping (VSM) could exhibit the common processing sequence of a production flow from raw material to finished product (Rother and Shook, 1998). In designing or engineering, VSM could also exhibit the common engineering sequence of a product family from concept to launch (Beau Keyte and Locher, 2004). Within each product family, there are three areas of value stream that are tied together to influence the product cycle: concept-to-launch, order to cash and raw material-to-finished product (Tapping and Shuker, 2003). The first two areas incorporated lean management processes, while the last one dealt with the manufacturing processes.

2.4 Lean tools and applications

A number of lean tools and methods are well-defined and applied (Womack and Jones, 1996). Some of the tools and methods to support lean manufacturing include: pull system, cellular manufacturing, one-piece-flow, standard work, visual control, Kaizen, quick changeover, 5S and kanban event (Van Goubergen and Van Landeghem, 2002; Rahn and Consulting, 2001; Feld, 2000; Henderson, Larco, and Martin, 2000; Rother and Shook, 1998). However, compared to the rich set of lean tools, implementation methods of lean are relatively few (Lian and Van Landeghem, 2002). Applying tools without understanding the overall value-added process cannot yield sustainable results. Therefore, a value stream analysis from an overall viewpoint is a good place to begin.

In recent years, VSM appears to be the preferred way to implement lean transformation (Beau Keyte and Locher, 2004; B. Keyte and Branson, 2004; Irani, 1999; Rother and Shook, 1998). It helps map the current state, future state, and ideal state of a certain production or management process in the value stream. VSM maps the material and information flow and helps to identify value-added activities in the current state mapping. In the future or ideal state, it helps depict the efforts toward eliminating non-value-added activities in the values stream (Rother and Shook, 1998). VSM methodology was derived from the needs of facilitating manufacturing activities; therefore, few companies had experience of implementing lean principles in the nonproduction areas (Beau Keyte and Locher, 2004). However, since nonproduction costs took a large amount of the total cost in the product life-cycle (Tapping and Shuker, 2003), manufacturers tried to apply lean principles in the knowledge-based areas such as design, new product introduction (NPI), engineering, and product development (PD) (Baines et al., 2006).

To implement a VSM lean transformation in nonproduction area, Tapping and Shuker (2003) incorporated three phases of lean application to frame a lean office system. These three phases include the customer level, the process level, and the people's level. In customer level, manufacturers need to identify customer demand and allocate corresponding work accordingly. Some tools which can help define the customer demand include: takt time calculation, pitch calculation, buffer and safety resources. In process level, manufacturers need to create a continuous flow that can ensure both internal and external customers receive the right work units at the right time, in the right quantity. Some methods that can apply to create a continuous flow include: in-process supermarkets, kanban system, first-in-first-out (FIFO), line balancing, standardized work, and work area design. In people's level, manufacturers have to perform leveling process to evenly and effectively distribute workloads over the available time that can make the best use of people. Some methods that were used at this level include: visible pitch board, load leveling (heijunka) box, and runner system. As an indispensable component comprised of value stream of non-production area, engineering performs an important role toward maximizing customer's value (Baines et al., 2006).

In wood products industry, some research utilized Value Stream Mapping methodology. Czabke (2007) conducted a survey in the secondary wood products industry and list value stream mapping as an important just-in-time production practice in the lean manufacturing process. Espinoza (2009) utilized value stream mapping to portray the flow of information and materials and to identify specific quality control activities in the wood products supply chain. Also, based on the case study of three companies located in Honduras, Costa Rica and Guatemala, the researchers Quesada-Pineda, Haviarova, and Slaven (2009) utilized value stream mapping to conduct a quantified research analyzing the value-added times for wood products manufacturing companies in Central America. Key findings in the research include:

- Raw material inventory accounts for most of the waste in the three case study companies
- Value-added time range from 8.8 to 12.3 percent of total process time, with kiln drying process, contributed the most to the value-added time while other processes contributed little to the whole value-added time of manufacturing process.

Furthermore, Norman (2008) proposed a pull-based manufacturing system for the secondary wood product manufacturers to achieve product lead time reduction and on-time delivery to the final customer. Value stream mapping was used to evaluate a case study company's current state production performance. By implementing pull production and supermarket methodology, the results showed that the proposed future state can achieve the reduction of lead time from 15.1 hours to 7.5 hours.

Also, Leonard III (2005) utilized value stream mapping to evaluate the current state and design future state of a southern yellow pine lumber production system. By more closely synchronizing and planning operations with sawmill output, the lead time reduced from 35.3 days to a range of 10.8 to 14.9 days; future state capital inventory requirements were less than 50% of the current state inventory requirement.

Although value stream mapping can help manufacturers identify value-added steps and eliminate non-value added waste (muda) in a value stream (Rother and Shook, 1998), value stream mapping also has some drawbacks (Lian and Van Landeghem, 2002):

- Since VSM originally used "paper and pencil" to depict the current state of a process, it limits the level of detail and the number of different situations that people could depict. For instance, the difficulty of identifying inventory levels for various situations throughout the production process (McDonald, Van Aken, and Rentes, 2002).

- For companies undergoing a high product variety and low volume types, value stream mapping is hard to map all the product value streams.

- Not every person is capable of observing how the VSM could be transformed into the real world; it undervalues the actual performance of VSM.

Besides VSM, many lean tools and methods had been applied to various production or nonproduction areas (**Table 2.7**):

Table 2.7 Lean tools and methods

Tools and methods	Definition/description
Takt time	Determined by "time available" (e.g. daily work time) divided by "customer demand" (e.g. daily customer demand in terms of how many number of products).
Pull system	A system that controls the flow of production based on customer demand
Kanban	A scheduling approach that receives the "pull" from the demand and tells people what to produce, when to product it, and how much to produce.
Buffer resource	A level of stock maintained to prevent the risk of stock shortage resulting from volatile customer demand.
Safety stock	A level of stock maintained to prevent the risk of stock run-outs due to uncertainty of supply and demand.
FIFO	"First in first out", a way to manage inventory relative to time and prioritization
Standardization	The process of establishing the technical standard to have standard procedures or methods, avoid unnecessary mistakes, ease training and improve efficiency.
Heijunka	A method to balance workload to reduce waste and smooth the production processes for producing intermediate goods at a constant rate.

Furthermore, Tapping and Shuker (2003) proposed a set of administrative lean methods and techniques to analyze and transform management processes in three stages: demand, flow, and leveling. These tools, as shown in **Table 2.8**, include Pace the takt time, Create pitch, Buffer resource, Safety resource, 5S of working area, Problem solving project, Pull system, First In First Out (FIFO), Balance workload, Standard work, Work area design, Pitch Board, Heijunka Box, and Runner. Based on the study of Tapping and Shuker, Thummala (2004) applied value stream management principles to the software deployment process of a manufacturing company. In the case study, the value stream mapping method helped the company reduce the overall lead time of conducting the deployment request by 16% in the software development process. Tischler (2006) also utilized lean principles for the office area to streamline the inquiry processes of a university's admissions office.

Table 2.8 Administrative lean tools for different levels of use

	Customer Demand	Continuous Flow	Leveling
Administrative Lean Tools	• Pace takt time • Create pitch • Buffer resource • Safety resource	• Pull System • FIFO • Balance workload • Standard work • Work area design	• Heijunka Box • Runner • Pitch Board

In the furniture industry, lean strategies have been widely used in the production area (**Table 2.3**). Hunter, Bullard, and Steele (2004) proposed a new lean manufacturing system, the non-typical double D assembly cell, for furniture industry. Motsenbocker et al. (2005) conducted a case study on investigating the effectiveness of using flow-line technology to increase productivity in furniture industry. The benefits of using flow-line technology resulted in reduced lead time and inventory, more production space, labor savings, and increased productivity. Czabke (2007) conducted a case study to investigate the lean implementation in two US wood products companies and two German wood products companies. He found that:

- The implementation of Lean Thinking results in a more efficient and cost effective manufacturing performance.
- Lean thinking is suitable to apply to nonproduction area in secondary wood products industry.
- Other positives can be found by implementing lean practices and principles.
- Communication is a big challenge facing companies implementing Lean Thinking

By implementing lean principles, the result was an increased productivity of these four companies ranging from 10% to 275%.

Hunter (2008) incorporated Toyota Production System (TPS) for the furniture industry by proposing the cellular manufacturing subsystem in the upholstery furniture company. The benefits of the proposed TPS's double D cell included increased productivity, decreased labor cost, improved quality, relaxed line balancing problem, improved worker ergonomics and achieved continuous process improvement. Other research focused on analyzing the state of lean application in furniture industry (Quesada-Pineda, Haviarova, and Slaven, 2009; Espinoza, 2009; Quesada and Gazo, 2007; Cumbo, Kline, and Bumgardner, 2006; Schuler and Buehlmann, 2003). **Table 2.9** shows a summary of lean implementations in the furniture industry.

Table 2.9 Applications of lean in the furniture industry

Author	**Application of Lean research**	**Results and findings**
Schuler and Buehlmann (2003)	Benchmarking and paradigm shifts	Lean manufacturing is an essential element for strategic renewal of business model for U.S. furniture industry
Hunter et al. (2004)	Propose the implementation of a new lean manufacturing system for furniture industry	By the new manufacturing system, the company achieved an 11% increase of productivity and a direct labor reduction
Motsenbocker et al. (2005)	Case studies of the application of a new flow-line technology based on lean manufacturing concepts for the furniture and wood component supplying industries	The plant wide realized benefits of lean implementation presented as over 40,000 square feet of floor space cleared for new uses; lead time reduced by 80%; 83%, 78% reduction of finished goods and raw material goods inventory; $800,000 reduction of work-in-process inventory; $3 million savings in annual labor; and 42% increase in productivity
Cumbo, Kline, and Baumgardner (2006)	Benchmarking and case study	Over half of the 145 investigated wood products companies had implemented lean manufacturing.
Czabke (2007)	A case study of investigating lean implementation in the US and German secondary wood products industry	By applying lean manufacturing, the productivity of these four companies increased ranging from 10% to 275%
Quesada-Pineda and Gazo (2007)	Benchmarking	Lean manufacturing practices, like pull system scheduling, are positively related to the performance of furniture manufacturing companies
Hunter (2008)	Propose TPS's double D cellular manufacturing subsystem in furniture industry	The productivity increased by 20% and the reduction of labor by 36.4%.
Espinoza (2009)	Value Stream Mapping for visual control	Identified specific quality control activities in the product supply chain
Quesada-Pineda, Haviarova, and	Value Stream Mapping for quantified analytical research	Identified key wastes in three case study companies; identified value-added activities in the production processes

Slaven (2009)

2.5 Summary of literature review

Value stream mapping is an important tool for implementing lean transformation since it facilitates mapping the flows of information and materials, identifies various types of wastes, and finally it makes the value stream more efficient in improving future state process (Womack and Jones, 1996a). Value stream mapping demonstrated its effectiveness in streamlining the manufacturing processes toward maximizing customer value (Womack and Jones, 1996a; Rother and Shook, 1998). However, nonproduction activities appear to have a significant impact in determining production cost (Anderson, 1990; Prasad, 1996; Boothroyd, Dewhurst, and Knight, 2001; Ehrlenspiel et al., 2007; Tapping and Shuker, 2003), and manufacturers are trying to apply lean principles in the knowledge-based areas such as design, new product introduction (NPI), engineering, and product development (PD) (Baines et al., 2006). Applications of VSM in nonproduction area include the areas of sales process (Barber and Tietje, 2008), health care (Kim et al., 2006), university's admission inquiry process (Tischler, 2006) and information management (B. Keyte and Branson, 2004).

Lean principles and techniques were used in previous research to streamline the manufacturing process in secondary wood products industry, especially to enhance the productivity of furniture manufacturing process (Hunter, Bullard, and Steele, 2004; Motsenbocker et al., 2005; Hunter, 2008). In wood products industry, VSM as an implementation tool, showed its effectiveness in streamlining the manufacturing process (Czabke, 2007; Espinoza, 2009; Quesada-Pineda, Haviarova, and Slaven, 2009). However, other than manufacturing, lean principles could create benefits to nonproduction processes in the secondary wood products industry (Czabke, 2007). As engineering is an important process in determining the production cost of wood products, research on combining engineering with lean principles has not been found in secondary wood products industry.

The literature review incorporates the fields of engineering and value stream mapping. The following (**Table 2.10**) is a summary of the literature:

Table 2.10 Summary of literature reviewed

1.	Value stream mapping is an effective lean implementation tool to identify and eliminate waste as well as observe and improve information and material flow.
2.	Engineering plays an important role in determining production cost. It is an important process in implementing design for manufacturability.
3.	Engineering change directly affects the product development cost and lead time. Engineering changes for improvements and engineering changes for errors are two types of engineering change order.
4.	The lean implementations applied to non-production area have a similar structure to production area such as encompassing steps of pacing customer demand, achieving continuous flow, and leveling individual workload.
5.	Lean principles have potential to be applied in knowledge-based activities. Lean engineering was developed in aerospace, construction, and software industries.
6.	Process efficiency is an important indicator to the efficiency of information flow in the current value stream. Improved Process efficiency optimizes the engineering efficiency and can effectively reduce the engineering lead time.
7.	The Lean tools applied to administrative value stream are developed based on adopting and extending the lean tools applied to the production area.
8.	By applying lean principles to optimize the internal business processes, it showed evident improvement in productivity in the wood products industry.
9.	Value stream mapping has been applied to secondary wood products industry mostly in analyzing supply chain and manufacturing process. Research on applying VSM in product engineering area was almost non-existent in the furniture industry.

CHAPTER 3 METHODOLOGY

3.1 Introduction

The research will be conducted based on a case study company. The purpose of the case study is to investigate the current engineering processes addressed in the study objectives of Chapter 1. This investigation is projected to encompass three phases (**Figure 3.1**). The first phase, the literature review (pre-study), includes two aspects – a questionnaire design and an on-site study plan. In the questionnaire section, the appropriate case study company will be identified. For the selected company, a questionnaire will be designed based on the summary study of literature reviewed and prepared to investigate the potential company's engineering process. Concurrently, a phone interview will be conducted to verify whether the designed questions are applicable to the case study company to guarantee the best reliability and quality of results.

The second phase, data collection (on-site study), includes two categories – a questionnaire and data for VSM. Through issuing the questionnaire, multiple forms of information concerning engineering process and engineer performance will be acquired. Personal interviews will also be conducted to collect corresponding information on the current engineering process. Besides issuing the questionnaire, data for value stream mapping, such as customer demand, process lead time, and completion of work unit will be collected. The methods for collecting the data include issuing data collection sheet and analysis of plant documents content. Additionally, through direct observation, the information concerning process boundary, process components and types of waste will be identified.

The last phase, data analysis (post-study), includes two categories – data analysis and results/conclusion. The data analysis section will analyze the data collected from the on-site case study using both quantitative and qualitative methods. The data will be used to generate questionnaire analysis, current state value stream mapping, and future state value streaming mapping. The last part will present the results and conclusions from the research, state the limitation of the research and look ahead at possible future research.

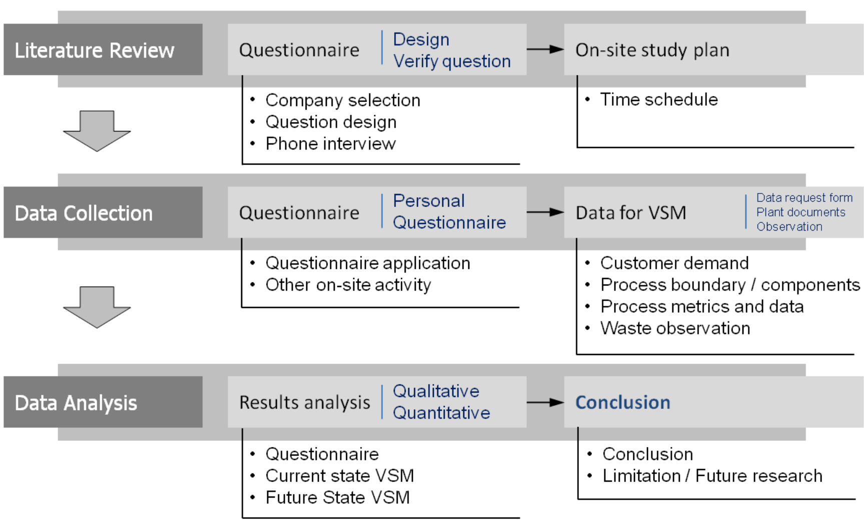


Figure 3.1 Methodology used to develop survey, collect, and analyze data

3.2 Questionnaire design

3.2.1 Company selection

Due to a limited budget and time frame for an overseas case study, this investigation will focus on only one potential company. The selection of the case study company will be based on several aspects such as company size, product type, customer, location and turnover (Robb and Xie, 2003; McNamara, 1972). Some measurements used to determine the company size include the number of manufacturing plants, number of employees and turnover. The ideal company for the case study is one that produces diversified product types, which will help generate sound and practical results for this research.

Concerning the size of the company, it currently has 10 manufacturing plants employing over 10,000 workers. The annual sales turnover was around $90 million in 2009. The product types of the company which include both solid wood and upholstery products for different American and European customers. It has been making furniture products for 20 years and is located in the northeast part of China. The company is very close to the port. Therefore it shows a transportation advance in producing furniture products to a great deal of overseas furniture brands. The company has been making case goods and upholstery products for many established US customers. Most of these customers have been involved in the furniture business for two decades and their businesses account for a large amount of the household furniture market share in the US. The product lines of this company are concentrated in American style furniture but diversified on product architecture (the way to construct the furniture). Because of the wide customer base, the company carries a wide range of product types and a large engineering group. The company runs four business units. Three of the business units produce solid wood products and one produces upholstery products. The engineering group consists of four individual engineering departments associated with different business units. The whole engineering group has over forty product engineers and over twenty industrial engineers.

3.2.2 Design questionnaire sections and relevant questions

The questionnaire's design will focus on investigating engineer's responsibility, process metrics, engineering efficiency and related impact factors. The questionnaire was organized into four sections – Lean metrics, Engineering lead time, Job completion and accuracy, and Engineering change.

Lean metrics

Lean metrics could help people understand the impact of their efforts toward continuous improvement and waste elimination (Tapping and Shuker, 2003), therefore, the questionnaire includes 11 metrics to measure the quality of the current engineering performance and each metric will be evaluated by each respondent (product engineer). These 11 metrics include process time, value-added time, queue time, engineering error rate, lead time, number of people in the group, overtime, changeover time, percent of completion, inventory, hardware and software reliability (Keyte and Locher, 2004; Barzizza, Caridi, and Cigolini, 2001).

Engineering lead time

Many industries focused on development lead time as a measure of competitive performance in the product development process (Keyte and Locher, 2004; Clark and Fujimoto, 1989). This section will focus on analyzing different factors affecting engineering lead time. These influential factors include engineering process time, development tool, and engineer competency (Keyte and Locher, 2004; Clark and Fujimoto, 1989).

Job completion and accuracy

Beau Keyte and Locher (2004) indicated that job completion and accuracy is an important indicator used to measure the quality of engineering design. The question designed for analyzing this metric includes the average number of production documents and production document completion rate.

Engineering Change (EC)

Engineering change is a significant driver of product development costs and lead time (Loch and Terwiesch, 1999). Engineering changes (ECs) refer to making design changes to an existing product (Barzizza, Caridi, and Cigolini, 2001). It includes changes for improving production efficiency as well as the changes for assuring product quality and performance (Balakrishnan and Chakravarty, 1996). The questions designed for this section include engineering error rate, and the percentage of time on issuing Engineering Change Orders (ECOs).

3.2.3 Phone Interview

To ensure a comprehensive and appropriate questionnaire, phone interviews were conducted after completing the design of the questionnaire's first draft. One purpose of the phone interview was to verify the questions in the questionnaire. The questionnaire was sent in advance through email to the engineering supervisor who helped review each section of the questionnaire during the phone interview and gave feedback. Thus the viability of each section of the questionnaire was assessed through the phone interview (Coon, Pena, and Illich, 1998) and the engineering supervisor was interviewed in this process. The supervisor answered all the inquiries and provided additional information to help design questions that fit the actual conditions of the engineering group.

The second purpose for the phone interview was to collect pre-study information from the engineering group such as the experience of the engineers, knowledge of lean concepts and problem-solving methods. Thus additional questions were developed that complement the four major sections in the questionnaire (Burke and Miller, 2001). Also from the phone interview, the questionnaire incorporated specific engineering terms used by this company, such as engineering documents referring to a file that includes all the engineering drawings, bill of materials, specifications, instructions and other essential materials to facilitate the production process. Furniture engineering signifies the product design concepts transformed into the final engineering files that could be used to fabricate specific products. Primary furniture engineering process refers to major value-added engineering activities toward product structure design. Secondary furniture engineering process refers to subordinate value-added activities used to assist and realize the product engineering for production.

3.3 On-site study plan

To ensure the quality of the study, the on-site study plan was important due to the limited time frame and budget. The on-site study plan included key details such as documenting daily activities and information to ensure the needed results were obtained. The on-site case study was scheduled for 17 days. Each day aimed to finish certain tasks. **Table 3.1** shows the Project Agenda during the case study.

Table 3.1 Project Agenda during Case Study

ID	Task Name	Method	Duration	Start	Finish
1	Lean Engineering project start		25 days	7/25	8/13
2	**BEFORE CASE STUDY**		**5 days**	7/25	7/29
3	Prepare the Excel Investigation Forms		1 days	7/26	7/27
4	Verify survey		1 days	7/27	7/28
5	**DURING CASE STUDY**		**17 days**	8/2	8/18
6	Lean Manufacturing Presentation			8/2 p.m.	
7	Send out the survey questionnaire				
8	Current State Analysis		15 days	8/3	8/17
9	Identify the value stream		3 days	8/3	8/5
10	Determine the process boundary (customer/supplier)	Context diagram	1 days	8/3	
11	Determine customer requirements and supplier responsibilities	Interview(Interface analysis)			
12	Determine product family	Work unit routing analysis Pareto diagram	1 days	8/4	
13	Determine each main engineering processes	Observation	1 days	8/5	
14	Determine unit and metrics	Interview/survey			
15	Create Process Flow Chart	Functional flowchart			
16	Data collection				
17	Measuring process lead time	Data collection form	1 day	8/6	
18	Measuring single process (Cycle Time/Queue Time)	Data collection form	1 day	8/9	
19	Identify VA/NVA activities	Observation	1 day	8/10	
20	Analyze customer demand	Observation	1 day	8/11	
21	Measure WIP within processes				
22	Collect data for EC orders				
23	Engineering error rate for a certain month of the period	Observation	2 day	8/12	8/13
24	Engineering improvements for a certain month of the period	Observation			
25	Time spent on issuing ECO to the overall lead time	Observation			
26	ECOs for specific job shops	Observation			
27	ECOs data analysis (Process Capacity)		2 days	8/14	8/15
28	Current State Mapping				
29	Create Process Attribute Sheet	Interview	2 days	8/16	8/17
30	Draw current state mapping	eVSM/AutoCAD			
31	Initial ECO brainstorming based on current state data analysis			8/18	
32	Project Presentation (optional)		1 day	8/18	
	AFTER CASE STUDY				
	Verify Results				
	Analyze data				
	Proposal for Future State				
	Project Report and Survey Analysis				

3.4 Questionnaire application

Concerning the limited time frame and on-site cost during the case study, the questionnaire was considered the primary method to collect information and address the research objective. The questionnaire was given to the supervisors of each engineering group and then the supervisors would forward the survey to the engineers of their respective group (Robb and Xie, 2003; Frey and Oishi, 1995). The sample size was limited to the number of engineers in each engineering group at the time of study. Therefore, the sample size of the solid wood group was 32 respondents, and the sample size of the upholstery group was 15 respondents. Before each respondent worked on the survey, questions were carefully explained as concerns arose from respondents. Then the supervisor in each engineering group helped collect the completed questionnaire.

During the case study, a number of KPIs, such as engineering lead time, document error rate, and engineering throughput were identified to understand the current engineering performance. In the meantime, certain key information collected from on-site study (parallel to the application of questionnaire) included customer demand, process boundary/components, process metrics, and different types of waste in the current engineering process. The methods used for collecting the information included data collection sheet, direct observation, and looking over plant documents (Bonoma, 1985).

3.4.1 Questionnaire application

The survey questionnaire was sent out to the supervisors in each engineering groups. Interviews with these supervisors were also conducted to assist in assessing validity and methods variance (Robb and Xie, 2003). Before each respondent completed the questionnaire, questions were carefully explained as concerns arose. These concerns were among the following: requested illustration of certain questions or definitions, needed permission to answer certain questions, or whether the answers they gave were in the correct form. Then the supervisor in each engineering group collected and gave the completed questionnaires to the researcher.

3.5 VSM data collection and interview

The research followed the structure of defining process boundaries, identifying main processes, analyzing customer needs, selecting and measuring process metric, calculating system metrics as well as and generating current and future state Value Stream Mapping (VSM) (Keyte and Locher, 2004). A data request form was used to collect data of processing time and inventory for the VSM (Tapping and Shuker, 2003).

During the case study, interviews were also conducted with multiple supervisors and product engineers. The primary focus of the interviews was to obtain personal information concerning process sequence and performance. Different Key Performance Indicators (KPIs) were measured and data was collected using a standard data collection form. For instance, the expected KPIs results to be collected included lead time, work-in-progress inventory, cycle time and queue time. The results of these KPIs were gathered from each engineer's individual answer on the data collection form. The secondary focus of the interview was to collect process information in order to analyze process boundary, product family elements, customer demand, and engineering change orders (ECOs).

3.5.1 Determine customer demand

The customer can be either external or internal. An external customer indicates the real customer who buys products or services, while an internal customer refers to the functions or departments inside the company (Tapping and Shuker, 2003). In this study, the customer was an internal customer and defined by engineers through interviews and discussions. By accessing the customer's requirements, the specific needs of the engineering process could be better understood so a more demand driven or "pull system" could be designed to level and better allocate the engineering resources. The following **Table 3.2** is a summary of information collected by analyzing the customer demand profile:

Table 3.2 Accessing the Customer Demand

Data samples	**Data Collection Method**
(1) Average number of orders per month (in the last six months)	Content analysis of plant document
(2) Number of orders for the current month	Content analysis of plant document
(3) Available days of work time (during a month)	Personal interview
(4) Average products per Day	= (1) / (3)
(5) Daily available work time	Content analysis of plant document
(6) Takt time	= (5) / (4)
(7) Total process cycle time	Current state VSM
(8) Engineers needed	= (7) / (6)

* TBD: To be determined

The fundamental data for customer demand analysis, which is an electronic version of engineering archives for the previous six months, was requested before the case study started. Then through personal interviews, the data of monthly and daily engineering work time was collected. Also the number of orders in the current month was obtained from the existing engineering documents.

Before collecting data, a unit for collecting data was determined. This unit gave a basis to further calculate the work-in-progress inventory (number of units/customer daily demand). An appropriate unit provided much more convenient future lean implementation, such as pacing takt time. Based on a previous study, "drawing" or "order" were the ideal units for analyzing an engineering process (Keyte and Locher, 2004).

After having a suitable unit defined, the customer demand was analyzed. The following table (**Table 3.3**) is a summary of data collection method for two different kinds of units.

Table 3.3 Data Collection for Certain Type of Units

Measurements for drawing unit	**Measurements for order unit**	**Data collection method**
Orders for a certain period	Orders for a certain period	Departmental documents
Drawings per order		Calculation of existing data
Total Drawings per month		Calculation of existing data
Available workdays within a measuring period	Available workdays within a measuring period	Personal interview
Drawings per day	Orders per day	Calculation on existing data
Available engineering hours per day	Available engineering hours per day	Personal interview
Takt time	Takt time	Calculation on existing data

After accessing the customer demand and identifying the takt time, a Worker Balance Chart helped compare the current processing time of each engineering step in relation to takt time. WBC aided in determining whether the current engineering staffing level is in pace with customer demand or not. In order to calculate customer demand and to conveniently apply lean tools for streamlining the future state value stream mapping, the average number of monthly customer demand was calculated based on the most recent three month data (Keyte and Locher, 2004).

3.5.2 Identify supplier and customer boundary requirements

During the case study, the supplier and customer of the engineering process were identified. The supplier was the last upstream internal process. The engineers were interviewed to collect their requirement demands for the upstream supplier. Different customers of the engineering process were interviewed as well and information was collected about what their specific requirements for the engineering process were. A context diagram was utilized for this analysis.

Context Diagram (supplier/customer) was used for system engineering which reflected the interaction between a system and its outside interfaces (Kossiakoff and Sweet, 2003).

3.5.3 Process Metrics

Each main engineering process and its sequence were defined through personal interviews with the supervisors and manager, and then consistent metrics were used as the basis to identify both value-added and non-value-added time for each engineering process. The metrics helped identify and quantify both value-added and non-value-added functions and then determined the suitable lean tools for improvements. During the case study, the actual data of essential process KPIs, such as cycle time, demand rate, queue time, percentage of job completion and accuracy, engineering error rate, were collected through the data request form and survey questionnaire.

In order to obtain accurate original data of processing time for each essential engineering phase, the data request form was used to collect processing results from different product engineers, then the average value was obtained to determine the processing time for each engineering process in the value stream. From direct observation, the information on the number of engineers was also obtained.

The inventory data in terms of unfinished design tasks was obtained from the case study company's Engineering Completion Report. This report was posted on the notification board inside the engineering department for the convenience of each team member to keep track of the current month's projects.

3.5.4 Waste and error Investigation

After the process value analysis, the waste was explicitly identified and categorized it into the classification of nine types of waste as stated in the literature review (Keyte and Locher, 2004; Prasad, 1996). Also, a waste analysis chart helped summarize the waste activities in the process (**Table 3.4**). Waste type lists all nine types of waste in the non-production area. Process refers to all the essential single processes that comprise an engineering environment. "Waste element" is all the waste activities identified in the value stream.

Table 3.4 Waste Analysis and Data Collection method

Waste Type	Process	Waste Element
Overproduction	Direct observation	Direct observation
Correction	Direct observation	Direct observation
Material movement	Direct observation	Direct observation
Extra processing	Direct observation	Direct observation
Inventory	Direct observation	Direct observation
Waiting	Direct observation	Direct observation
Excessive motion	Direct observation	Direct observation
Underutilized people	Direct observation	Direct observation
Unnecessary transfer of information flow	Direct observation	Direct observation

The data of engineering errors was obtained from the Engineering Change Summary Report. This report included information on the statistics of engineering errors from the previous months.

3.6 Data analysis

Data analysis falls into two parts. The first part uses different quantitative and qualitative methods to analyze the data in the questionnaire. The second part uses VSM method to analyze the current engineering efficiency.

3.6.1 Questionnaire analysis

Descriptive statistics were used to analyze and explain the data in the study (Sprinthall, 2003). Bar and pie charts were used to show the response rate, distribution, and variance of data. In addition, the radar chart helped show the response frequency and the box plot chart was used to indicate the survey data's average, median, and quartiles distribution (Ott and Longnecker, 2008). Inferential analysis – the Unequal Variance Two-sample t-Test (Ruxton, 2006), was used to compare the actual customer demand (in terms of orders) of solid wood and upholstery engineering groups.

3.6.2 Current State Value Stream Mapping

Process boundary analysis: after acquiring the information on process boundaries (customer and supplier), the context diagram was used to analyze the requirements from the customer end and also the engineering requirements for the supplier end.

Main process analysis: in order to analyze the overall engineering process first, the functional flowchart was used to depict the whole process flow (including non-upholstery engineering and upholstery engineering).

Then, VSM was utilized as a visualization tool to describe the current state of an engineering process and to help incorporate potential process improvement for the future state implementations. The VSM focussed on one product family instead of tracking the whole product collection. Focusing on a single product family by analyzing a set of similar product architecture provided an easy way to track down the general engineering procedures.

For creating the current state VSM, data collected from on-site visit was converted, calculated, adjusted, and summarized. The data of monthly customer demand was converted into the basis of daily demand. The daily demand was used for calculating the inventory (in form of days) within the processes. To analyze the metrics of each essential individual process, a process categorization was conducted first in order to combine similar or unnecessary small processes into more generalized main processes. This was necessary to extract and present only important process information to the current state VSM. Then metrics such as process time, number of operators, error rate and tool reliability were calculated for each process.

Next, the data collected was utilized to generate the current state value stream mapping (VSM). The current state VSM focused on identifying the waste within the engineering process and then potential improvement methods will be proposed for the future state VSM. **Figure 3.2** shows an implementation diagram that illustrates the processes for generating the overall project.

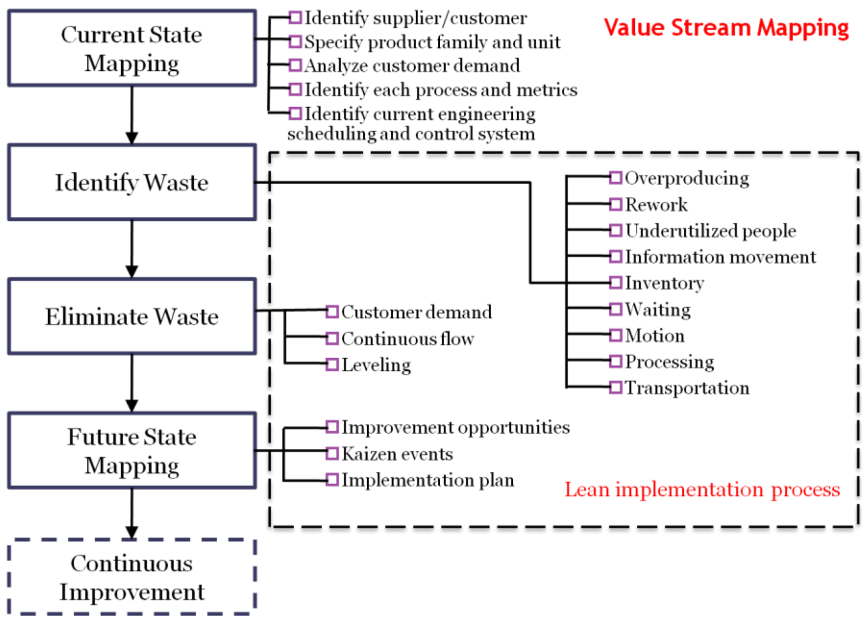


Figure 3.2 Value stream mapping method

3.6.3 Future State Value Stream Mapping

Based on current state value stream mapping, different types of waste were identified in the engineering process. The identified waste items were categorized into several types of waste defined in section 3.5.4. Furthermore, by analyzing and comparing processing time and inventory of each process, the bottleneck processes were identified. Root causes analysis of these types of waste was further conducted by using Ishikawa Diagram (Fishbone Diagram) methodology. Then countermeasures were proposed and incorporated into the future state value stream mapping. The future state value stream mapping followed the direction of five lean principles (Womack and Jones 1996a) and processes in different stages such as defining customer demand, creating continuous flow, and leveling workload (Tapping and Shuker 2003). Many lean tools and methods were used to streamline and transform the engineering process. According to the literature review, a set of lean tools had been used to transform the administration area which included: pace the Takt Time, create pitch, buffer resource, safety resource, 5S of work area, problem-solving project, pull system, FIFO, balance workload, standard work, work area design, visible pitch board, Heijunka box and runner (Beau Keyte and Locher 2004; Tapping and Shuker 2003).

3.7 Summary of Methodology

The overall methodology falls into three stages. The first stage was mainly to design the survey questionnaire and verify the usability of each question. The second stage was to conduct the on-site case study. Research data was collected for two purposes. One purpose was to collect data from the survey questionnaire. The data was used to achieve the first objective of the research. The other purpose was to collect data for value stream mapping. The data of value stream mapping was collected by issuing standard data request form, conducting personal interviews and using direct observation. The data was used to realize the research's second and third objectives. The third stage was to analyze the existing data for research results and conclusions.

CHAPTER 4 MEASURING ENGINEERING PROCESS EFFICIENCY

4.1 Abstract

Efficient engineering processes are critically important for furniture manufacturers. However, most furniture manufacturers have been controlling their product drawings and engineering documents merely by the release date without a systematic method to measure internal processes and how it affects product cost, engineering quality and customer satisfaction. This research was conducted through a case study in a furniture plant located in China, producing American style furniture products. The objective was to investigate the company's current engineering process, identify non-value-added activities and analyze the engineering performance based on certain Key Performance Indicators (KPIs) such as lead time, document error rate, and engineering throughput. A survey questionnaire was sent out to the engineering group to determine the current engineering efficiency. Results show that "product complexity" and "engineer competency" are the two most influential factors that impact the engineering process lead time. Most engineers spend 10 to 20% of their daily work time issuing engineering change orders (ECOs). Upholstery and non-upholstery (solid wood) engineering groups showed a difference in engineering throughput, customer diversity, and production document error rate. From this research, it is concluded that ECOs are significant drivers of engineering lead time. Also, the current processes include a large amount of non-value adding activities, interfering with engineers' ability to prepare production documents for downstream jobs and affecting the overall manufacturing process.

4.2 Introduction

The goal of Lean Thinking is to use the least amount of resources and time to deliver desired customer value through a continuous flowing value stream (Womack and Jones, 1996). In the furniture industry, lean strategies have been widely used in the production area (Cumbo, Kline, and Bumgardner, 2006). Schuler and Buehlmann (2003) indicated that lean manufacturing is an essential element for strategic renewal of the business model in the U.S. furniture industry. Moreover, through a survey of 145 wood products companies in the US, Cumbo, Kline, and Bumgardner (2006) found that a majority (55%) of these companies had been implementing lean manufacturing at the time of the study. Within the subsectors, 56% of cabinet makers, 71% of upholstered and 53% non-upholstered furniture manufacturers indicated they were doing lean implementations. Quesada-Pineda and Gazo (2007) illustrated that lean manufacturing practices, like pull system scheduling, are positively related to the performance of furniture manufacturing companies. Motsenbocker et al. (2005) conducted a case study to investigate the effectiveness of using flow-line technology to increase productivity in the furniture industry. The benefits of this technology were reflected on reduced lead time and inventory, more production space, labor savings, and increased productivity. In another case study, Czabke (2007) investigated lean implementation in two US wood products companies and two German wood products companies. He found that:

- The implementation of Lean results in a more efficient and cost effective manufacturing performance.
- Lean is suitable for nonproduction areas in the secondary wood products industry.
- Communication is a big challenge to implement Lean

Hunter (2008) proposed to incorporate the Toyota Production System (TPS) in the furniture industry by the implementation of a cellular manufacturing subsystem in upholstery furniture production. According to the author, the benefits of the proposed TPS's double D-shaped manufacturing cell include increased productivity, decreased labor cost, improved quality, relaxed line balancing problem, improved worker ergonomics and continuous process improvement.

The application of lean thinking in nonproduction areas, especially the engineering process, has been given extra attention in other industries during the last decade (Donald Reinertsen, 2005; Middleton, Flaxel, and Cookson, 2005; Browning, 2003; Haque, 2003; Freire and Alarcón, 2002). However, research on lean thinking has not been conducted in the furniture industry. In the wood furniture industry, engineering also plays an important role in the product life cycle. Engineering not only helps materialize design concepts, but also facilitates mass production and mass customization (Da Silveira, Borenstein, and Fogliatto, 2001). Therefore, there is a need in the furniture industry for an efficient engineering process. This research aims to analyze the current engineering performance and key performance indicators through a survey questionnaire given to the case study company's engineering group.

4.3 Theoretical Background

The lean thinking concepts were introduced in 1990 by (Womack, Jones, and Roos, 1990) in their study that compared the manufacturing performance of the automobile industry between Western and Japanese car makers. The goal of lean thinking is to use the least amount of resources and time to deliver customer value through a continuously flowing value stream (Womack and Jones, 1996). It encompasses five basic principles to eliminate "waste" (waste in this context is understood as any activity that does not add value from the customer's point of view):

- Specify value
- Identify the value stream
- Implement flow
- Implement pull
- Pursue perfection

The first principle means to "specify the value" from the customer perspective, not from the engineers' point of view (or any other people within an organization). "Identify the value stream" signifies figuring out all the processes to deliver a product or service to customers. "Flow" indicates generating continuous value-creating steps, making them flow, and reducing batch sizes for a single-task process. "Pull" represents developing customer value from a pull system instead of push. Every process along the value stream should be aligned with the customer's needs and satisfy these needs in a timely manner. "Pursue Perfection" signifies to endlessly strive for perfection, avoiding waste and errors, and keep implementing continuous improvements (Womack and Jones, 1996). The same authors indicated that lean principles also fit in areas outside manufacturing operations. Baines et al. (2006) pointed out that lean principles have great potential benefits when applied to knowledge-based activities such as new product development (NPD) and engineering. Karlsson and Ahlstrom (1996) classified engineering as one of the interrelated techniques in lean product development. Morgan and Liker (2006) described the engineering process as that which "raw materials consist of information – customer needs, past product characteristics, competitive product data, engineering principles and other inputs that are transformed through the product development process into the complete engineering of a product that will be built by manufacturing."

Engineering plays an important role in determining the production costs. Prasad (1996) depicted the cost associated with fixing a mistake in the product life-cycle and indicated that fixing problem at the early stages in the product life-cycle costs less than detecting and fixing the problem during later stages. He also stated that this allows more opportunities for making improvements. Moreover, Anderson (1990) in his book "Design for Manufacturability" mentioned that "by the time a product has been designed, only about 8% of the total product budget has been spent. But by that point, the design has determined 80% of the cost of the product." Similarly, Boothroyd, Dewhurst, and Knight (2001) stated that over 70% of production costs are determined in the product design stage. Ehrlenspiel et al. (2007) also discussed how significant the decisions made in the product development stage are for the product lifecycle. However, in traditional sequential engineering processes, manufacturing engineers lack an effective communication channel with the product engineers, and thus the best opportunity to use engineering guidelines to control cost and achieve manufacturability is missed at an early stage of product life cycle (Eppinger et al., 1994).

Considering the previous findings, this research aims to conduct a current state analysis of the engineering process for a typical manufacturer of American-style furniture through a questionnaire study, and to try and find the influential factors controlling the engineering lead time, error rate, job completion and accuracy.

4.4 Methods

Case study methods were used to evaluate the current state of the engineering process, including questionnaires, personal interviews, analysis of plant documents, and direct observations all of which helped to increase the reliability of the data collection process (Bonoma, 1985). Considering the travel cost as well as the scattered locations of each interviewing group during the case study, a questionnaire was utilized as the major case study method (Moser and Kalton, 1972; Hochstim and Athanasopoulos, 1970). Another consideration for using the questionnaire method was the time availability the respondents in the engineering groups, thus by using a questionnaire, the respondents were free to allocate their time to complete the questions without interrupting their work (Hoyle, Harris, and Judd, 2002). The questionnaire was structured in five parts:

- Engineering experience and awareness of lean concepts and problem-solving methods
- Engineering process metrics
- Factors affecting engineering lead time
- Factors affecting job completion and accuracy
- Engineering changes

In order to obtain the most reliable results for the research, the quantitative data was combined from the questionnaire with the qualitative data from interviews and observations to generate results (Bourgeois III and Eisenhardt, 1988). For detailed methods on data collection and data analysis, refer to chapter 3 – Methodology.

4.5 Results and Discussion

The results section is organized in five major parts. The first part displays the results of engineer experience and knowledge of lean concepts and problem-solving methods. The second part is the process metric section that indicates the important metrics to reflect the engineering performance. The third part reveals the factors that could influence the engineering lead time. The fourth part illustrates the job completion and accuracy of the current engineering process. In the last part, the most frequently occurring errors in the engineering documents are presented, as well as the analysis of the impact of issuing Engineering Change Orders on engineering lead time.

4.5.1 Engineering experience and awareness of lean concepts and problem-solving methods

In this case study company, the non-upholstery (solid wood) and upholstery engineers exhibited different experiences of product engineering. **Figure 4.1** shows that 38% of the upholstery engineers had more than 6 years of experience while the majority of solid wood engineers, in **Figure 4.2**, had 3-5 years of work experience. However, the junior engineers (less than 2 years) in the upholstery engineering group account for 39% of the overall engineering crew, whereas in the solid wood group they account for 30% of the crew among the overall solid wood unit. Furthermore, there are 31% of entry-level engineers (less than 1 year) in the upholstery engineering group compared to just 6% of entry-level engineers in the solid wood engineering group. Thus, from the survey results, the overall number of engineers above the junior level in the solid wood engineering group is larger than the same level of engineers in the upholstery engineering group.

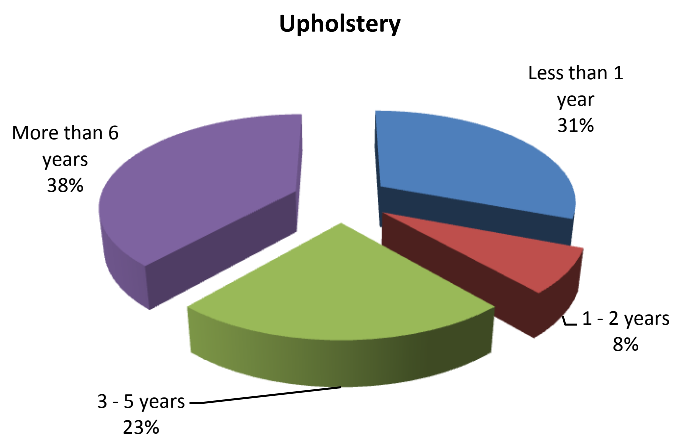


Figure 4.1 Engineering Experience of upholstery group

Figure 4.2 Engineering Experience of solid wood group

The reason that the upholstery engineering group lacked experienced engineers was because, at the time of the study, this group was preparing and training junior level engineers for a new upholstery plant. So the number of entry level engineers in this group looks relatively high. Another reason was that some experienced upholstery engineers left the company for various reasons. On the other hand, the engineers in the solid wood plant were relatively stable, and few entry-level engineers were recruited in recent years. The current engineering capacity can also be reflected on the lead time of production documents. The solid wood products group had a lead time 17% faster than that of upholstery products.

Also of interest in this study was learning how much experience each engineer has on lean concepts and problem-solving methods. So a question was asked, based on a 1 to 5 scale, of how familiar the engineer was with the lean concepts and problem-solving methods defined in the questionnaire.

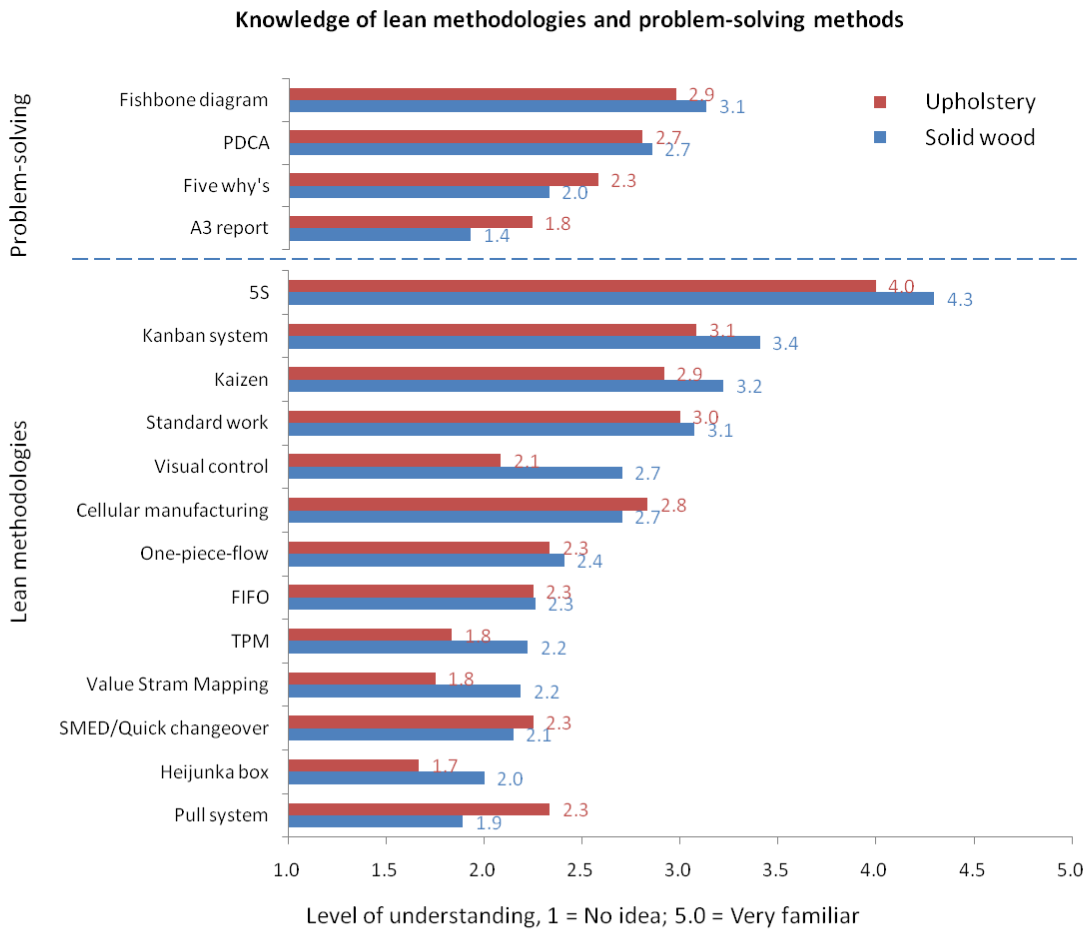


Figure 4.3 Knowledge of lean concepts and problem-solving methods

The company has been implementing lean principles in the production area since 2003, and like most other companies, they started with the "5S" initiative (Feld, 2000). This is the reason why 5S was the most acknowledged lean method known by all the engineering groups. On the other hand, some lean concepts like "kanban system," "kaizen," and "standard work" (Van Goubergen and Van Landeghem, 2002; Rahn and Consulting, 2001; Feld, 2000; Henderson, Larco, and Martin, 2000; Rother and Shook, 1998), had been implemented by the company but were not as effective as "5S." Thus the rating on some of these methods, in **Figure 4.3**, was not as high as 5S. The on-site lean manufacturing workshop not only let the associates have an in-depth understanding of the lean principles that they had implemented, but also familiarized them with other useful lean methods and problem-solving methods.

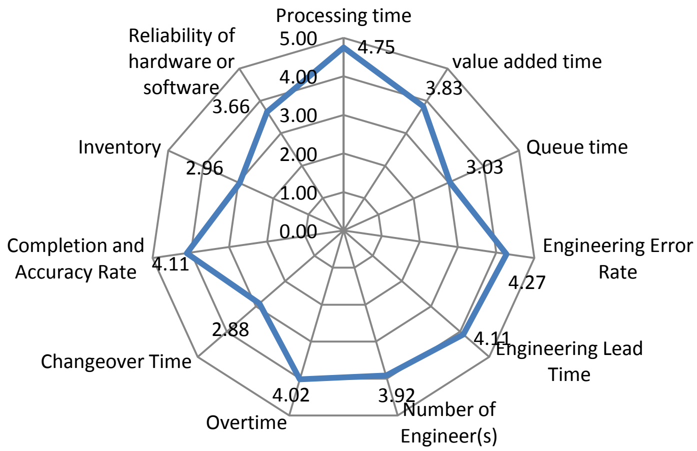
4.5.2 Engineering process metrics

From the personal interview, the engineering manager helped us to define that the furniture engineering process referred to all kinds of product engineering activities to generate engineering documents for the downstream manufacturing process. Lean metrics could help people understand the impact of their efforts toward continuous improvement and waste elimination in this process (Tapping and Shuker, 2003). Therefore, the questionnaire included 11 metrics that reflect the quality of the current engineering performance and each metric was evaluated by all engineers. These metrics are described and defined in **Table 4.1**:

Table 4.1 Metrics

Metrics	Description
Process time	The accurate time spent on making engineering documents
Value-added time	The total sum of each major process time
Non value-added time	The time not spent on making engineering documents
Engineering error rate	The total number of errors that has been made during a period of time divided by the total number of engineering documents made within the same period
Lead time	The sum of process time and non-value-added time
Number of people	The total number of engineers in the engineering group
Overtime	The extra time spent on doing work after the regular work time
Changeover time	The time required to prepare an engineering task to change from making good results of the last engineering task to making the first good result of the new engineering task
Percent of completion	The percentage of production documents that delivered on time
Inventory	Unfinished engineering orders from customers
System reliability	The percentage of time that a specific hardware or software does work

Figure 4.4 shows that "Processing Time," "Engineering Error Rate," "Engineering Lead Time," and "Completion and Accuracy Rate" were the top-rated metrics; this reflects the current engineering performance in both solid wood and upholstery engineering groups.



Response rate on a scale of 1 to 5, 1 is "unimportant", 5 is "very important"
Figure 4.4 Identified Engineering Performance Metrics

4.5.3 Factors affecting engineering lead time

The engineering lead time refers to the total amount of time each engineer spent on making preproduction documents and mass production documents. The production lead time means the total lead time of each product life cycle toward delivering customer desired products, which encompasses the processes of selling and marketing, design, engineering, manufacturing, packaging and all other necessary steps. Thus the engineering lead time is a portion of the production lead time. So the engineering lead time positively impacts the on-time delivery of products to the customer. In this context, it is necessary to know the percentage of time the engineering process takes toward the overall production lead time. Generally, the shorter the engineering lead time the more it will be reserved for the other necessary manufacturing processes. **Figure 4.5** shows that over half of the engineers perceive the current engineering lead time accounted for 21% to 40% of the overall production lead time. Some products may even take up to 61% to 80% of production lead time on engineering. These products are usually custom furniture with a high price, even in a small batch of orders.

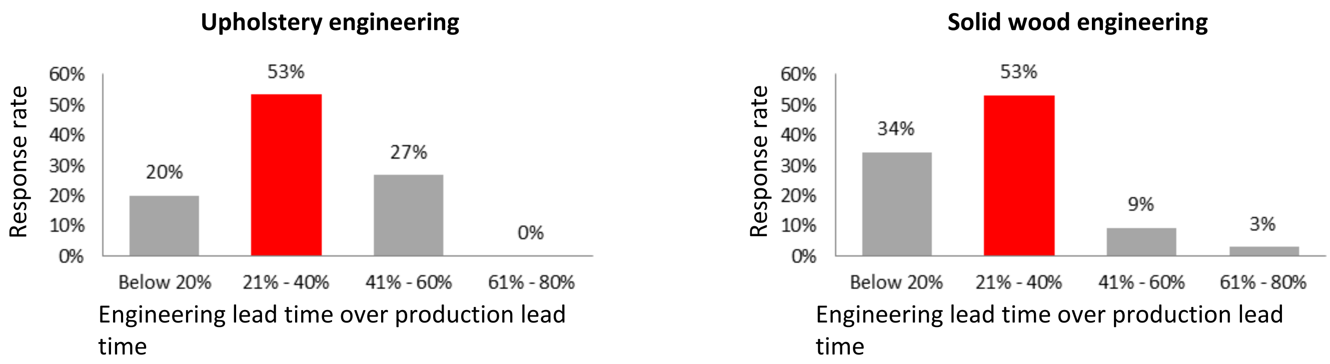
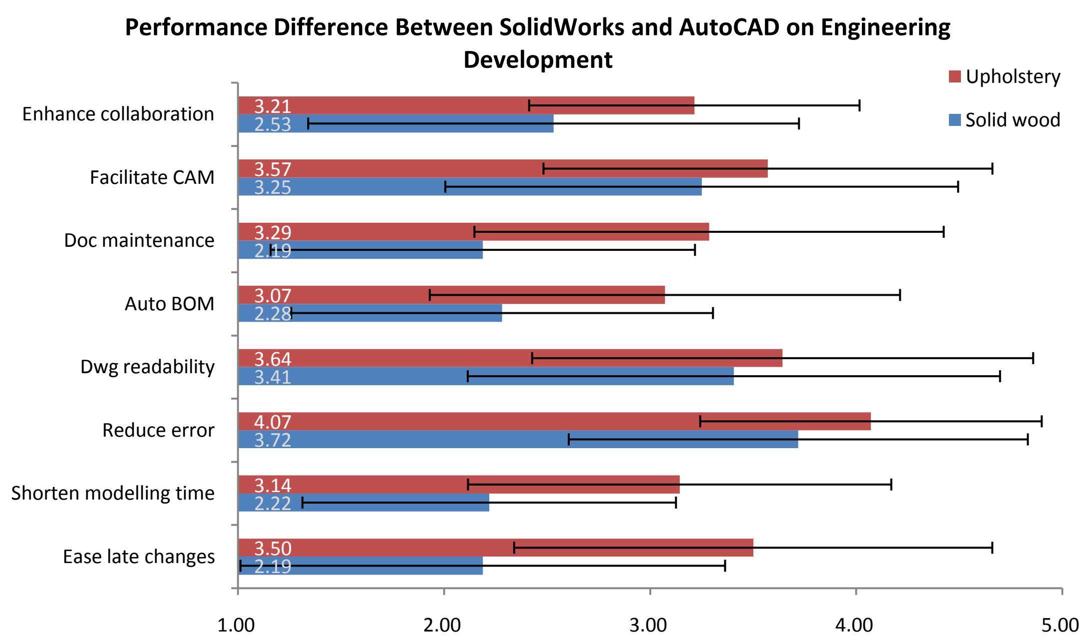


Figure 4.5 Engineering lead time versus production lead time in two engineering groups

To further explore which factors are the major contributors of longer lead times, ten factors were included in the questionnaire for evaluation purposes. The results showed, from both solid wood and upholstery engineers, that "Engineers experience/competency" and "Product architecture complexity" were the top two factors that could influence the engineering lead time. The results were concluded from the responses of thirty-three solid wood engineers and fifteen upholstery engineers. Also, "Tool" was considered the least influential factor that could impact the engineering lead time. However, the company had been using two engineering design tool kits at the same time – SolidWorks and AutoCAD. These tools exhibited different impacts on engineering jobs (other than lead time) in terms of the capability to enhance collaboration, facilitate computer-aided manufacturing, maintenance engineering documents, and automation generation of bills of material. **Figure 4.6** explains that these two engineering solutions are supposed to have different impacts on the engineering lead time. SolidWorks had been mainly applied in the upholstery engineering process in this company. The results, in **Figure 4.6**, imply that SolidWorks might provide more benefits for the upholstery engineering process. From direct observation it was seen that the upholstery products usually needed to create the 3D model for product frames, and SolidWorks explicitly presented its advantage on creating complex frame models, generating bill of materials, reducing design errors, and creating reader-friendly drawings.



Response rate on a scale of 1 to 5, 1 is "strongly disagree", 5 is "strongly agree"
Figure 4.6 Performance difference using SolidWorks as the primary engineering design tool

To help illustrate how product complexity has an impact on engineering lead time, a question was designed to select the corresponding lead time for developing each product within a standard product set. In this question, two standard sets of products for solid wood product lines and upholstery product lines were separately defined. Engineers indicated the time spent on completing each engineering task within a certain standard product set. The products within the standard solid wood products set included mirror, nightstand, drawer chest, armoire base, armoire hutch, dresser, and bed. The products within the standard upholstery product set included ottoman, chair, sofa chair, loveseat, tufted chair, sleeper sofa, and sofa.

Following the standard product sets in the non-upholstery group, **Figure 4.7** shows that the bed, armoire hutch, and dresser are the top three products that need longer engineering time, for which most engineers need "5 to 6 days" to finish these products. From the upholstery group results, it could be observed that more upholstery products require "5 to 6 days" of engineering lead time compared to solid wood products. These upholstery products include sofa chair, sleeper sofa, tufted chair, love seat, and sofa. In fact, the reason more upholstery products take a longer lead time is because the upholstery products usually include more engineering steps compared to the solid wood products. For example, upholstery products usually need a certain amount of time to wait for the fabric suppliers to deliver the samples for making the mock-ups; every piece of fabric needs to be measured on a special device to digitalize the contour and dimension of the fabric; and every product needs a fabric specification in addition to the manufacturing specification to facilitate the mass production process. All these tasks need extra engineering lead time of upholstery products.

Figure 4.8 presents a summary of the average lead time to complete each type of product within a standard set of product line. The variation of lead time to finish each type of product illustrates product architecture complexity has a positive relation to the engineering lead time. For example, in a solid wood product set, beds (which usually have the most difficult product structure) take the longest engineering lead time which is about 5.8 days, whereas the nightstand (which usually has the easiest product structure) takes about 1.9 days of engineering lead time.

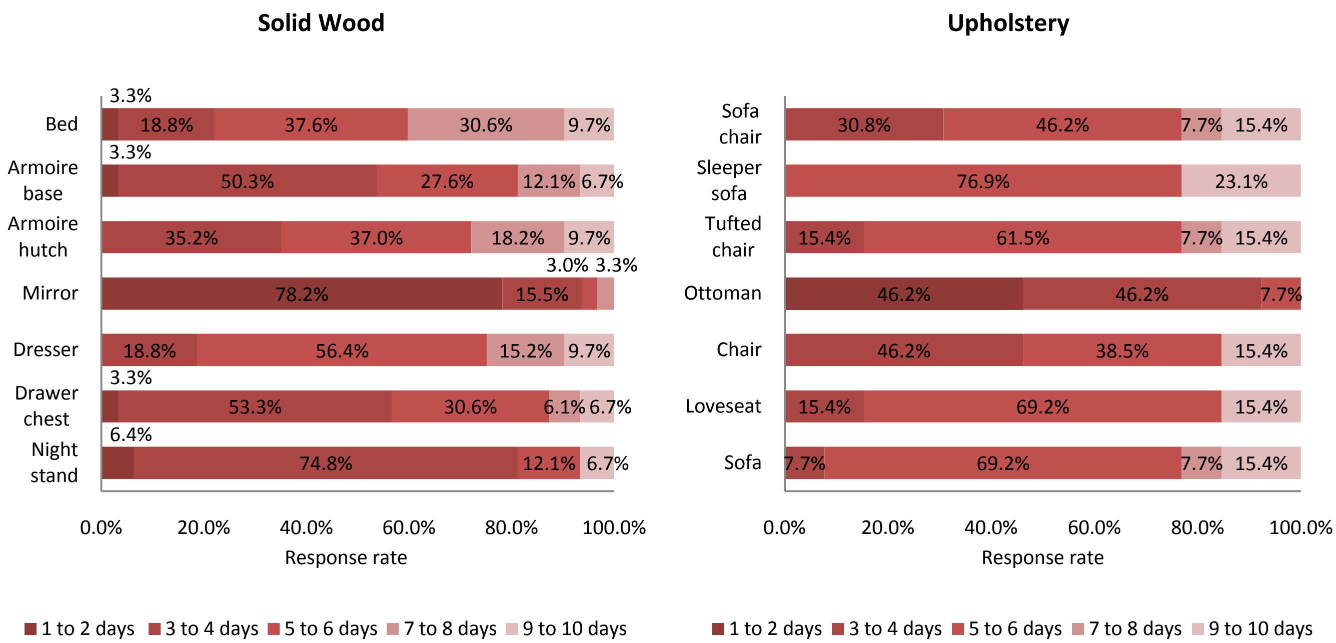


Figure 4.7 Average lead time distribution of each product

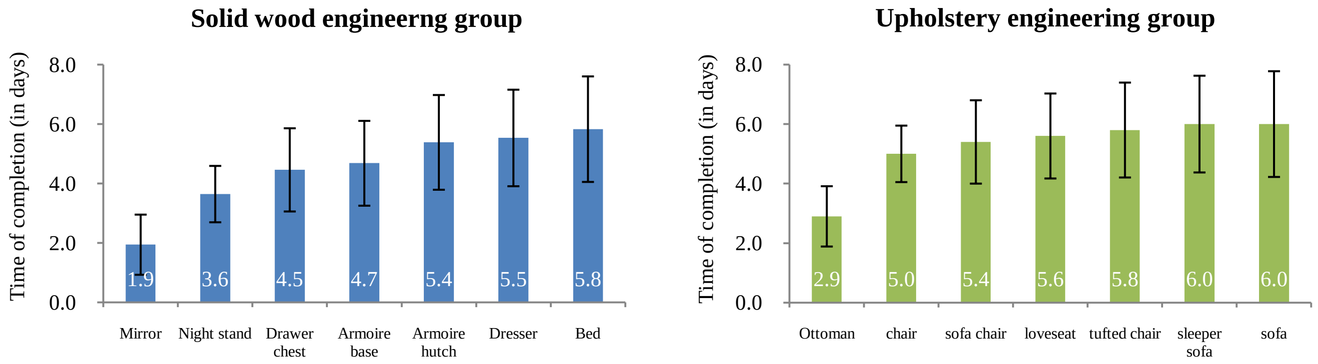


Figure 4.8 Average engineering lead time for each product

4.5.4 Factors affecting job completion and accuracy

4.5.4.1 Customer Demand

To find whether the fluctuation of customer demands impacts engineering performance, an investigation was conducted to find how many customers each engineer had served during the last six months. Although the overall T-test, in **Figure 4.9,** shows there are no significant differences between solid wood engineering and upholstery engineering in the average number of customers that were served, it is still easy to notice that upholstery engineers on average had dealt with "1 to 2" customers in the last six months, while most solid wood engineers had served "3 to 4" customers within the same time period.

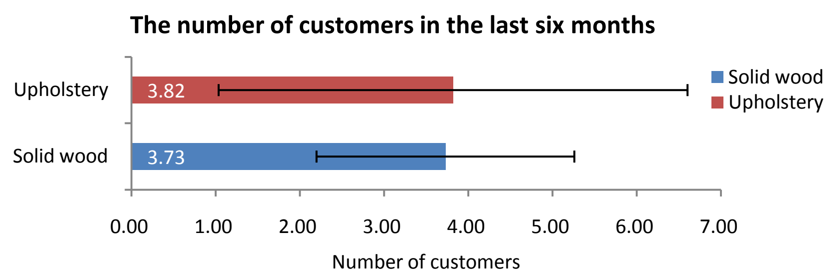
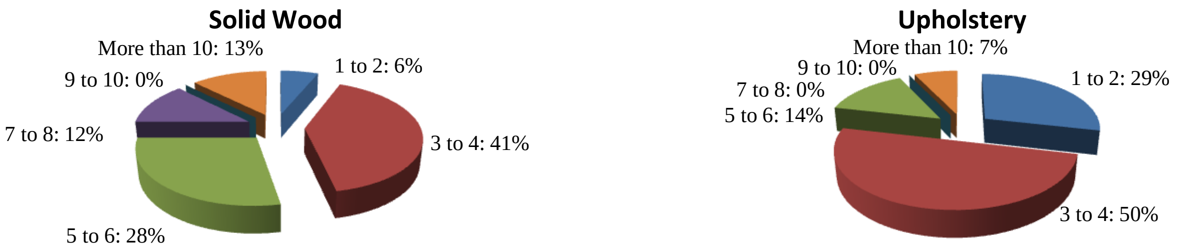


Figure 4.9 Average customer number

4.5.4.2 Engineering Throughput

To understand the current engineering throughput, each engineer was asked the number of engineering documents they could generate per month. The engineering documents include both preproduction documents and mass production documents. From their answer, **Figure 4.10** shows that most engineers were likely to complete "3 to 4" engineering documents per month for the job shops. It could also be observed that, in the upholstery engineering group, there is no difference in the quantity of preproduction and mass production documents released per month. **Figure 4.11** shows that there is a difference in the number of production documents generated in the solid wood engineering group and upholstery engineering group. This somehow reflects the previous results which showed that the solid wood engineers have more experience than the upholstery engineers. So the average number of jobs completed by solid wood engineers was higher than the jobs completed by upholstery engineers.

▸ *Generation of Preproduction Documents*



▸ *Generation of Mass Production Documents*

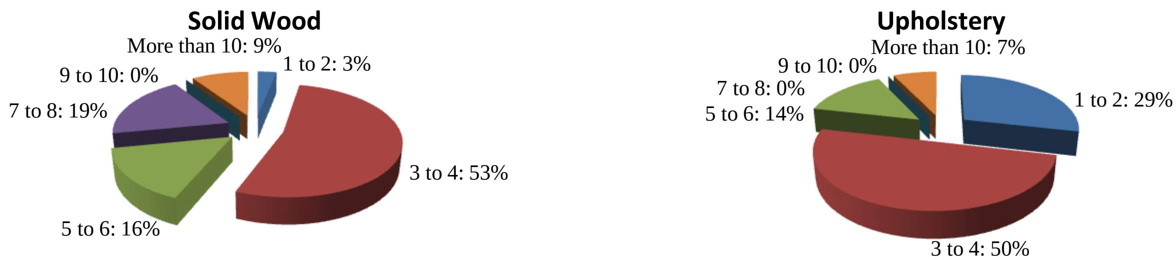


Figure 4.10 Respondent distribution on engineering throughput

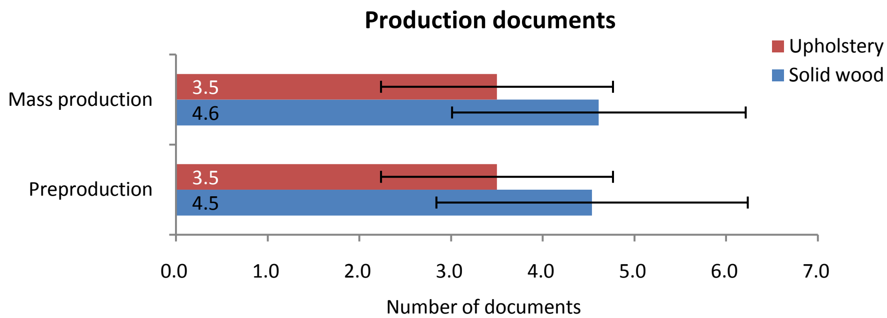


Figure 4.11 The average number of preproduction and mass production documents generated per month in each engineering group.

4.6 Engineering Change

4.6.1 Error rates

Error rate is an important factor that influences the overall performance of the engineering process. Consequently, the amount of errors on average each engineer made in their engineering documents was measured. **Figure 4.12** and **Figure 4.13** show that the majority of engineers in both groups had “1 to 2 errors” for each type of engineering error. From this observation, it was found that each type of error would inevitably happen but differed on how many it had occurred. There were just a few countermeasures used to prevent errors from happening. Through personal interviews with engineering supervisors, it was discovered that checking errors manually is probably the only way to prevent them. Although SolidWorks software could help to detect some drawing errors, it still cannot detect errors in the bill of materials (BOMs) because most of BOMs jobs still rely on manual entry instead of automated generation of BOMs.

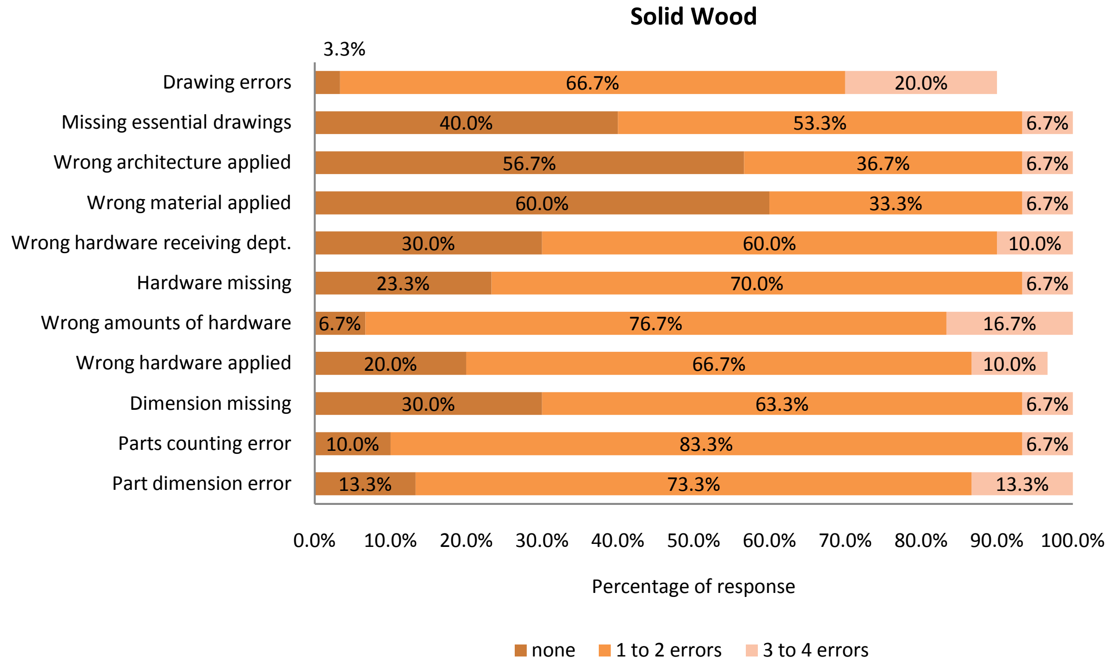


Figure 4.12 Respondent distribution of engineering error rate in solid wood engineering group

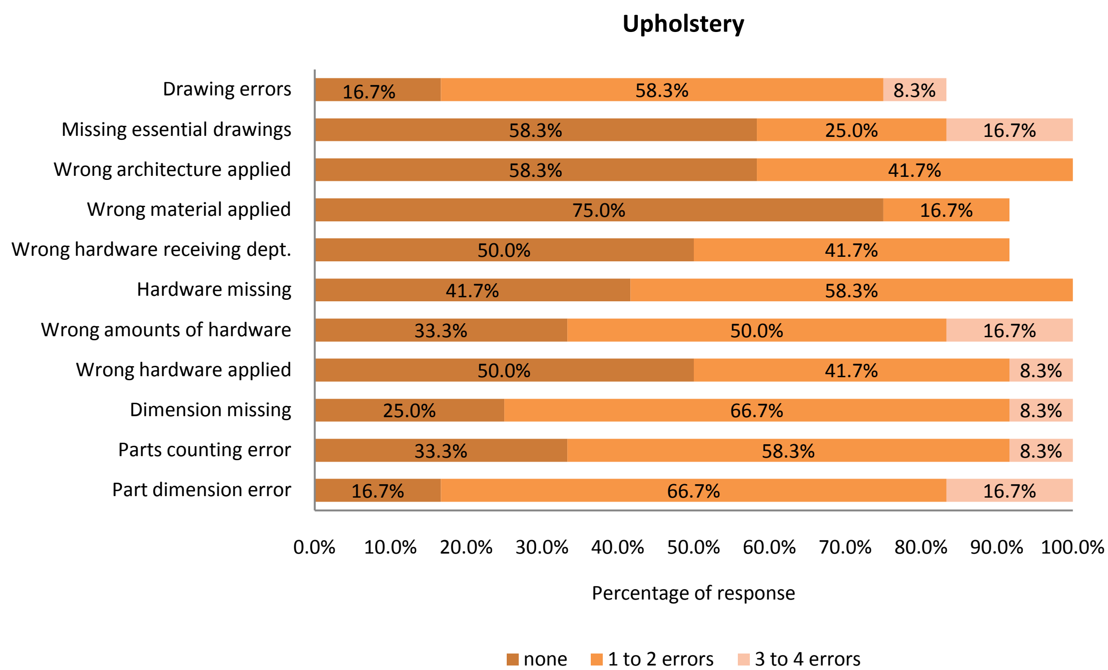


Figure 4.13 Respondent distribution of engineering error rate in upholstery engineering group

Comparing individual errors, **Figure 4.12** and **Figure 4.13** also show that "drawing errors" and "part dimension errors" are the most frequently occurring errors in both engineering groups. Furthermore, it could also observe that for almost each type of error except "dimension missing", the average number of errors for the solid wood group is higher than the upholstery group. A reason for this might be because the solid wood group made more engineering documents than the upholstery group, so it has a relatively higher possibility of generating more errors.

4.6.2 Engineering Change

Because engineering change is a significant driver of product development cost and lead time (Loch and Terwiesch, 1999), a question was designed to ask what percentage of time each engineer spends daily on issuing Engineering Change Orders (ECOs). Thirty-three solid wood engineers and thirteen upholstery engineers provided valid responses. **Figure 4.14** and **Figure 4.15** show that most of the engineers spent less than 20% of their daily engineering time on issuing the ECOs. Engineers were also asked to give a specific time period. Twenty-three percent of upholstery engineers gave "5%-15%" of their daily work time and forty-six percent of engineers provided the answer of "10%-20%" of their daily work time. On the other hand, in the solid wood section, eighteen percent of engineers answered that issuing ECOs seize "5%-15%" of their daily work time, forty-five percent of engineers spent "10%-20%" of their daily time on issuing the ECOs and three percent of engineers answered of "1%-10%" of his daily engineering time. The current state implies that most engineers spent 10%-20% of their daily working time on the rework. That accounted for almost 50 minutes to nearly 2 hours in a day (8-hour work days) doing non-value-added work. In the current engineering process, usually right after releasing the mass production documents, there is a severe increase of engineering changes needing ECOs. Sometimes the engineers were required to spend the whole day working on the ECO without doing any other engineering tasks.

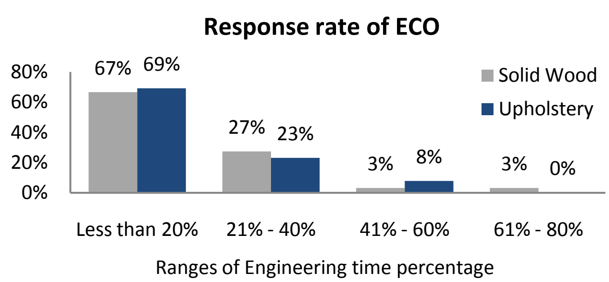


Figure 4.14 Response rate on ECO percentage

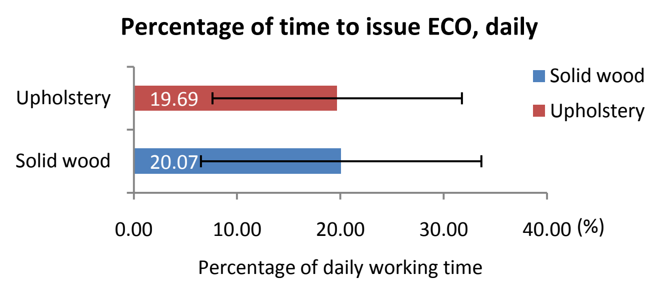


Figure 4.15 Time spent on ECO

4.7 Conclusions

The current engineering process in this particular case study exhibits unnecessary engineering tasks regarded as waste. These wasteful processes might interfere with the engineers' ability to effectively and efficiently prepare production documents for downstream jobs. "Generate production documents" is the top responsibility for furniture product engineers. But, currently, most engineers were distracted by many non-value-added tasks. For instance, 10%-20% of engineering time was spent on releasing Engineering Change Orders (ECOs). In order to leave more engineering time on addressing value-added activities, for example, the company might consider assigning some responsibilities to specific people in production to help engineers issue a portion of ECOs, such as adding screws for strengthening certain product structures. This type of modification does not need big changes of product design or architecture. In this sense, it not only helps balance the workload and provides more flexibility for the product engineers, but also solves the dilemma where product engineers do not have time to issue ECOs for an urgent production change and industrial engineers in production cannot work on this change until they receive the relevant ECOs from engineering.

Processing time is one of the most important lean metrics used to measure engineering performance and it varies depending on the type of customer and products. Although the average number of customers serviced in upholstery engineering and solid wood engineering shows no statistically significant difference, the average number of production documents generated by each engineering group is different. The difference indicates that the engineering capacity (in terms of completed customer orders) of the solid wood group appears to be larger than the capacity of the upholstery group.

From the case study, it was learned that:

- Lean concepts and problem-solving methods are still deficient in the current engineering group.
- "Processing Time," "Engineering Error Rate," "Completion and Accuracy Rate," and "Engineering Lead Time"

are four of the most important factors to impact engineering performance in the case study company.

- Engineering lead time accounts for a large portion (21 to 40%) of the overall production lead time.
- Product complexity and engineer competency are two of the most significant influential factors that impact the engineering lead time.
- Upholstered products usually have longer lead times than solid wood products.
- Currently, the average throughput (in terms of the average number of production documents) of the solid wood engineering group is higher than the upholstery group.
- The frequency of each type of error is similar between the solid wood engineering group and upholstery engineering group.
- Engineering change orders (10 to 20%) account for a big portion of engineers' daily work time.
- 3D engineering design solution is having positive impacts on household furniture engineering tasks in terms of enhanced collaboration, facilitated Computer-aided-Manufacturing, easy document maintenance, automatic BOM generation, readable drawings, reduced engineering errors, shortened modeling time, easy to make late engineering changes.

This research presents some limitations. First, the time period of this case study was short. Second, only the engineering groups from this single case study company were included in the survey. The research did not include more companies to make a broad conclusion on the whole industry. Third, the numbers of engineers involved in the survey were not equally distributed between the upholstery engineering group and the solid wood engineering group. It was not easy to generate better statistic results.

Based on this study, future research should focus on:

- Using lean principles to further identify waste in furniture engineering processes through value stream mapping
- Develop specific methods to further eliminate waste and improve engineering efficiency, with emphasis on:
    - Shortening process times and overall engineering completion lead time
    - Reduce engineering job batch sizes
    - Countermeasures to prevent engineering errors
    - Increase customer satisfaction
- Finding opportunities to promote other companies involved in this type of research that focuses on finding lean opportunities in the non-production area.

CHAPTER 5 USING VALUE STREAM MAPPING TO ANALYZE AN UPHOLSTERY ENGINEERING PROCESS

5.1 Abstract

This study presents a systematic approach of streamlining an upholstery furniture engineering process based on a case study in one of the largest export-oriented furniture manufacturers in China. The approach encompasses an analysis of the current state of the engineering process and the proposal of a lean future state value stream map (VSM). The current state analysis includes the definition of the product family, analysis of current customer demands, and the definition of the process metrics of the engineering process. Data was collected during a half month visit to the furniture plant in China. Results from the current state VSM shows that the value-added ratio of the current engineering process is 26.0%. A lot of engineering steps present deficiencies such as the processes of creating drawing, compiling mass production documents, checking and signing-off engineering documents, creating CNC programs, and generating packaging files. After the current state VSM, it is found that unpredictable process cycle time and expediting engineering change orders are two major problems in the current engineering process. Based on current state VSM, the research focuses on countermeasures to solve the root causes of the major problems and proposes the best practices for the future VSM.

5.2 Introduction

The goal of Lean Thinking is to use least resources and time to deliver desired customer value through a continuous flowing value stream (Hoppmann, 2009). Among different types of lean implementation methods such as pull system, cellular manufacturing, one-piece-flow, standard work, visual control, Kaizen, quick changeover, 5S, and kanban event (Rahn and Consulting, 2001; Van Goubergen and Van Landeghem, 2002; Feld, 2000; Henderson, Larco, and Martin, 2000; Rother and Shook, 1998), value stream mapping (VSM) appears as an important tool to facilitate the lean transformation because it maps both the information flow and materials flow, identifies various types of wastes, and streamlines the value stream to the future state (Womack and Jones, 1996b).

VSM has demonstrated its effectiveness in streamlining the manufacturing processes to maximize customer value (Womack and Jones, 1996b; Rother and Shook, 1998). However, nonproduction activities such as design and engineering, appear to have a significant influence on production cost and lead time (Ehrlenspiel et al., 2007; Tapping and Shuker, 2003; Boothroyd, Dewhurst, and Knight, 2001; B. Prasad, 1996; Anderson, 1990), so a lot of industrial participants are trying to engage in applying lean principles in the nonproduction activities of knowledge-based areas such as design, new product introduction (NPI), engineering, and product development (PD) (Baines et al., 2006). Other applications of VSM in non-manufacturing industries could be found in sales process, health care, admission inquiry process and information management (Barber and Tietje, 2008; Kim et al., 2006; Tischler, 2006; B. Keyte and Branson, 2004).

In the secondary wood products industry, lean principles and techniques had demonstrated its effectiveness, especially on enhancing the productivity of furniture manufacturing process (Hunter, 2008; Motsenbocker et al., 2005; Hunter, Bullard, and Steele, 2004). VSM also showed its power in streamlining the manufacturing process for the wood industry (Quesada-Pineda, Haviarova, and Slaven, 2009; Espinoza, 2009; Czabke, 2007). However, lean principles could also create benefits to nonproduction processes in the secondary wood products industry such as the engineering process (Czabke, 2007). The impact of the engineering process in the production cost is extremely important (Baines et al., 2006); however, research emphasis in the application of lean principles to the engineering process has not been found in furniture manufacturing industry. This study exhibits a road map to evaluate current state value stream mapping of furniture engineering processes to identify both value-added and non-value-added engineering activities towards fulfilling customer requirements. In the meantime, future state will be analyzed and evaluated according to KPIs found through survey questionnaire and process efficiency investigated through on-site study to give solutions as to how valid and useful the future state would be to the industry.

5.3 Literature review

5.3.1 Lean engineering

Lean Thinking principles have been mostly applied to manufacturing activities. However, practitioner and researcher have given so much attention to the implementation of lean principles and the mapping of manufacturing processes, that they overlooked the importance of other non-manufacturing processes such as design and engineering that directly affect the cost in the product life-cycle (Baines et al., 2006). Womack and Jones (1996a) indicated that lean principles are also a fit for areas outside manufacturing processes and these principles have great potential and benefits if applied to knowledge-based activities such as design, new product development (NPD), engineering, and product development (PD) (Donald Reinertsen, 2005; Middleton, Flaxel, and Cookson, 2005; Browning, 2003; Haque, 2003; Freire and Alarcón, 2002). Some examples of lean applications in engineering process can be found in the aerospace, automotive, software and construction industries (Baines et al., 2006). For example, Freire and Alarcón (2002) developed a lean design process for a construction project based on lean manufacturing concepts and methods. They proposed four stages to carry out effective methods in the design process for improvements:

- Diagnosis and evaluation
- Changes implementation
- Control
- Standardization

Following the above methodology, Freire and Alarcón applied seven lean tools on five potential areas of a product development process in the construction industry. The applied lean tools resulted in an effective engineering performance which led to increased value-added activities, reduced product unit errors, largely decreased waiting time and reduction of cycle time.

Furthermore, Haque (2003) conducted a research of lean engineering in the aerospace industry. He restated five-step lean principles applied to a manufacturing process (Rother and Shook, 1998; Womack and Jones, 1996a) and further redefined each principle in a lean engineering manner. Then he applied three different lean applications (*Kaizen on a design process*, *Single piece flow in New Product Introduction (NPI), off-line development to speed time to market*) at three different levels – process hierarchy, detailed design, and project management, on three case study companies. He also mentioned the importance of modular design as a lean tool to facilitate product engineering on easing future modification or evolution of products and the reuse of design elements. In the case of an "off-line development of products" illustration, modular design showed its effectiveness on reducing lead time by 25-50%. Other research by Browning (2003) came up with the conclusion that applying lean to the product development processes is not all about minimizing cost, shortening cycle time and reducing waste, but its application can also maximize customer value. Middleton, Flaxel, and Cookson (2005) also showed an application of how the lean manufacturing concepts could be transferred to lean implementation in software development. The techniques and principles were utilized to streamline the software engineering process include in **Table 5.1**:

Table 5.1 Lean practices in software engineering

Methods	**Explanation**
Continuous-flow processing	By handling work in small batches, jobs can begin earlier and certain mistakes in requirements can be quickly identified.
Customer defined value	By visiting customer, cross-functional team can ensure the product features that is under development can meet all the customer requirements
Design structure matrix (DSM) and flow	Use Kano analysis to connect the voice of the customer with data, which enables scope/features trade off decisions that are developed on facts
Takt time	Pace work according to customer demand; break down projects into manageable units
Linked processes	By placing component parts near one another, travelling within the office building is effectively reduced
Standardized procedures	Enable transfer of people between projects as needed
Eliminate rework	Try to find the root cause of a defect and then permanently resolve it; meanwhile, invest more time understanding the customer need and context
Balancing loads	Analyze the skills needed per unit of work and rearrange skills to eliminate the bottlenecks and finally eliminate the delays
Posting results	To give constant feedback to learn where problems and errors are, then the staff can figure out when the work can be done and how much capacity is available
Data driven decisions	Enable self-management of team and reduce supervision costs. Also reduce the number and duration of meetings.
Minimize inventory	Breakdown the project into smaller parts, only a small amount of work can go through the system at any given time

Reinertsen (2005) incorporated lean manufacturing methods to deal with the inherent variability in product development process. Five key methods were applied to streamline the product development process, queue management, batch size reduction, cadence, rapid local adjustments, and waste elimination. **Table 5.2** shows some of most important past research on lean product development and engineering.

Table 5.2 Literature on lean product development and engineering

Author	Title	Outcomes
Freire and Alarcón 2002	Achieving Lean Design Process: Improvement Methodology	Proposed a methodology to achieve a lean design process for the construction industry by applying seven tools for improvement based on five areas – client, administration, project, resources, and information.
Haque 2003	Lean Engineering in the Aerospace Industry	Proposed applying lean principles to three different levels of engineering processes: • Detailed design level • Project management level • Design strategy level
Browning 2003	On Customer Value and Improvement in Product Development Processes	Demonstrated the effectiveness of "maximizing value" as a preferred way to incorporate "lean" in the product development process architecture compared to the effectiveness of "minimizing cost and time"
Reinertsen 2005	Let It Flow	Proposed to apply five key methods of lean manufacturing to address the inherent high variability of product development. The methods encompassed queue management, batch size reduction, cadence, rapid local adjustments, and waste elimination
Middleston et al. 2005	Lean Software Management Case Study: Timberline Inc.	Demonstrated the effective application of lean principles in software engineering.

The above examples show the similarities of specific methods used for streamlining the engineering process were inherited from the lean production methods.

5.3.2 Value Stream Mapping (VSM) in wood products industry

In the wood products industry, research had utilized Value Stream Mapping methodology. Czabke (2007) conducted a survey in the secondary wood products industry and listed value stream mapping as an important Just-in-time production practice in the lean manufacturing process. Espinoza (2009) used value stream mapping to portray the flow of information and materials and to identify specific quality control activities in the wood products supply chain. Also, based on a case study of three companies located in Honduras, Costa Rica, and Guatemala, Quesada-Pineda, Haviarova and Slaven (2009) utilized value stream mapping to conduct quantified research analyzing the value-added times for wood products manufacturing companies in Central America. Key findings in the research included:

- Raw material inventory accounts for most of the waste in the three case study companies
- Value-added time ranged from 8.8 to 12.3 percent of total process lead time. The kiln drying process should be targeted first rather than other processes to improve the value stream.

5.4 Methods

This research was conducted through a case study of a large household furniture manufacturer in China. Seventeen days were spent in the upholstery product engineering department collecting relevant process information including process time, inventory, customer demand, error rate, and types of processing waste. The methods used for collecting the process data included data entry sheet, direct observation, and engineering archives. Then, the current state VSM was generated based on these process data. Furthermore, through waste analysis, several improvement opportunities were proposed and the future state VSM was applied. For data collection and analysis method used, please refer to chapter 3.

5.5 Results

The results section shows the general engineering functional flow chart to help give an initial understanding of the engineering processes in the case study company. Before proceeding to VSM, several analysis were conducted concerning process metrics. First, customer demand was calculated on a daily basis. Then the product family was defined for further planning for the VSM. Second, the process analysis section was composed of process boundary analysis and main process analysis. The boundary analysis used the context diagram to analyze the interaction between the engineering system and its external factors. The main process analysis identified and categorized each main process. Additionally the process metrics were analyzed and current state VSM presented. The next step was to discover the waste and unnecessary steps in the current state mapping. Several proposals were given to streamline the process and then the future state VSM was developed.

5.5.1 General Engineering Function

Before proceeding into the details of the engineering process, a brief functional flowchart (see **Figure 5.1**) provides an overall understanding of the whole engineering function associated with other departments in this company. This process flowchart represents a typical engineering sequence for designing most of the case goods and upholstery products in this company.

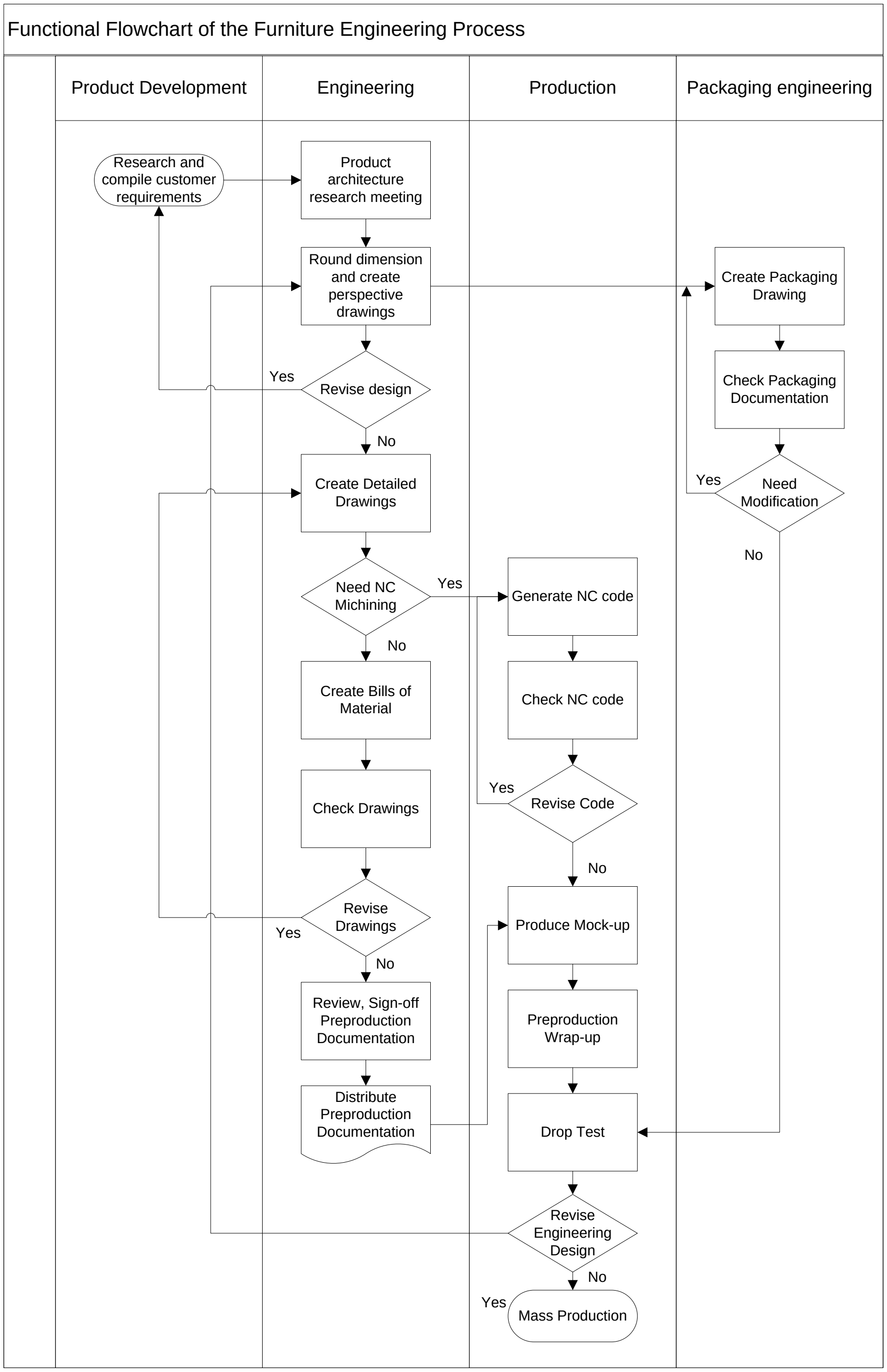


Figure 5.1 A typical furniture engineering process by using functional flow chart

By using the functional flowchart shown in **Figure 5.1**, the typical furniture engineering process was identified. Engineering interacts with several internal departments. The department of Product Development is considered as the supplier of the engineering department since they provided the original files and product specification to the engineering process. Also the production department can be seen as the internal customer of the engineering process since engineering gives the production documents to fabricate the products.

From the chart (**Figure 5.1**), it was observed that the Product Development department took the product specification and original drawings to the Engineering department through product structure discussion meeting. Then the engineers started to round dimensions on the original drawings and created the perspective drawings. As long as the overall dimension was defined, packaging engineer could work on preparing the packaging files for Production. At the same time, product engineers gave their feedback on where changes to the original design were needed to accommodate production capacity. Their feedback was sent back to Product Development department for customer confirmation and then the next iteration was started. After product engineers confirmed the information from the customers' drawings, they generated detailed drawings. Since the detailed drawings contained the fabrication drawing for each component, certain parts of the drawings that needed accurate fabrication were sent to Computer Numerical Control (CNC) programmers to complete the NC code and later were sent to the CNC machining group in the Production for debugging and making adjustments. As detailed dimensions had already existed in the drawings, the bills of material (BOM) could be generated at this time. Except for some specifications formulated to facilitate the production process, the production document was almost finished. Next, the engineering supervisor checked the preproduction documents and returned them to the responsible engineer for any further necessary modification. If no more changes were needed, the engineering manager signed-off the preproduction document and distributed it to Production for fabrication.

The mock-up group in the manufacturing plant used the preproduction document to fabricate the mock-up. Since the CNC machining group in the production had already debugged the CNC code, the fabrication template and any essential mold (like dies) program for fabrication was generated for the mock-up process. When the mock-up products were built, production used the packaging file and wrapped the products up for the first trial and then tested for the drop test. If any problems arose during the mock-up, the production associates informed the engineer who was responsible for the product to make modifications on the mass production documents. When all the necessary revisions and iterations were completed and no more changes were made at this stage, the mass production document was compiled and issued to the manufacturing plant to begin mass production.

5.5.2 Product family and customer demand analysis

5.5.2.1 Product family analysis

Product family refers to a set of products that share a common platform but have individual features and functionality satisfying a variety of customer needs (Meyer and Utterback, 1993). By focusing on the product family and analyzing a process of similar product architecture, an easy way for new product development could be provided that could save engineering time, improve product quality and reduce manufacturing costs.

The product family is defined by two considerations – engineering procedures and historical customer demand (frequency of orders). If a collection of products possessed a similar structure and manufacturing methods, it could be considered a product family. On the other hand, if a collection of products with similar structure and engineering procedure had been ordered frequently by customers, it made sense to create a product family for these product groups to ease engineering and manufacturing efforts.

In the furniture engineering and manufacturing process, the product architecture is diversified for different products. Solid wood products and upholstery products are two types of general product classifications for household furniture. Solid wood furniture typically includes the collection of bedroom, living room, and dining room furniture such as drawer chest, armoire, bed, china cabinet and so on. Therefore case goods are the typical products in the solid wood collection. On the other hand, the upholstery products mainly include sofa, ottoman, chair, bench, loveseats and so on. The majority of products in the upholstery plant are fabric-based products. Since this case study was conducted in the upholstery plant, the product family was defined from a set of typical upholstery products that shared similar structure with the same engineering procedures and had a constant demand from the existing customer base.

After researching customer orders for all collections of upholstery products incurred in the last six months (Beau Keyte and Locher, 2004), in **Figure 5.2**, it was observed that five types of products accounted for 86.4% of orders. The products included sofa, chair, ottoman, sofa chair, and loveseat. Three products (sofa, chair, and loveseat) shared the very same product architecture but were differentiated in length within each product collection. In other words, an engineer had to create sofa engineering documents, and then the documents of loveseat and chair could be easily created by scaling and stretching the design elements in the existing documents. Since these three types of products shared the same product architecture, their engineering, manufacturing, planning and packaging process were similar in complexity. From the order frequency perspective, these three types of products represented 60 percent of customer orders during the previous six months. From the above analysis, the product family was identified as sofa, loveseat, and chair products.

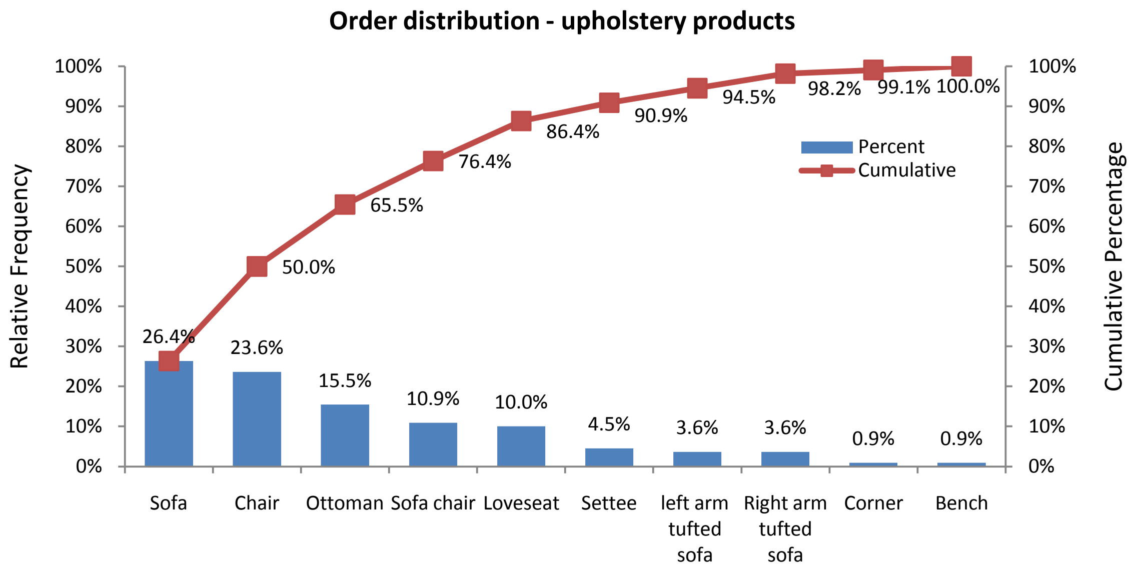


Figure 5.2 Customer demand of upholstery products in the last six months

5.5.2.2 Customer demand analysis

A few indicators were used to analyze the customer demand in the primary and secondary engineering process based on the data for the last six months. These indicators include "average orders per month", "total number of current monthly orders", and "orders per day". Based on these important indicators, two important measurements were calculated ("Work-In-Progress (WIP) inventory" and "takt time") for analyzing the process efficiency. The WIP inventory is the basis for calculating the total lead time for delivering the finished products or service in the value stream (Beau Keyte and Locher, 2004). The takt time synchronizes the pace of completing each work unit to the pace of customer demands (Rother and Shook, 1998).

As the total number of orders within the product family for the last six months was 159 product orders, the information shown in **Table 5.3** was summarized for the primary engineering process:

Table 5.3 Indicators for primary process

Indicators	Unit	Value
Average orders per month	Orders	26.50
Total # of cur. monthly orders	Orders	43.00
Available monthly work time	Days	24.50
Orders per day	Orders	1.76
Daily available work time	Min.	480.00
Takt time	Hr.	4.50

The “orders per day” is essential for further calculating the days used to consume the inventory (in terms of engineering orders) within different processes. This information allows calculations for the elements of value stream mapping.

5.5.3 Process analysis

5.5.3.1 Process boundary analysis

Context diagram was used to show the interaction between a system and its important external factors (Kossiakoff and Sweet, 2003). It was used to analyze the system boundary of the engineering process. From **Figure 5.3**, two suppliers were identified in the current engineering design system: Product Development and Production. In this situation, Product Development performed the following tasks:

- Fabricated original product samples and ship to customer for confirmation
- Confirmed with customer on design changes and acquire product original drawings from customer
- Compiled engineering and fabrication specifications for each product collections and handover to engineering to generate production documents
- Delivered the customer-confirmed color board to facilitate finishing and production

On the supplier side, the production department needed to make sure that they could deliver the updated production plan to the engineering department on a timely basis since this schedule was the foundation for creating the engineering plan. Production plan was developed based on customer orders. The production time was calculated backwards from the shipping date on the order. Because engineering usually took a significant portion of production lead time, an accurate engineering plan could ensure the on-time delivery of products. According to the survey results (see previous chapter), engineering accounted for 21%-40% of production lead time.

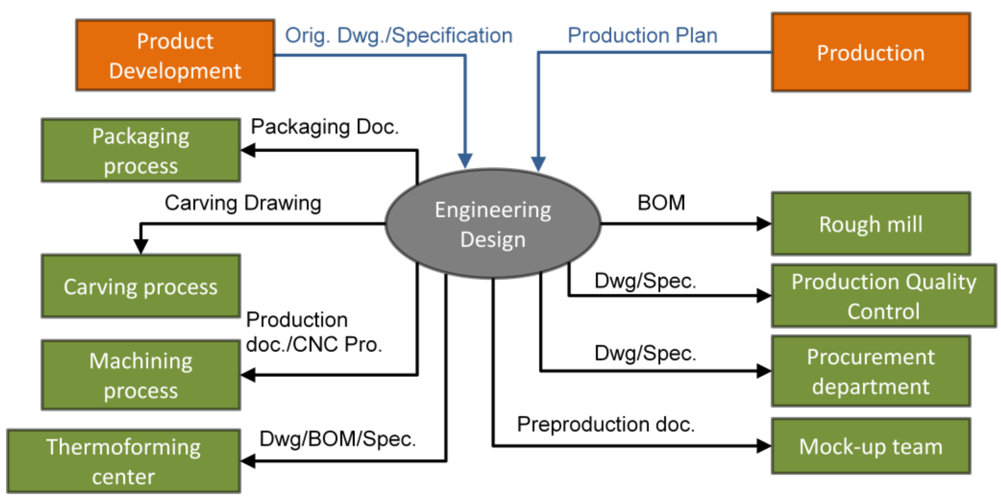


Figure 5.3 Engineering design context diagram

From the customer perspective, engineering provided service for a number of manufacturing processes. These processes were the downstream customers of the engineering processes. The interactions between engineering department and downstream customers are explained below:

- Rough mill: responsible for processing the raw material into treated material to be prepared for machining process. So engineering provided BOMs for the rough mill by providing the following information:
  - The quantity of materials needed to be prepared
  - The rough and net dimension of each pre-machining component
  - The number of each component
  - The board dimension for panel gluing or brick stacking

- Machining process: engineering needed to provide machining process with a number of essentials:
  - Fabrication drawings for making components
  - Assembly drawings for subassembly and final assembly of products
  - Profile drawings for verifying the precision of component fabrication accuracy
  - Programs for CNC manufacturing
  - BOMs to check component dimension and part number
  - BOMs to require hardware and accessories for assembly

- Production quality control: engineering provided essential assembly drawings, instructions, and specification to help ensure the quality of products during production process

- Thermoforming center: in general, this process had three functions:
  - Provide wood-based panel to production plants. In this situation, engineering needed to prepare bills of material for thermoforming process that indicated the amount and dimension of the material in demand.
  - Fabricate fancy panel for production. For this, engineering provided them with veneer drawings for parquetting veneer on face panels.
  - Fabricate plywood panel. In this case, the engineering provided drawings to verify the shape of fabricating panels. Also, the CNC engineers were responsible for providing programs for the die fabrication.

- Carving process: engineering provided carving drawings to the carving mills

- Packaging process: packaging engineer was in charge of generating packaging documents for packaging process. A packaging document typically includes the drawings, bills of material, and instructions for a specific furniture product.

- Procurement department: engineering provided drawings and specification for the new material and tooling purchase.

- Mock-up team: this team implemented preproduction, a necessary step before mass production. It had the full function in mass production. Thus engineering not only provided preproduction documents for this process, but also tracked the fabrication progress and helped solve problems due to design flaws.

5.5.3.2 Main Process analysis

Andersen and Fagerhaug (2001) defined a process as "a logic series of related transactions that converts input to results or output." The engineering process is an important component of a business process since it is "a chain of logical connected, repetitive activities that utilizes the enterprise's resources to refine an object (physical or mental) for the purpose of achieving specified and measurable results/products for internal or external customers" (Gothenburg, 1993)

After having identified the product family, the different processes of engineering used to make the family of products were identified as well. **Figure 5.1** shows a typical furniture engineering process by using a functional flow chart. Furthermore, based on the initial study, 15 major processes for engineering the sofa products were identified. Each process is explained in **Table 5.4**:

Table 5.4 Main Engineering Process

ID	Process	Interpretation
1	Research Product Architecture	Generally, this process is fulfilled by a product architecture discussion meeting. The attendees include associates from three departments which are Product Development, Engineering, and Production. The goal of this meeting is to figure out product architecture in the context of customer requirements, engineering feasibility, and product manufacturability.
2	Create drawings and bills of material (BOM)	Drawings include perspective drawings, assembly drawings, part drawings, cutting tool drawings for fabrication. BOM includes both bills of material and bill of hardware.
3	Create fabric cutting drawings	The previous step completes the drawings for solid wood and wood-based components. Since most of the upholstery products contain fabric material, the fabric cutting drawing is generated to telling the production associates how to process the fabric.
4	Apply new material SKU#	Since new product inevitably needs to use new material, so engineers need to apply new SKU# for each type of material to facilitate the procurement process
5	Create law tag	This is a mandatory tag shows that the product attributes are compliance with the local law for distributing and selling in the destination market
6	Fill out material purchasing form	As long as the SKU# is approved, engineer can start to fill out the purchasing form to order certain materials and attach essential drawings and specification to the use of suppliers
7	Create sofa specifications	The specifications include both design specification for engineering details and manufacturing specification for fabrication details
8	Create 2.5 axis CNC programs	The programs include all the precision machining by the CNC machine such as certain component fabrication templates, part routing programs, and plywood dies for the thermoforming process
9	Check/sign-off/distribute preproduction documents	After all the above processes, preproduction documents are established which contain all the essential drawings, bills of material, instruction, and specifications for fabricating a product or product family. Next, the engineering supervisor will check the document, then the document will sign-off by the engineering manager and distribute to the manufacturing plant.
10	Follow up preproduction mock-up process	After releasing the preproduction document, engineers also need to coordinate with production associate on fabricating the mock-up and collect feedback on fabrication difficulties in the mock-up process
11	Compile mass production document	According to the fabrication feedback in the mock-up process, engineers could start improving the engineering design and making adjustments in the mass production document
12	Check/sign-off/distribute mass production documents	Engineering supervisor and manager do the same process to check, sign-off, and distribute mass production documents
13	Create fabric manufacturing specification	This process paralleled with the process of generating production documents. The document not only include detail design specifications, but also contains detailed information on fabric material and what specific area of a certain product will apply this material
14	Create packaging document	This process happens after the process of generating production documents. The packaging document include all the drawings, BOM, and specification for packaging a furniture product
15	Create 5-axis CNC program	This process parallel with the process of generating production documents. It usually deals with 3D-shaped components that are difficult to generate in the 2.5-axis CNC machine.

5.5.3.3 The differentiation of primary and secondary engineering process

Depending on the attribute of the engineering tasks, the engineering process could fall into two major engineering activities – the primary engineering process and the secondary engineering process. Through the interview, the engineering supervisor defined the primary furniture engineering process as major value-added engineering activities toward product architecture design. Secondary furniture engineering process refers to subordinate value-added activities used to assist and realize the product engineering for production.

Primary engineering process encompasses all the regular engineering activities toward generating the production documents, whereas the secondary engineering process encompasses specific engineering tasks that are only performed by certain technical engineers. Some engineers have multiple roles in completing engineering tasks in both primary and secondary process. **Table 5.5** lists the primary engineering process and the secondary engineering process.

Table 5.5 Engineering Process

Primary engineering process:	• Research Product Architecture • Create drawings and bills of material (BOM) • Create fabric cutting drawings • Apply new material SKU# • Create law tag • Fill out material purchasing form • Create sofa specifications • Create 2.5 axis CNC programs • Check/sign-off/distribute preproduction documents • Follow up preproduction mock-up process • Compile mass production document • Check/sign-off/distribute mass production documents
Secondary engineering process:	• Create fabric manufacturing specification • Create packaging document • Create 5-axis CNC program

5.5.4 Process metrics and unit

Lean metrics could help people understand the impact of their efforts toward continuous improvement and waste elimination (Tapping and Shuker, 2003). In order to determine the appropriate process metrics, a relatively larger selection base which has 11 metrics (**Table 5.6**) was prepared. Then the engineers gave their individual rankings of these metrics on a scale of 1 to 5. The final process metrics were determined from the top four higher ranked metrics.

Table 5.6 Definition of each process metric

Metrics	Interpretation
Processing time (cycle time)	The time that the engineer spent on generating the production documents without doing any other tasks
Value-added time	The sum of each process cycle time
Queue time	The time that the engineer did not spend on value-added activities such as making phone calls.
Error rate	The number of error occurred in each production document divided by the total number of production documents
Engineering lead time	From the moment that Product Development department handed the new products over to the moment that the production documents were completed and distributed to the production plants
Number of engineers	The total number of engineers in an engineering unit
Overtime	The extra time spent outside the normal work time
Changeover time	The time that engineers needed to convert from one task to another
Completion & accuracy rate	The number of on time delivered and minor error production documents divided by the total number of production documents
Inventory	The number of unfinished engineering tasks between the processes
Reliability of tool	The reliability of all the essential software and hardware in completing the engineering tasks

Four most highly ranked lean metrics for the value stream mapping were identified: “processing time,” “queue time,” “lead time,” and “completion & accuracy rate”. Since the “processing time” equals the “lead time” minus the “queue time”, the process metrics were chosen as “processing time” and “completion & accuracy rate”.

5.5.5 Process cycle time and Lead Time

Because of the time limit of this on-site case study, it was difficult to track the process time of each engineer. So under the recommendation of the engineering supervisor, three engineers were selected from the engineering group that could represent the most accurate process cycle time an engineer typically took to complete each engineering process. An evaluation form was used to collect results from these engineers. The average value of process cycle time for completing each engineering process is shown in **Table 5.7**. From this, the value-added time was calculated as 8.8 days.

The results of non-value-added time were collected by using the following methods. First, a day was defined as the checkpoint to count the unfinished orders within different processes. Second, an evaluation form was sent out to each of the engineers (15 upholstery engineers). On the form, the engineers indicated which step they had completed from a current order and how many orders they had not finished. Thus, knowing how many orders had not been finished (inventory) prior to certain engineering steps (**Table 5.7**), the total lead time could be calculated by summing up all the value-added time and non-value-added time. Thus, the lead time of the primary engineering process was calculated as 133.9 days.

Table 5.7 Value-added time versus non-value-added time

Value-added Time (Process cycle time):	Min.	**Non value-added Time:**	Days
1. Research product architecture	120	Prior "Research product architecture"	1.3
2. Create frame and fabric drawings and dimension table	714	Prior "Create frame and fabric drawings and dimension table"	2.1
3. Create fabric cutting drawings and hardware table	274	Prior "Create fabric cutting drawings and hardware table"	2.2
4. Apply new material code	15	Prior "Apply new material code"	2.2
5. Create law tag	20	Prior "Create law tag"	2.2
6. Fill out material purchasing form	15	Prior "Create material purchasing form"	2.2
7. Create sofa manufacturing specification	20	Prior "Create sofa frame description"	2.2
8. Create 2.5-axis and 5-axis CNC programs	375	Prior "Create template and CNC programs"	10.2
9. Check/Sign-off/Distribute preproduction documentation	1080	Prior "Check/Sign-off/Distribute preproduction documentation"	19.3
10. Create packaging docs.	310	Prior "packaging docs."	18.0
11. Compile mass production documentation	605	Prior "Compile mass production documentation"	25.0
12. Check/Sign-off/Distribute mass production documentation	696	Prior "Check/Sign-off/Distribute mass production documentation"	12.2
Total process cycle time (in days)	**8.8**	**Total lead time (in days)**	**133.9**

5.5.6 Value Stream Mapping – Current State

Before generating the current state VSM, some single steps in the main engineering processes in **Table 5.7** needed to be grouped together to form major processes in the current state VSM. In this case, the processes of "create frame, fabric drawings/dimension table," "apply new material code," "create law tag," and "run new material purchasing work flow" were combined as "create drawings and instructions". Similarly, "Create fabric cutting drawings and hardware table" and "create sofa manufacturing specification" were combined as "create BOMs and specifications." So steps were integrated from 12 steps to 8. The reason for separating the processes "create drawings and instructions" and "create BOMs and specifications" during the investigation was that it was much easier to track the process cycle time of each smaller activity instead of tracking the whole activity, which usually took a longer period of time in a discontinuous basis.

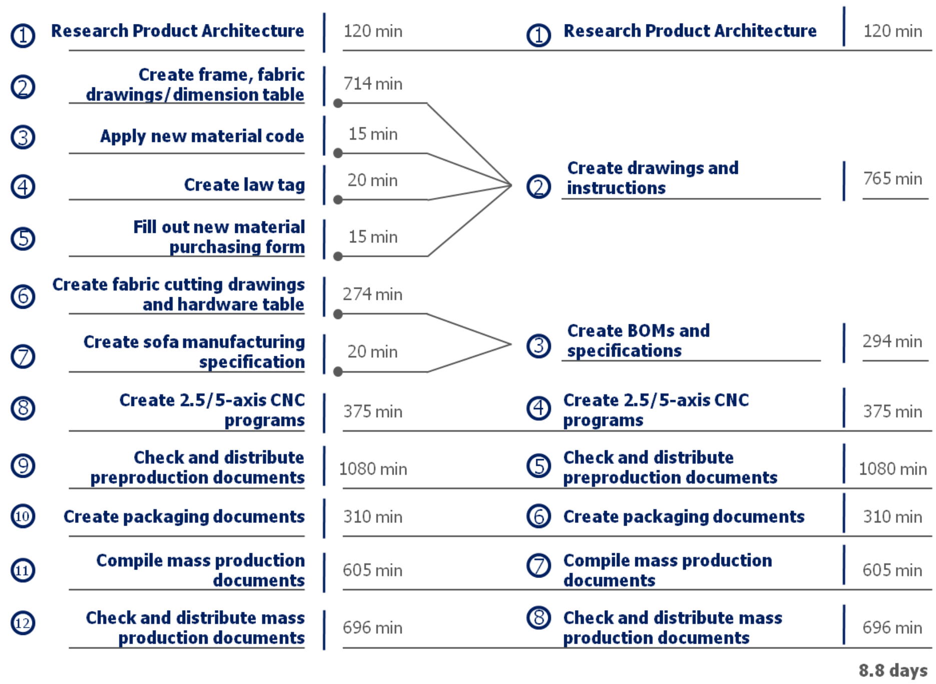


Figure 5.4 Group some of the small events into individual activity

After grouping, integrated value-added time and non-value-added activities are presented in **Table 5.8**.

Table 5.8 Restructured primary engineering process

Value-added Time (Process cycle time):	Min.	**Non value-added Time**	Days
1. Research (research product architecture)	120	Prior to “Research product architecture”	1.3
2. Drawing (create drawings and instructions)	764	Prior to “Create drawings and instructions”	8.7
3. BOM (create BOM and specification)	294	Prior to “Create BOM and specification”	4.4
4. CNC (create 2.5 and 5 axis CNC programs)	375	Prior to “Create 2.5 and 5 axis CNC programs”	10.2
5. Check (check/sign off preproduction docs).	1080	Prior “Check/sign off/distribute preproduction docs”	19.3
6. Packaging (create packaging docs).	310	Prior “Create packaging docs.”	18.0
7. Compile (compile mass production docs)	605	Prior “Compile mass production docs”	25.0
8. Check (check/Sign-off mass production docs).	696	Prior “Check/Sign-off/Distribute mass production docs.”	12.2
Total process cycle time (in days)	**8.8**	**Total lead time (in days)**	**133.9**
Total processing time (in days)	**34.8**		

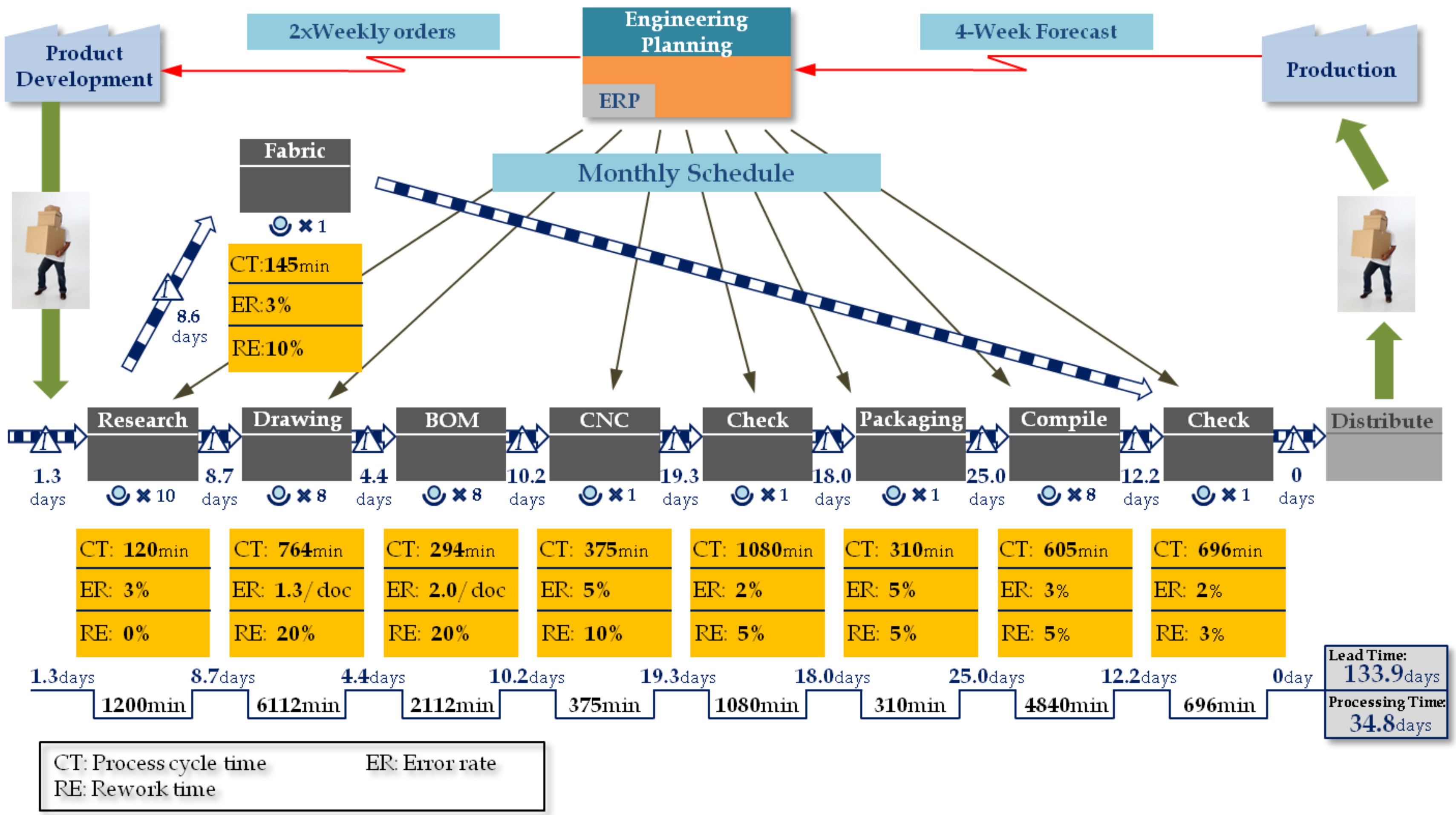


Figure 5.5 Current State Value Stream Mapping (VSM)

5.5.7 Current State Analysis

Current state overview:
As all the elements in the value stream had already been identified, a current state VSM was generated to have an overall picture of the current engineering process (**Figure 5.5**). In the current state VSM, both supplier and customer are internal. The internal customer is production. Production informed engineering of the production schedule four weeks prior to anticipated need. Based on the production schedule, engineering developed a schedule for making new products. The engineering supervisor oversaw the monthly schedule and triggered each individual engineering activity. A Material Requirement Planning system was used to develop and manage this schedule.

The supplier is the internal Product Development department. Product Development oversaw communication with external customers, collecting all the customer requirements, compiling these into specification files, and delivering original drawings and customer specifications to engineering. New product requirements were handed over to engineering through group discussion meetings where Product Development presented important new product designs and engineering specifics to the engineering group. This meeting was organized twice a month, which meant Engineering requested customer specifications for new product development every two weeks.

In the engineering process, there were nine individual engineering activities which are listed in **Table 5.5**. The process cycle time varied from 120 minutes (research product architecture) to 1080 minutes (check preproduction production document). The work-in-progress orders between each engineering activity varied from 1.3 days to 25 days. The engineering lead time was about 133.9 days, whereas the value-added time was just 34.8 days. The value-added ratio was 26.0% which is represented by using the value-added time (34.8 days) divided by the non-value-added time (133.9 days).

Problems:
From current state value stream mapping, two major contributors to the overall lead time, shown in **Figure 5.5,** are excessive work-in-progress orders and unbalanced process cycle time. Recall the initial study in chapter 4, a couple of things had been distracting engineers' value adding capability. The two most important ones were the unpredictable and unbalanced process time, making it difficult to level workloads and distractions due expediting engineering change orders (ECO). The following discussion will focus on finding the root causes of these problems. By identifying root causes to these problems, a future state VSM can be developed to present the countermeasures.

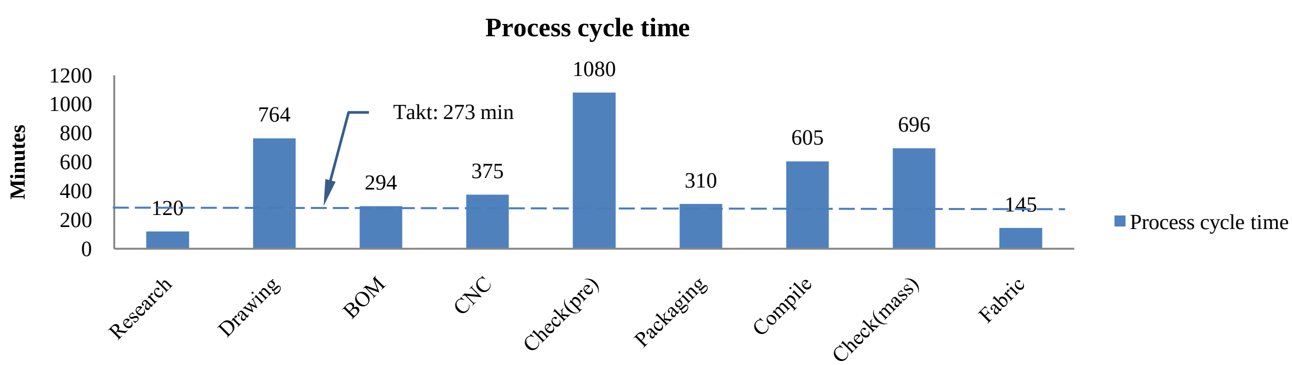


Figure 5.6 Takt time versus process cycle time

In **Figure 5.6**, it shows that only three processes could keep pace with customer demands. Several processes exhibited very high cycle times. For instance, engineering could not work on compiling mass production documents for a couple of days before they got all the production feedbacks from mock-up process. Furthermore, engineering supervisors and managers could not guarantee their regular day time work to check engineering documents because they got interrupted all the time. So significantly and costly overtime must be used or the company got behind. From observations, many interruptions led to "unpredictable and unbalanced process cycle time" as well as "excessive engineering change orders (ECO)." This translates into excessively long cycle times to complete an engineering activity. These interruptions can be summarized as different types of waste. From direct observation, the following types of waste (**Table 5.9**) could be identified that constantly interrupted engineers' value-added work:

Table 5.9 Interruptions in the engineering process

Type of Waste	Examples
Waiting	• Waiting the design changes from the customer approval • Waiting the feedback from the mock-up process
Extra processing	• Interruption while creating drawings (phone calls, inquiries, computer breakdowns). • Various copies/formats of part drawings
Correction	• Work on engineering changes
Excess motion	• Printer and plotter were far from reach
Transportation	• Long travel distance in the process of generating engineering documents (review)
Underutilized people	• Unevenly distributed tasks • Limited authority of engineers (waiting for approval)
Inefficient information flow	• Inefficient Office Automation (OA) system for engineering inquiry • Inefficient communication between product engineers and production associates

5.5.8 Root Causes Analysis:

The root causes of the two major problems found in the previous section, unpredictable and unbalanced process cycle time, as well as expediting engineering change orders (ECO), in the current engineering process can be explicitly expressed in **Figure 5.7**. Each root cause is explained the following discussion.

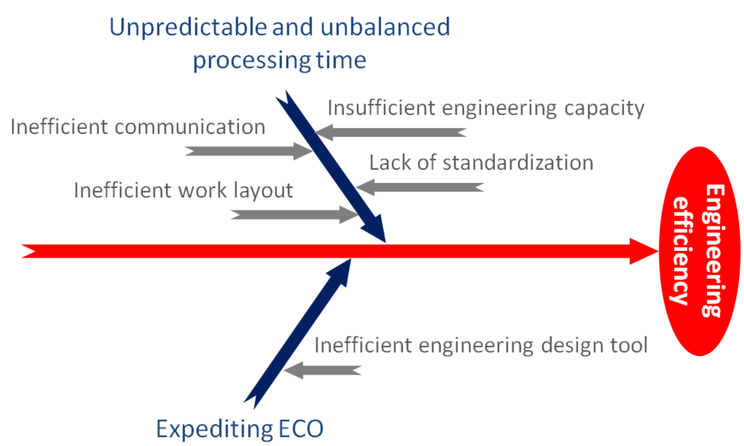


Figure 5.7 Root causes of two major problems

Lack of standardization:

In the current process, many parts and assembly models did not have standard drawings. The engineers employed their own designs of commonly used parts and assembly, and this lack of standardization led to parts proliferation and large inventory in the manufacturing process. Also, the lack of standardization increased the possibility of errors in the engineering design and finally product engineers took a large portion of time issuing engineering change orders (ECO). From the previous study in chapter four, 67%-69% of the engineers answered that it took 10%-20% of their daily work time to address ECOs. ECOs were considered as reworks and did not create value to customers.

Inefficient communication:

Inefficient communication includes the communication with external and internal customers. External customer refers to the real customers who purchased the products. Sometimes, a design change needed to be confirmed with the external customers, which took several weeks. This made the engineering lead time unpredictable. From the previous study in chapter four, engineering lead time accounted for 21%-40% of the overall production lead time. The confirmation process contributed to the engineering lead time.

Communication with internal customers in production was another problem. From the current state VSM in **Figure 5.5**, the "compile" process had the longest process cycle time which implied overtime was used to keep pace with customer demand. A major cause for overtime was the mock-up process. Engineering had to wait a couple of days to collect the mock-up feedback before they worked on compiling the mass production document. This waiting time created unpredictability in the compiling process cycle time and it also contributed significantly to the overall engineering lead time.

<u>Insufficient engineering capacity:</u>
Lack of people on certain tasks resulted in unbalanced process cycle time and inevitably increased overtime. For example, there was one supervisor in charge of checking all the engineering documents. Although checking and signing-off engineering documents was one of their responsibilities, the supervisors also had other tasks, such as preparing engineering work plans, solving engineering-driven problems in production, communicating with suppliers and meeting with customers. Therefore the supervisor in each engineering group had difficulty managing all these tasks. The available working time of an engineering supervisor was 480 minutes a day and the takt time was 273 minutes. This meant the supervisor needed to check, sign-off, and have someone distribute the engineering document at least once a day. The supervisors were too busy to check the production document once a day. Sometimes they needed to travel and no one could take over their tasks.

<u>Inefficient work layout:</u>
In the current office environment, engineering and other departments share one printer. The printer was placed in a separate room where on average it took 25 to 30 seconds for an engineer to travel by foot to pick up a piece of paper. Even worse, the printer was packed with print-outs from several departments and it took a while for the engineers to search for their documents and collect all the drawings needed.

<u>Inefficient engineering design tool:</u>
Based on the survey study in chapter 4, "drawing errors" and "part dimension errors" were the two most frequent errors in the engineering documents. Also from the survey study, the results showed that SolidWorks (a 3D engineering design software) was capable of reducing design errors and generating bills of material (BOM), which demonstrated the importance of an efficient design tool for improving engineering performance.

Next, the use of future state VSM has the potential to solve these root causes in the engineering process. Although the future state is not the ideal state; it shows the big picture of lean transformation process for a specific value stream. The future state VSM will not solve all the problems but it could be the next stage of improvement that is likely achievable within a specified time and cost budget.

5.5.9 Future State Analysis:

<u>Countermeasures for "Lack of standardization":</u>
In current engineering process, standardization is supposed to focus on two things. One is the standardization for managing the work load; the other is the standardization of quality engineering design. The effects of work load management is indicated in the huge process cycle times in steps such as "Drawing", "Compile", and "Check". The engineers are responsible for managing and evening out their work load. Without a standardized procedure, none of engineers were efficient in managing their work loads.

Besides, the effects of quality design are evident in several parts that do not have a standard model to generate drawings. This lack of standardization results in confusion and errors in the downstream processes. Engineers develop individual designs and architecture leading to parts proliferation in the manufacturing process and excessive engineering errors. Also no standard drawing format exists for production documents, which causes difficulty finding useful information on the drawings when needed.

A potential countermeasure for solving the work management problem is to balance and level engineer work load through process combination and automation. An implementation is to combine "Drawing", "BOM", "Check" (preproduction document), and "Compile" (mass production document) into one process "DWG/BOM", then focus on changing the way of creating drawings and automating generation of BOM based on existing design. Previously, each engineer created drawings from beginning to end for a product. This led to large process cycle time because no method existed to manage the work load. However, work load balance could be better managed if parts drawings were separated into smaller job pieces. For instance, the supervisor could assign one person to create drawings for a sofa arm frame, another person to create one for a back frame and so on; in the end, a new engineering document will be compiled by putting together the drawings from each engineer. Furthermore, by using SolidWorks, the engineering team could also generate bills of material (BOM) based on an established 3D model. So the process cycle time for creating BOM will be zero. In this way, work load would be managed at a smaller scale and could predict processing time more accurately.

Countermeasures for "Inefficient communication":

The inadequate communication between engineering and external customers led to situations in which the customer could make changes anytime during the engineering process. This inevitably resulted in a lot of rework and an unpredictable process cycle time. Therefore it was necessary to establish a Frozen Zone to control the number of customer changes. The Frozen Zone set an end point where customers could not make further product changes.

On the other hand, it can be observed from **Figure 5.5**, that the process cycle time of the "compile mass production document" process is much longer than the takt time. This is because engineering could not start compiling the mass production document until they received the summary report of changes from the mock-up process. So the "compile" processing time is not long (less than one work day) based on the investigation, but the process cycle time shows a longer time period which averaged ten days. While waiting, engineers started working on other projects to offset their time loss. In this case, the countermeasure was to create a mock-up progress log which recorded the feedback from mock-up processes on a daily basis, so engineers could work on the engineering changes immediately instead of waiting for the final report. The processes of "check preproduction document" and "compile mass production document" could be eliminated because all the changes were completed in time and conducted in a steady pace in parallel with the mock-up process instead of on a sequential basis, which involved a lot of waiting. Also the same work log solution could be applied to the processes of "CNC" and "Packaging" which could reduce process cycle time by 30% (from 375 minutes to 263 minutes) and 20% (from 310 minutes to 248 minutes) respectively.

Countermeasures for "Insufficient engineering capacity":

According to the current state VSM, the "check" process runs out of capacity and it is hard to catch up with customer demand. Therefore, appropriate check methods and capacity planning are needed to deal with the bottleneck.

The proper check method helps to shorten the process cycle time. Usually, after completing the engineering documents, the engineer printed out all the drawings, bills of material, and specifications for the engineering supervisor or manager to review. Then these files were returned to engineers to make changes and print again for sign and distribution. This process involved waste and extended the engineering process cycle time. The online checking does not need to print every drawing or file and each engineer can work on corrections immediately as long as they receive the electronic files from supervisors or manager.

Furthermore, from **Figure 5.5**, check process had one operator (which was one of the two engineering supervisors). Due to not enough operators in this process, it could not keep pace with t customer demand therefore caused significant overtime. In order to meet to the takt time, in the future state, the check process involves all the engineering management in this process, which includes two engineering supervisors and one manager. Also there will be just one "check" process in the future state VSM. So the process cycle time of checking engineering documents would be reduced from 1776 minutes on average to 296 minutes, plus the effect of on-line review is supposed to reduce 10% of process cycle time to 266 minutes. In this way, the process cycle time of the check process is more close to the takt time. .

Countermeasures for "Inefficient work layout":

Currently, the engineering work layout is not well organized. Some engineers had to walk around to deliver material to the supervisor on the other side of the work area. The printer and plotter were far away forcing the engineers spend a portion of their day traveling back and forth to print out drawings. It is necessary to propose a work cell layout to enhance productivity so supervisors and engineers can physically work together and office supplies are easy to reach.

Countermeasures for "Inefficient engineering design tool":
The appropriate design tool can help prevent "drawing errors" and "part dimension errors" identified in previous study (chapter 4). Although SolidWorks cannot guarantee improvement on the speed of engineering design, it can help improve the quality of engineering design with less errors and flaws. The design features in SolidWorks are helpful in solving excessive engineering change orders (ECO) problems. For instance, SolidWorks can check the existing 3D model and find any interference (overlapped area of components in the assembly) in the current design to prevent potential design flaws in the drawing. This proactive solution can help reduce design changes. Additionally, SolidWorks can also automate bills of material (BOM) which needed manual entry before.

Table 5.10 is a summary of all the root causes, countermeasures, and kaizen events. According to the countermeasures, the future state VSM is generated suggesting target improvement areas and the potential improvement outcomes that could be achieved.

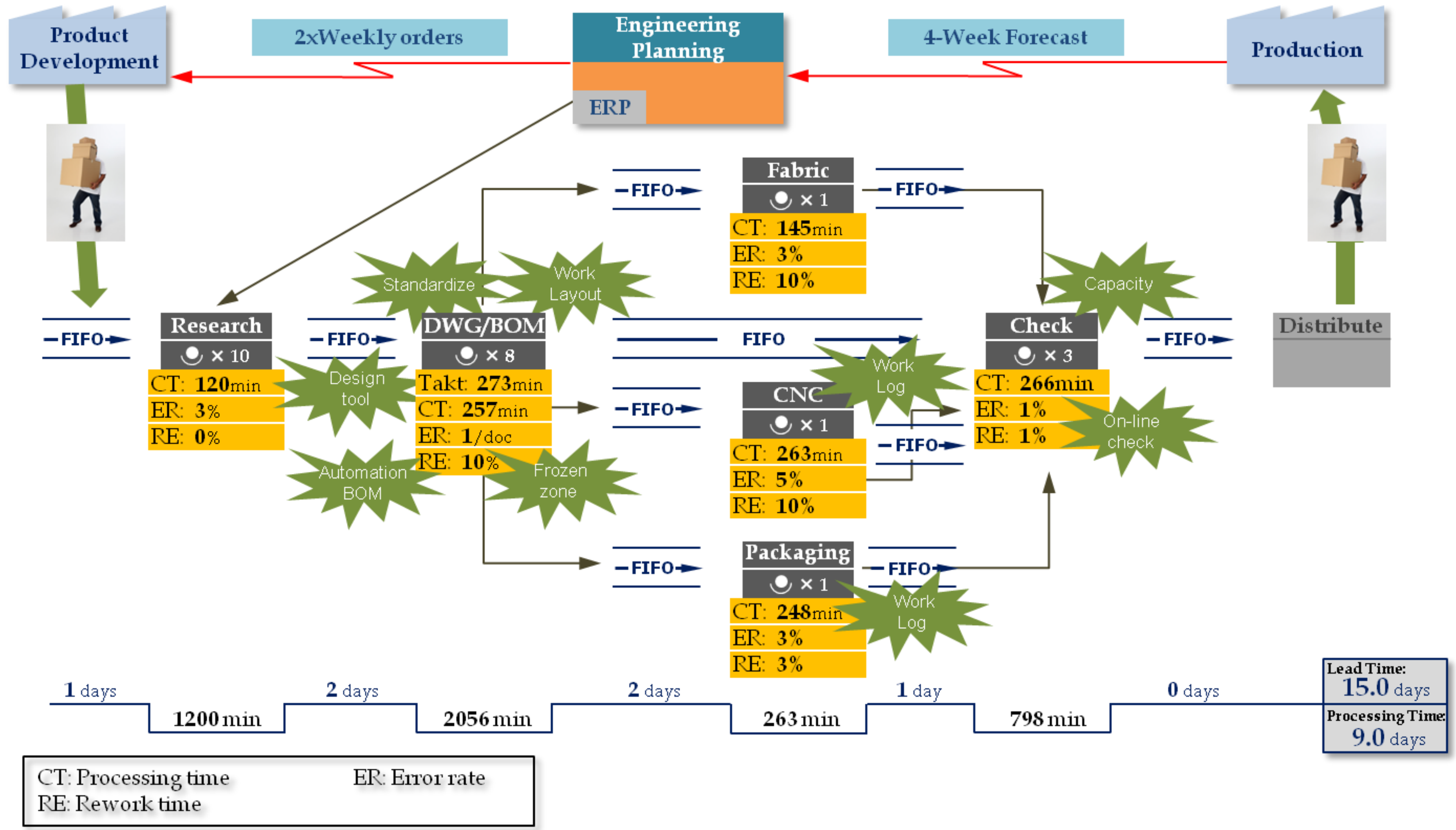


Figure 5.8 Future State Value Stream Mapping (VSM)

In the future state VSM (**Figure 5.8**), engineering planning sends work instruction to the first process step at the beginning of the value stream. The overall process is flowing in a First-In-First-Out basis. The starting point of the process is to send new orders to “research” process from Product Development. The FIFO lane will keep the order inventory in 1 day maximum. Then researched orders will pass on “DWG/BOM” process for creating drawings and bills of material in a 2-day FIFO maximum. Specific kaizen events aim to balance certain processes and improve engineering performance. For instance, the kaizen events proposed for “DWG/BOM” process include standardization, BOM automation, new design tool, frozen zone, and work layout planning. The downstream processes like “Fabric”, “CNC”, and “Packaging” will also receive jobs on FIFO basis. Finally, all the work will send to “check” process for final approval. The total lead time of future state VSM is 15.0 days, or an 88.8% reduction from the current state VSM. The processing time of future state VSM is 9.0 days, or a 74.1% reduction from the current state VSM.

Table 5.10 Summary of countermeasures and kaizen implementation

Root causes	**Countermeasures**	**Kaizen burst**
Lack of standardization	• Process standardization: combine and eliminate processes • Work standardization: separate and balance engineer work load	“Standardization”: Standardize design models, drawing formats
		“Automation BOM”: Writing special micro program in SolidWorks to automate the process of generating BOM
Inefficient communication	• Improve communication with customer • Improve communication with supplier	“Frozen zone”: Control the expediting changes from customer
		“Work log”: Summarize production feedback on daily basis for engineers. Increase the speed of making essential changes for mass production documents before releasing
Insufficient engineering capacity	• Improve work method • Increase people utilization	“Online-check”: The engineering management check the documents on-line to eliminate paper waste and unnecessary processing time
		“Capacity”: Utilize all the engineering supervisors and managers for checking process
Inefficient layout	• Reorganize work layout	“Layout”: Move necessary office supplies close to engineers; propose work cell layout for current work environment
Inefficient engineering design tool	• Use 3D dimension-driven engineering design solution – SolidWorks	“Design tool”: utilize SolidWorks to reduce the chance of making design errors and reduce the number of ECO

The following **Table 5.11** is a summary of what could be implemented and improved in the future state VSM compared to current state VSM:

Table 5.11 Metrics comparison – current state versus future state

	Process cycle time			Error rate			Rework time		
	Current state	Future state	Change	Current state	Future state	Change	Current state	Future state	Change
Research	120min	120min	0%	3%	3%	0%	0%	0%	0%
Drawing	764min	257min	66.4%	1.3/doc	1.0/doc	23%	20%	10%	50%
BOM	294min			2.0/doc			20%		
CNC	375min	263min	30%	5%	2%	60%	10%	5%	50%
Check (Preproduction)	1080min	-	-	2%	-	-	5%	-	-
Packaging	310min	248min	20%	5%	3%	40%	5%	3%	40%
Compile	605min	-	-	3%	-	-	5%	-	-
Check (Mass production)	696min	266min	61.8%	2%	1%	50%	3%	1%	66.7%
Fabric	145min	145min	0%	3%	3%	0%	10%	10%	0%

From **Table 5.10**, it can be observed that the proposed countermeasures will help to balance and level the process cycle time, and also reduce the error rate. This table would establish a dashboard of target performance metrics with which design engineers can gauge, monitor, and sustain their improvement progress toward the Future State Value Stream.

5.6 Conclusions:

The results indicate the current engineering process is inefficient. The processes of "Drawings", "Check", and "Compile" exhibited long processing cycle times. The current state process takes a lot of overtime to address expediting orders. Waiting, interruption, inefficient engineering system and uneven workload were typical problems resulting in long lead time for engineering

Insufficient engineering capacity is a major contributor resulting in the "Check" bottleneck. There is only one supervisor in charge of checking and signing-off all the engineering drawings and documents. However, the supervisor also needs to deal with other important tasks and it is difficult to guarantee the daily work time needed to check and sign-off engineering documents. Another bottleneck process, "Compile," also takes a large process cycle time. This is because sequential engineering involves a lot of time to fix design flaws and errors before releasing the final engineering documents.

Bottlenecks and large inventories also showed in secondary engineering processes such as "CNC" and "Packaging." Lack of people in the secondary processes also led to capacity shortage especially when overproduction happened in the upstream processes (primary processes), which made it even harder to pace the customer demand. Excessive inventory piled up between these processes.

In future state VSM, several fundamental countermeasures were proposed to balance and level the engineering process. Point kaizens, such as standardization and setting up frozen zone, helped significantly to reduce design iterations so that only one "Check" process was needed and "Compile" process could be eliminated. From the future state VSM, the lead time was reduced from 133.9 days to 14.7 days. The FIFO lane was used to make the overall processing time predictable. Standardization also helped group similar product structures which saved several engineering efforts in new product development. Also, cross training was an essential measurement implemented to buffer the unexpected demands.

From this case study, the current engineering process was shown exhibiting many types of waste such as different interruptions distracting engineering from creating value-added work. By using VSM, the process was streamlined by identifying the steps of the longest processing time and the largest inventory. Then the proposed countermeasures were used to flow the whole value stream. The results indicated the following conclusions to facilitate future research.

- Identifying the product family, customer demands, process boundary, main process and defining process metrics and calculation is essential prior research to depict accurate data on the current state VSM.

- In the current state VSM, the processes of creating drawing and bills of material, checking and signing-off, and compiling the mass production documents develop bottlenecks, and point kaizens are an effective means to streamline these individual processes for more balanced process cycle time.

- FIFO lanes are helpful for the overall engineering process flow and reduce lead time.

- An appropriate engineering design tool is important to facilitate engineering performance such as fast drawing delivery and reduced error rate. For instance, the design features in SolidWorks are helpful in solving the excessive engineering change orders (ECO) problem, by having predefined design models. Also, SolidWorks has the function to check existing 3D model to locate any interference (overlapped area of components in the assembly) in the current design, preventing potential flaws in the drawings. This proactive solution can greatly help reduce design errors.

However this research has some limitations. First, the research was based on a case study of one furniture manufacturer, although it was an ideal candidate for this research, there was still not sufficient evidence to generate sound results for the overall industry. Second, the respondents for collecting accurate processing time only included three product engineers. Although they were best associates available to generate meaningful data, it was still not sufficient to reflect the performance of the overall system. Third, the limited time frame restricted the research to be conducted within one month period. More accurate and exclusive conclusions could be made if there were enough time to address more of the monthly data. Fourth, it would be ideal to have several kaizen events be implemented based on this study in the case study company. However, the geographical constraints and limited research funding prevented the countermeasures from this research to be implemented and the results verified.

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Appendix A Questionnaire

Survey Questionnaire on Current Engineering Process

The survey is intended to collect information from each product engineer on their understanding of the current engineering process. The results will help us to better analyze and improve the existing engineering process. Personal information will not be revealed to any third party. Please feel free to give us your best knowledge of the current process. Thank you for your participation!

RESPONDENT INFORMATION

1. What Business Unit are you currently working at?

- ☐ Unit 1 (Plant 5 ☐ | Plant 7 ☐)
- ☐ Unit 2 (Plant 3 ☐ | Plant 6 ☐)
- ☐ Unit 3 (Plant 10 ☐ | Plant 11 ☐)
- ☐ Unit 4 (Plant 8 ☐ | Plant 9 ☐)

2. What is your position?

- ☐ Engineering manager
- ☐ Engineering supervisor
- ☐ Product engineer

Other position(s), please indicate: __________________

3. What is your current experience level in the engineering job?

- ☐ Entry level (less than 1 year)
- ☐ Junior (1 – 2 years)
- ☐ Mid level (3 – 5 years)
- ☐ Senior (6 years and more)

4. What kinds of the following tasks are you responsible for as an engineer in your business unit?

- ☐ Determine the product architecture
- ☐ Complete production documents (bills of materials, bills of hardware, detailed drawings)
- ☐ Making procurement material (drawings and specification) to suppliers
- ☐ Plot drawings for product profile verification in the manufacturing process
- ☐ Issue Engineering Change Orders, revised drawings based on customer requirements and production needs
- ☐ Production documents maintenance
- ☐ Check production documents
- ☐ Sign-off production documents
- ☐ CNC programming
- ☐ Product packaging engineering
- ☐ Create customer-confirmed component files for archive

Other responsibilities, please indicate: ____

5. How many engineers are there in your business unit? _____

6. Please check the products making by your engineering group:

- ☐ Bedroom
- ☐ Living room
- ☐ Kitchen
- ☐ Upholstery
- ☐ Dining room
- ☐

Other product collections, please indicate: __________________

ENGINEERING PERFORMANCE

7. How important are the following Key Performance Indicators (KPIs) on describing the current engineering performance? (1 = Unimportant; 2 = Of Little Importance; 3 = Moderately Important; 4 = Important; 5 = Very Important)

	Unimportant 1	2	Moderately Important 3	4	Very Important 5
Processing time (The accurate time spent on making production documents)	☐	☐	☐	☐	☐
Value-added time (The total sum of each processing time)	☐	☐	☐	☐	☐
Queue time (The time not spent on making production documents and the time suppose to spend on completing the documents wait in the queue. It is the non value-added time)	☐	☐	☐	☐	☐
Engineering error	☐	☐	☐	☐	☐
Lead Time (The sum of processing time and queue time)	☐	☐	☐	☐	☐
Number of people	☐	☐	☐	☐	☐
Overtime	☐	☐	☐	☐	☐
Changeover time (e.g. The time spent to change the paper in the printer; or the time to load another software from the current)	☐	☐	☐	☐	☐
Percent complete and accurate (the completion rate of accuracy of the first time delivering of documentations by deadline)	☐	☐	☐	☐	☐
Inventory (unfinished tasks in the queue)	☐	☐	☐	☐	☐
Hardware and software reliability	☐	☐	☐	☐	☐

Others, please indicate:____________________

8. How many production documents on average you made per month for your plant?

	1-2	3-4	5-6	7-8	9-10	More than 10
Preproduction	☐	☐	☐	☐	☐	☐
Production	☐	☐	☐	☐	☐	☐

9. How many customer have you served in the last six months?

# of Customer(s)	1-2	3-4	5-6	7-8	9-10	More than 11
	☐	☐	☐	☐	☐	☐

10. If you are a upholstery product engineer, please answer the question of 10-b;
If you are a solid wood product engineer, please answer the question of 10-a.

10-a. In a standard bedroom product collection, what are the average engineering hours for you to complete each of the following type of product:

Days	1-2	3-4	5-6	7-8	8-9	More than 10
Nightstand	☐	☐	☐	☐	☐	☐
Drawer Chest	☐	☐	☐	☐	☐	☐
Dresser and Mirror	☐	☐	☐	☐	☐	☐
Mirror	☐	☐	☐	☐	☐	☐
Armoire Hutch	☐	☐	☐	☐	☐	☐
Armoire Base	☐	☐	☐	☐	☐	☐
Bed	☐	☐	☐	☐	☐	☐

10-b. In a standard upholstery product collection, what are the average engineering hours for you to complete each of the following type of product:

Days	1-2	3-4	5-6	7-8	8-9	More than 10
Sofa	☐	☐	☐	☐	☐	☐
Loveseat	☐	☐	☐	☐	☐	☐
Chair	☐	☐	☐	☐	☐	☐
Ottoman	☐	☐	☐	☐	☐	☐
Tufted chair	☐	☐	☐	☐	☐	☐
Sleeper sofa	☐	☐	☐	☐	☐	☐
Sofa chair	☐	☐	☐	☐	☐	☐

11. What is the percentage of time on average you spend to issue the Engineering Change Orders per day?

- ☐ Below 20% per day, please indicate a specific range _____% - _____%
- ☐ 21%-40% per day
- ☐ 41%-60% per day
- ☐ 61%-80% per day
- ☐ Above 81% per day, please indicate a specific range _____% - _____%

12. What is on average of your engineering design ERROR rate caused by the following reasons in the production documents that you made?

Number of errors:	None	1-2	3-4	5-6	7-8	Above 8
Part dimension error	☐	☐	☐	☐	☐	☐
Wrong amount of assigned parts	☐	☐	☐	☐	☐	☐
Dimension missing	☐	☐	☐	☐	☐	☐
Wrong hardware applied	☐	☐	☐	☐	☐	☐
Wrong amounts of hardware	☐	☐	☐	☐	☐	☐
Hardware missing in BOM	☐	☐	☐	☐	☐	☐
Wrong hardware receiving dept.	☐	☐	☐	☐	☐	☐
Wrong material applied	☐	☐	☐	☐	☐	☐
Wrong architecture applied	☐	☐	☐	☐	☐	☐
Missing essential drawings	☐	☐	☐	☐	☐	☐
Drawing errors	☐	☐	☐	☐	☐	☐

13. Please indicate on a scale of 1 to 5 of the following factors (1 = Unimportant; 2 = Of Little Importance; 3 = Moderately Important; 4 = Important; 5 = Very Important) that you think would be important to affect the engineering hours and lead time?

	Unimportant 1	2	Moderately Important 3	4	Very Important 5
▸ Product architecture complexity	☐	☐	☐	☐	☐
▸ Development tool (e.g. AutoCAD vs. SolidWorks)	☐	☐	☐	☐	☐
▸ Engineering process (e.g. traditional vs. simultaneous engineering)	☐	☐	☐	☐	☐
▸ Engineering design specifications	☐	☐	☐	☐	☐
▸ Changes required by customers or manufacturing plants (e.g. time to modify and reissue drawings)	☐	☐	☐	☐	☐
▸ Cost consideration	☐	☐	☐	☐	☐
▸ Sample delivery speed from vendors	☐	☐	☐	☐	☐
▸ Engineers experience and competency	☐	☐	☐	☐	☐
▸ The research effort to ensure the quality	☐	☐	☐	☐	☐
▸ Communication and collaboration	☐	☐	☐	☐	☐

14. What percentage of time does Engineering take in the overall product delivery time (From the time of customer placing the order to the time of products are produced and ready for shipping)?

- ☐ Below 20% of the product lead time
- ☐ 21%-40% of the product lead time
- ☐ 41%-60% of the product lead time
- ☐ 61%-80% of the product lead time
- ☐ Above 81% product lead time

15. Has your engineering department ever used “Design for Manufacturing” methodologies to develop new products (such as Design For Assembly, Group Technology, modular design, drawing retrieval systems, parts commonality list, feature commonality list, etc.)

- ☐ Yes.
- ☐ No.

ENGINEERING TOOLS

16. What CAD software have you been used or using for product engineering?

- ☐ AutoCAD
- ☐ SolidWorks
- ☐ SurfCAM
- ☐ ChinaCAM
- ☐ Gerber
- ☐ Other CAD/CAM tools or applications, please indicate: __________________

17. Compared to AutoCAD, what benefits you agree of using SolidWorks for product engineering?

	Strongly Disagree 1	Somewhat Disagree 2	Don't Know 3	Somewhat Agree 4	Strongly Agree 5
Easy to make late design changes	☐	☐	☐	☐	☐
Shorten the engineering time	☐	☐	☐	☐	☐
Reduce the engineering error rate	☐	☐	☐	☐	☐
Improve readability of drawings	☐	☐	☐	☐	☐
Facilitate the auto generation of BOM	☐	☐	☐	☐	☐
Ease documentation maintenance	☐	☐	☐	☐	☐
Facilitate CAM	☐	☐	☐	☐	☐
Enhance team collaboration and CE	☐	☐	☐	☐	☐

LEAN CONCEPTS AND APPLICATIONS

18. To what degree are you familiar with the following lean concepts? (1 = No idea; 2 = Not familiar; 3 = Heard about it; 4 = Familiar; 5 = Very familiar)

Lean Tools and systems	No idea 1	2	Heard about it 3	4	Very familiar 5
Pull System	☐	☐	☐	☐	☐
Cellular Manufacturing	☐	☐	☐	☐	☐
One-piece-flow	☐	☐	☐	☐	☐
Standard work	☐	☐	☐	☐	☐
Visual control	☐	☐	☐	☐	☐
Kaizen	☐	☐	☐	☐	☐
Kanban system	☐	☐	☐	☐	☐
SMED/Quick changeover	☐	☐	☐	☐	☐
TPM	☐	☐	☐	☐	☐
5S	☐	☐	☐	☐	☐
FIFO	☐	☐	☐	☐	☐
Heijunka Box	☐	☐	☐	☐	☐
Value Stream Mapping	☐	☐	☐	☐	☐

Problem-solving	No idea 1	2	Heard about it 3	4	Very familiar 5
Cause-and-effect diagram (Fishbone)	☐	☐	☐	☐	☐
Five why's	☐	☐	☐	☐	☐
PDCA	☐	☐	☐	☐	☐
A3 Report	☐	☐	☐	☐	☐

Appendix B Permission to use **Figure 2.1**

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