A Framework for Process–Waste Mitigation in Off-site Construction during the Design Phase

by

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ABSTRACT

Despite accounting for a tiny percentage of total construction expenses, a wasteful design process is more likely to cause delays or errors, resulting in low productivity, budget overrun, undesirable outputs and wasting resources. This study aims to examine the design process through Lean principles to identify non-value-added activities or resources, evaluate different methods and propose solutions to eliminate or mitigate them. Value stream mapping is used in addition to statistical analysis to map the process to identify the challenges and waste areas. A framework is developed to help evaluate processes and increase efficiency during the design phases in offsite construction and built-to-order companies, thereby reducing the cost and duration of the project. Moreover, simulation is used to assess the recommended interventions. The simulation shows the estimated improvements resulting from implementing the suggested interventions, as an expected improvement of 47.3% reduction in design lead time with a utilization ratio of 13.7%. The framework is generic and applicable to all construction industry aspects. The innovation of this framework resides in the precise procedures and direction offered to improve these phases utilizing Lean tools.

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Chapter 1: Introduction

1.1. Motivation

As design significantly impacts a construction project's success due to its influence on various project factors, it lies at the heart of numerous enduring construction problems. Hasty designs, non-standardized design processes, and poor design management practices affect all project stages, from customer approval to maintenance, leading to overbudget spending or delays. Improving the design process to achieve a more desirable outcome is one way to avoid these challenges.

Design is a method of problem-solving. The customer's requirements and desires turn into a physical form using precise processes and technical specifications during the design phase. When a project's environment is complicated and the values of its players are diverse, it might be challenging to define a problem. Thus, reducing non-value-adding operations and increasing efficiency to enhance the design process increases the likelihood of achieving better results. Efficiency is using the fewest resources necessary to complete a task (Wandahl et al., 2021), and Lean thinking aims for it by reducing the waste of resources and improving flow (Koskela, 2000). In recent decades, the Architectural, Engineering and Construction (AEC) industry has tried to improve performance by implementing new techniques such as off-site construction and Lean tools such as Value stream mapping, Just in Time and Last Planner in construction projects.

Off-site construction refers to planning, designing, producing, delivering and installing building components for a construction project that occurs in off-site facilities, often stationed far from the worksite (Zaheraldeen et al., 2019). While many building components are produced in bulk (built to stock), other essential components are built to order in fabrication shops (Ballard &

Arbulu, 2004). Build-to-order is a manufacturing method in which things are not manufactured until a confirmed order is received. In this method, the end user determines the time and number of items produced. Along with its benefits, such as shorter construction times, less waste, better quality, cost-efficient, flexibility and increased safety, it also has some limitations and challenges (Hussein et al., 2021), such as delayed design information receipt, frequent design revisions, altered installation timing and sequence, and demand variability (Ballard & Arbulu, 2004), and hasty design work (Pasquire & Connolly, 2003).

Several studies aim to enhance the design process in the AEC industry. While these researches generally seek to integrate design with modern technology such as BIM to increase efficiency, there are few studies on the application of mitigating waste in the design process, particularly in midsize and small-size built-to-order plants for off-site construction. Consequently, this study aims to evaluate the design process to identify waste and suggest enhancements to the administrative scope of the design process, which is generally neglected. Defining a framework to standardize identifying and mitigating waste would help organizations improve their productivity and save on cost and time. This framework will address off-site construction and built-to-order production challenges, such as low utilization process, long design lead time and negative iterations.

1.2. Research Objectives

This research proposes a framework to evaluate and analyze waste in the design process. Based on the motivation and research gap, the main objectives to be determined through the research process are:

- Identify waste in the design process in the build-to-order off-site manufacturing.
- Develop a framework to evaluate different methods to mitigate and eliminate waste.

1.3. Thesis organization

The research is organized into six chapters. Chapter 1 introduces the research motivation and objectives of this study. Chapter 2 reviews Lean design, waste, and value stream mapping-related definitions and studies. Chapter 3 is dedicated to the methodology. This chapter presents the proposed framework and the research steps necessary to implement the framework's interventions. Chapter 4 introduces the case study and data collected during the research procedure. Chapter 5 uses value stream mapping and simulation to map the current situation. In Chapter five, the suggested interventions and their improvement are evaluated. Chapter 6 concludes with a discussion of the findings and results of the research.

Chapter 2: Literature Review

2.1. Overview

In this chapter, the literature regarding the proposed topic is discussed. The primary purpose of this chapter is to gain more knowledge and information about the design process as well as Lean design and Lean thinking. The main topics to cover in this chapter are the following parts:

Lean design: focuses on design management and its challenges, as well as what the results of previous studies show about using Lean thinking in design.

Waste: The nature of non-value-added activities and resources in construction and the design process is primarily discussed. This section also includes previous studies on waste and non-value-added items.

Value stream mapping: The literature on using value stream mapping as a Lean tool in manufacturing and construction is reviewed in this section.

2.2. Definitions

2.2.1. Lean design management

Lean Design Management is a term used to describe the management of design processes in the Lean approach (Uusitalo et al., 2017; Kalsaas et al., 2020). Lean design views the design process as an information-to-value conversion. It is due to the customer's involvement in every process step (Tzortzopoulos, 2020). Customers' needs are met via the design process, which entails gathering customer requirements, converting them into design solutions, and manufacturing the items following the design specifications, which means creating value (Tzortzopoulos, 2004).

Finding and capturing client requirements and translating product specifications into value creation are the most important lessons learned, according to Ballard and Koskela (1998). The Lean design aims to help companies meet their customers' needs, interact with customers and translate their requirements into completed goods and services. The value creation process of meeting customers' expectations happens through information collection and conversion cycles that result in the delivery of a product or service (Koskela, 2000).

2.2.2. Waste

Any non-value-added activity or resource that adds no value to the product is considered waste (Liker, 2004). Several sorts of waste have been assessed, demonstrating that waste is interpreted in various ways. In 1988, Ohno suggested the Seven Wastes of production (Ohno, 1988; Formoso et al., 2020). Figure 1 shows seven wastes proposed by Ohno (1988).

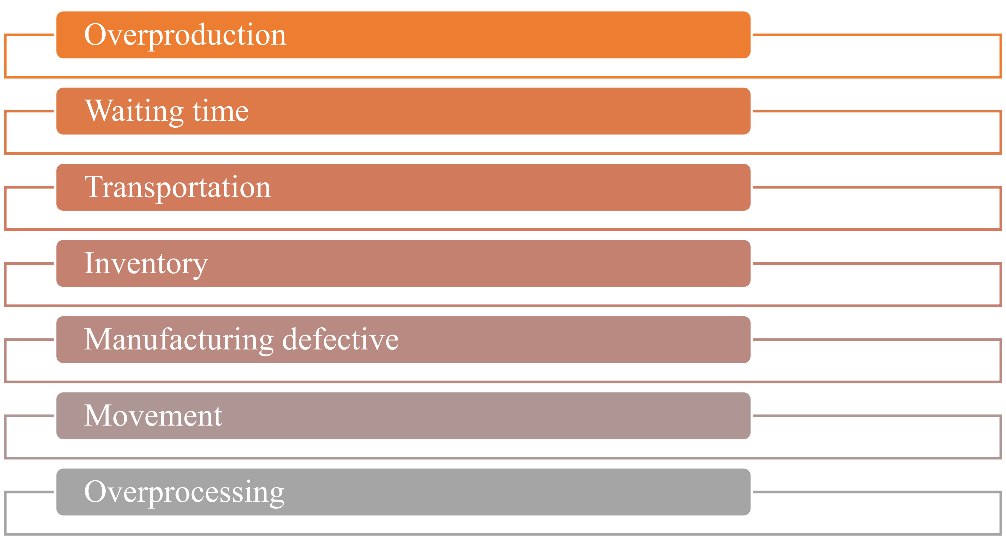


Figure 1. Seven types of waste, adjusted from Ohno (1988).

Ohno (1998) defined each type as followings.

- Overproduction Means making too much of something or making it before it is needed. In the manufacturing stage, it is a unit or material which could be overproduced; in the design stage, it is information. It is inefficient to produce more than is required or too quickly. It is for this reason that manufacturing must adhere to Takt time. It consumes resources like materials, personnel, and storage more rapidly than is required, resulting in various types of waste.

- Waiting time: Waiting in whatever form is a waste of time. Waiting might be for anything as simple as a response to a query or for something more complex. The process is halted as there is much idle time. It does not contribute anything to the operation or service, and customers will not pay for it. When it comes to wasting time, waiting is the most obvious source.
- Transportation: Transporting anything (resource, material, people, information) further than required, relocating and stocking wastes time and energy.
- Over-processing: lack of creating value or something the consumer desire and circulates in repetitive activities results in waste. Over-processing may result in wasteful actions such as rework and reprocessing or, in design, revisions which can be costly.
- Inventory: Anything that sits on a shelf is a waste of both time and money. Extra inventory requires more space and might become obsolete as the demands of the firm change. Unused records, extra supplies, and duplicate copies are examples of inventory waste. There is more to keep track of as a consequence of having more supplies or more to move if looking for anything, which is a waste of movement too.
- Movement: Any movement not required to complete a task is considered waste. All movement should provide value to the work unit or service of the client. Workplace practices and layouts might contribute to excessive walking, reaching, and bending.
- Manufacturing defectives: creating faulty output that must be reproduced is waste. Anything that has to be rebuilt or redone is a waste of resources. Lost productivity as a consequence of halting a regular activity to rectify defects or rework is also included in this waste. This type

of waste is the simplest to measure and identify. The term Yield refers to this type of waste and shows the number of defect-free outputs.

Ohno created this classification to aid the Toyota Production System in its mission to increase productivity in the production process. Ohno also states that overproduction must be regarded as the most important waste as it is a primary source of others (Bølviken and Koskela, 2016).

Three categories of activities are carried out in manufacturing to indicate a possible waste: non-value-adding operations, required but non-value-adding processes, and value-adding procedures (Berndt et al., 2016; Monden,2012). Figure 2 shows categories of activities from a waste perspective.

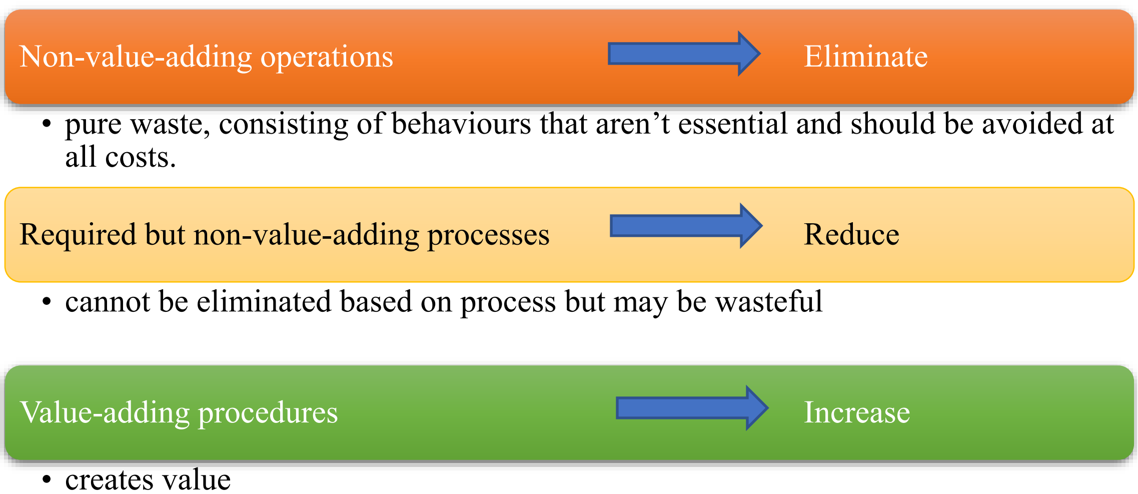


Figure 2. Categories of activities in manufacturing from a waste perspective

The first is sheer waste, consisting of behaviours that are not essential and should be avoided at all costs. The second form of activity is necessary but may be wasteful. The third category includes activities that create value by transforming raw materials into finished goods (Berndt et al., 2016; Monden, 2012).

2.2.3. Value stream mapping

A value stream refers to the flow of information and resources that results in consumers' value (Tapping & Shuker, 2003). Figure 3 shows the value stream outline.

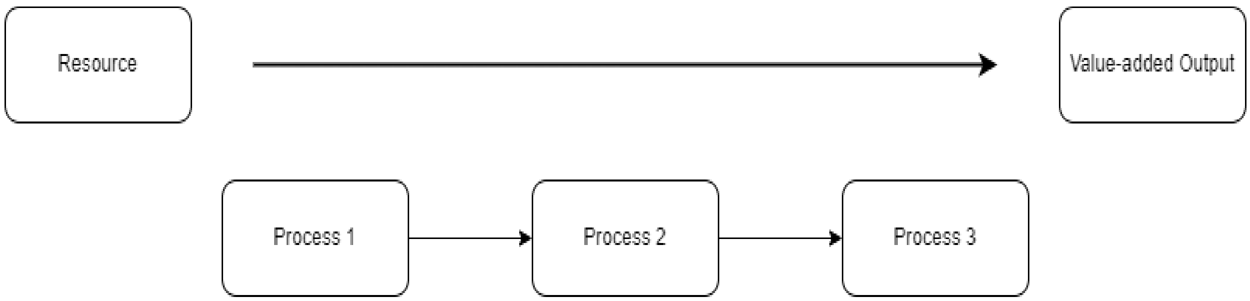


Figure 3. Value stream outline adjusted from Tapping & Shuker,2003

Value stream mapping (VSM) is a technique for presenting and evaluating a manufacturing process as a continuous flow of goods downstream and contributing value to them (Langstrand, 2016). VSM is a method for planning and connecting Lean efforts by collecting and analyzing data in a systematic way (Tapping & Shuker,2003). VSM is a helpful foundation for understanding how activities and operations are interrelated and create a basis for analyzing the process (Langstrand, 2016).

It is important to note that the value stream comprises all activities that contribute to creating a product or service and any other operations that result in waste. Operations, material movement, all control and steering operations, and information flow are all included in this (Forno, 2014; Berndt, 2016). In other words, VSM includes (Tapping & Shuker, 1999):

- All activities, including value-added and waste ones
- The stakeholders' communication through the process
- The interconnected system of activities and processes circulates materials and information through.

VSM is an idealized Lean production approach for improving material and information flows from product production through customer delivery (Berndt et al., 2016).

Hand-drawn maps of the existing and future states allow for identifying production bottlenecks and wastes, allowing production optimization. VSM is an excellent tool for gaining a comprehensive picture of production circumstances (Rother & Shook, 1999; Berndt et al., 2016). The manufacturing and delivery processes are optimized by applying value stream maps from a customer's perspective (Rother & Shook,1999). Also, to demonstrate results in less time and at lower costs, VSM is viewed as an essential technique.

The four phases of the classic VSM approach are as Figure 4 (Chen & Cox, 2012; Martin & Osterling, 2013; Rosenbaum et al., 2014; Abdelghani, 2021).

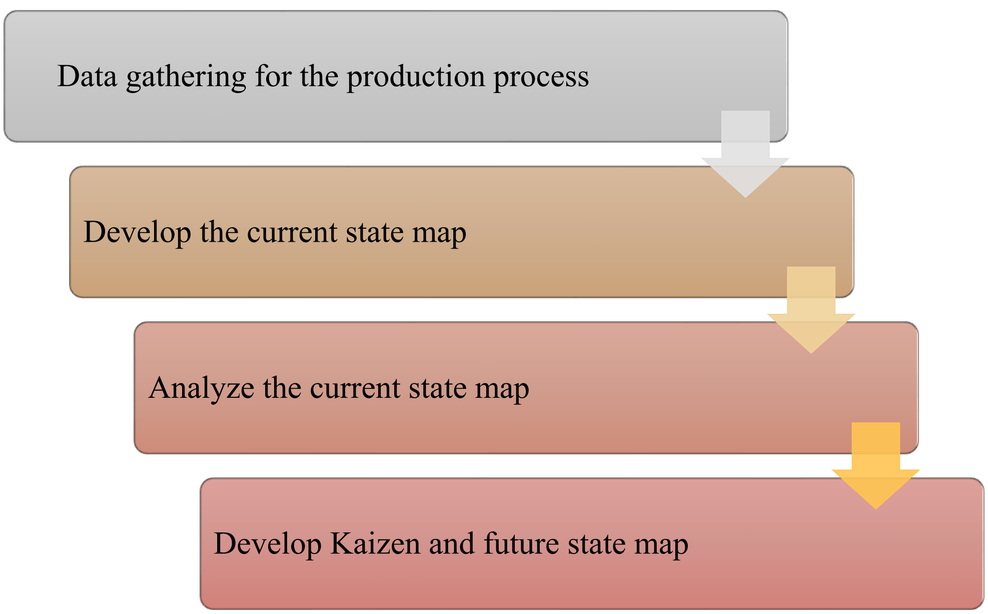


Figure 4. Main steps of the value stream mapping, adjusted from Chen & Cox, 2012

In 1999, Rother and Shook recommended choosing a product family first as there is no need to map everything according to their conclusion. They advised beginning with a customer-end selection from the product family and working rearward to upstream. They mentioned that this provides a better link between the chosen product and the customers.

Data gathering for the production process aims to know the process. Data on the process and the linkages among activities is gathered to understand the current process. Examples include inventory type and size, cycle time, change-over-time, equipment or process uptime and downtime, number of employees, shifts worked, available working hours and batch size. Data may be obtained through shop floor inspection, interviews, records, and information management systems. Following the observation and understanding of the process, mapping provides a clear image of the wastes that obstruct flow. The goal is to use a collection of symbols to depict the flow of work units and information. A value stream map is a vital tool for visually controlling process improvements since it provides a visual depiction of material and information flow for a specific value stream (Tapping & Shuker, 2003).

Although there is no global standard for value stream mapping, certain regularly used symbols might be helpful when learning the process (Langstrand, 2016). Figure 5 shows these elements.

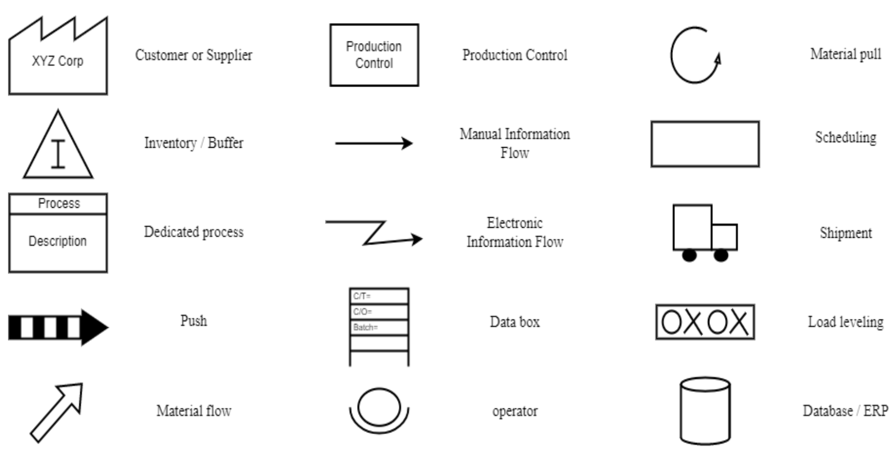


Figure 5. General template elements in VSM.

There are many ways to develop a current state map. The following examples are how to create a current state map for VSM. Rother and Shook (1999) suggested six main steps draw the current state map starting from drawing the customer and adding its related data and then adding more information to VSM at every step. Figure 6 shows the step suggested by Rother and Shook (1999).

Figure 6. Development of current state map for VSM adjusted from Rother and Shook (1999).

Tapping and Shuker (2003) suggested six steps to draw the current state map, similar to Rother and Shook (1998), starting with the customer and suppliers. Langstrand (2016) suggested another method to draw the current state map with four steps. Like others, he started with an outline but was more general. Figure 7 shows the method suggested by Tapping and Shuker, and Figure 8 shows the method suggested by Langstrand.

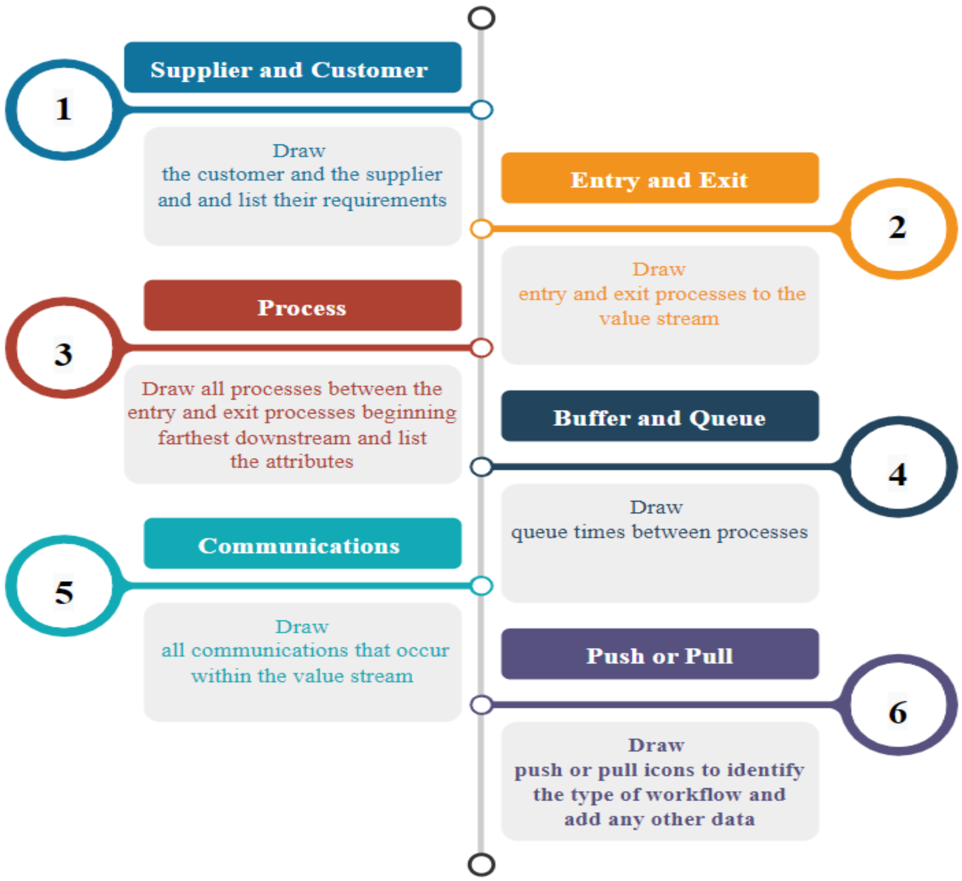


Figure 7. Development of current state map for VSM adjusted from Tapping and Shuker (2003)

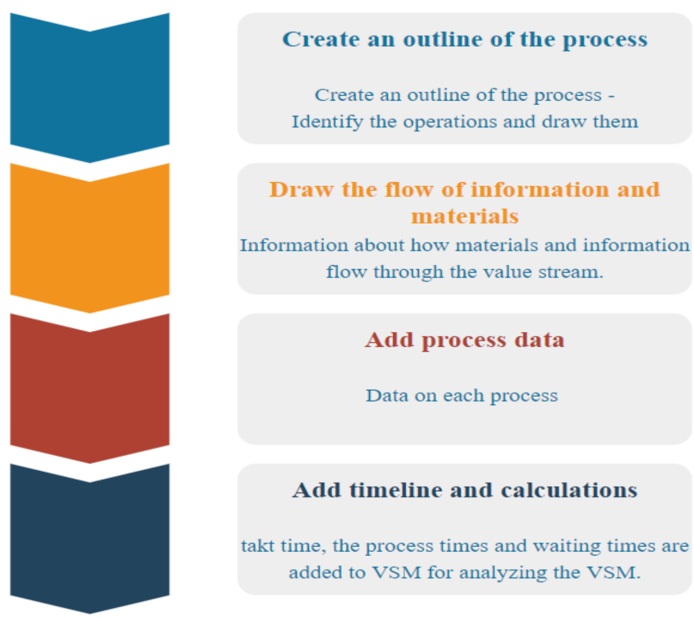


Figure 8. Development of current state map for VSM adjusted from Langstrand (2016)

The best way to comprehend the challenges is to analyze the current state map. Several parameters are to consider to analyze and understand the present situation: Analyze process capacity, identify bottlenecks, compare capacity and customer demand, flexibility and batch size, and look for waste.

The primary goal of VSM is to locate the sources of waste and remove them by putting in place a future state value stream that may quickly become a reality (Rother & Shook, 1999). Building a continuous flow or pull system is intended to create what is required when needed and precisely the required amount (Tapping & Shuker, 2003). Researchers made some suggestions to help map the future state value stream. They are mainly focusing on creating a continuous flow and balancing the process. Langstrand (2016) considered continuous flow, rebalancing, changing batch size, levelling out, reducing change over time and improving quality as the main points for improvements in the future state map. Tapping and Shuker (2003) also suggested continuous flow, control workflow, line balancing, implementing standardized work and determining the layout of the work area as the main targets in future state maps.

2.3. Background

2.3.1. Lean design management

In the 1990s, by emerging new concepts such as globalization, the manufacturing industry started researching how to respond to customer needs. The New Product Development Process (NPDP), born in those transformation environments, tackles challenges between complex design and production difficulties. The NPDP is a series of techniques and activities used by a company to create, design, produce, and market a product (Yin & Zhang, 2021; Ulrich, 2015). For example, the development process of engineered goods involves product planning, the creation of a concept, detailed design, manufacturing, testing and improvement (Yin, 2014). NPDP architecture is heavily impacted by various variables, including technological maturity, management strategies, corporate objectives and policies, culture and attitudes. NPDP has developed over time due to these factors (Yin & Zhang, 2021).

Tzortzopoulos (2004) describes the product development process in the built environment as the collection of actions required for the conception and design of a constructed product, from identifying a market opportunity to its delivery to the customer. It includes design management, design development, design-related activities that take place throughout production, and post-occupancy assessments.

In the product development process, design management focuses on organizing the design team and gaining knowledge of the team's nature, phases, and activities to enhance communication, coordination, and the seamless integration of information flow paths. According to the Design Management Institute (DMI), design management comprises the processes, choices, and strategies that allow the development and innovation of goods and services that bring organizational success and enhance the quality of life (DMI, 2019). It seeks to give techniques and approaches to design, including decision-making, regulating processes, assuring profitability and keeping costs within the intended range (Cooper et al., 2011). The customer's thoughts and guesses are conceptualized into a physical model by describing his demands and requirements in processes, drawings, and technical specifications throughout the design phase (Freire and Alarcon, 2002).

A primary goal of design is to convey as much information as possible about the intended product so that it can be produced or made (Gero, 1990). The other goal is to improve the design process, generating chances for producing high-quality, creative products via effective procedures (Tzortzopoulos and Cooper, 2007).

It is common to hear about design mistakes and failures (Koskela et al., 2018). Poor designs, design processes, and design management practices are at the root of many long-standing production and construction issues (Knotten, 2017; Biotto, 2019; Pikas et al., 2020). During the construction and maintenance of buildings, design errors have been the leading cause of structural failures, time and expense overruns, and catastrophic accidents (Chapman, 1998; Love & Li, 2000; Love et al., 2008; Pikas et al., 2020). When a project's environment is complicated and the values of its players are diverse, it might be challenging to define a problem. To some extent, the design problem determines how it will be handled throughout the development process. The term "wicked problem" (Whelton & Ballard, 2002) has been used to characterize design issues. There is no one-size-fits-all answer to a wicked problem; recognizing the problem and developing a solution requires a series of cycles of comprehension and formulation. (Buchanan, 1992; Whelton & Ballard, 2002). Thus, the information gathered to comprehend the possible solutions influence the problem. Problem resolution is constrained by a lack of time and resources since there is no single correct answer. An organized approach is required to identify problems and build the most effective solution to meet numerous viewpoints, design criteria, and project requirements (Buchanan, 1992; Coyne, 2005). Rework and non-value-adding activities during the design process can reduce the time it takes to improve the design, in addition to causing delays (Mryyian & Tzortzopoulos, 2013; Svalestuenet al., 2014).

Managing the design process is complicated by several elements, including iterations, the development of a project over time, learning, mutual interdependencies, and the involvement of many consulting companies as well as the client and construction firms and their subcontractors (Kaplan & Moum, 2016; Kalsaas et al., 2020). Poor communication and coordination among stakeholders and a lack of shared understanding among them may pose numerous challenges to the project in this environment (Koskela et al., 1997; Tzortzopoulos & Formoso, 1999; Whelton & Ballard, 2002; Tillmann et al., 2013; Gomes et al., 2016; Schöttle & Tillmann, 2018; Gomes & Tzortzopoulos, 2018).

The most crucial possibility for improving the design is adhering to correct management practices and providing an atmosphere where employees may learn from errors (Lopez et al., 2010). Poor design and design management methods, according to Kannengiesser and Gero (2009), are the outcome of a lack of a consistent underlying idea. In other words, improving building design and design management procedures necessitates a clear understanding of such activities (Kannengiesser & Gero, 2009). With the existing unstructured design management techniques, the likelihood of mistakes and disagreement increases when various teams employ diverse design approaches and lack norms for cooperation (Tauriainen et al., 2016).

There is a tendency for design managers to concentrate more on managing projects, tasks, resources and contracts than they do on the management of people, manufacturing processes and the environment (Howell et al., 2010; Koskela et al., 2002; Pikas et al., 2015). As a result, deliverables management has become disconnected and contradictory; deliverables management primarily focuses on creating models and drawings while needs, requirements and alternatives are inadequately stated and investigated (Pikas et al., 2017). Fragmentation contributes to a lack of coordination, excessive unpredictability, and poor communication in building projects (Ballard & Koskela, 1998; Kagioglou et al., 2000; Whelton & Ballard, 2002). For example, the briefing phase is carried out by a team separate from the production team responsible for delivering a project that meets predetermined design standards.

Lack of planning and control to decrease complexity and ambiguity, and to guarantee that the information flow is appropriate and consistent to support design decisions, is a critical problem in design management. Ballard and Koskela (1998) claim that the absence of clear deliverables in the early phases of design makes it difficult to estimate the quantity of work done and left. According to Whelton and Ballard (2002), poor processing requirements are a challenge that can lead to difficulties in identifying customers' needs and translating them into requirements and product specifications. Other researchers viewed design as a challenge because it requires considering and balancing the needs and goals of multiple stakeholders, which are frequently at odds (Ballard & Koskela, 1998; Tillmann et al., 2013).

Managers, on the other side, believe that excessively extensive design plans would limit innovative thinking (Khan, 2016). Design planning and control are still disregarded in construction, resulting in chaos and broad improvisation to handle design difficulties. Many design difficulties stem from failing to consider the interdependencies and priority connections among the different design activities.

Tzortzopoulos et al. (2020) categorized the design management challenges into three main categories: collaboration and shared understanding, requirements and value and process. Poor communication and coordination between stakeholders (Tzortzopoulos and Formoso, 1999; Whelton and Ballard, 2002), poor collaboration and lack of integration between design teams (Whelton and Ballard, 2002), and lack of shared understanding (Gomes and Tzortzopoulos, 2018; Tillmann et al., 2013) are the challenges facing design management concerning collaboration and shared knowledge. Inadequate requirement processing (Whelton and Ballard, 2002), difficulties in identifying or translating the client's need to value (Pikaset al., 2017; Whelton and Ballard, 2002), and insufficient time or effort to identify the values (Lima et al., 2009) were also cited as challenges and issues facing the design management when considering value. The last category mentioned by Tzortzopoulos et al. (2020) is the process. Design errors and rework (Svalestuenet al., 2014;

Mryyian and Tzortzopoulos, 2013; Tzortzopoulos and Formoso, 1999; Ballard and Koskela, 1998), lack knowledge about waste in design and its roots (Mryyian and Tzortzopoulos, 2013; Tzortzopoulos and Formoso, 1999; Ballard and Koskela, 1998), non-value-adding activities during the design process, causing delays and reducing the time to improve (Ballard and Koskela, 1998), missing information (Tzortzopoulos and Formoso, 1999), and poor adaptation of design flows (Tauriainen et al., 2016) are the challenges based on the design process.

In recognition of its critical role in delivering value to consumers, Lean Construction research has advocated adopting various methodologies to enhance the design. Value is produced as a possibility in design, embodied in manufacturing, and realized in the intended usage by the customer in the design-to-production cycle (Koskela et al., 2013; Kalsaas et al., 2020). As part of the Lean methodology, the design process is evaluated as a production unit (Ballard & Koskela, 1998). As a result, three perspectives are considered in Koskela's Transformation-Flow-Value (TFV) theory: 1) transformation, the process of taking product specifications and turning them into a final design; 2) flow, the exchange of information and data between the design process and its stakeholders; and 3) value generation, creating new value by meeting the needs of existing or potential consumers. According to Koskela, in 2000, Lean design management had three distinct roles. Based on TFV theory, there are three system stages: design, operation, and improvement (Koskela, 2000).

The design system has established principles, techniques, and technologies to enable and support these functions. A set-based design approach, organized work, and the reduction of negative iterations all assist in easing design processes, as do cross-functional teams, the Last Planner System (LPS), and associated technologies (Ballard & Koskela, 2009; Ballard et al., 2002; Pikas et al., 2020).

Planning, designing system activities, and modifying management operations are part of the system operation. Iteration management has been simplified using tools like the design structure matrix, collaborative planning, and other techniques (Ballard & Koskela, 2009). In design system improvement, the process focuses on acquiring contextual data to enhance design system conception and operation at various phases of project delivery and in the final design stage (Ballard & Koskela, 2009; Pikas et al., 2020).

Kalsaas et al., 2020, studied continuous improvement in the design phase. Their research examined the approach to managing the detailed design to find project lessons. The study was adopted from the Lean design management and design theory related to design as a phenomenon, including interdependencies and iteration.

Pikas and Koskela (2020) conducted a case study to demonstrate how new conceptions of design activity and Lean design management may be used to enhance design practices. Their process began with identifying issues connected to design and project management. Two rounds of interventions were then devised, deployed, and assessed. According to the methodologies and practices used by the company under investigation, it had chosen a transformational approach to design conception. In addition, it was noticed that the organization viewed design as a purely technical endeavour. These decisions may lead to self-inflicted issues and are underlying causes. Introducing techniques and practices consistent with the flow and value perspectives was intended to correct shortcomings in the choice of production theory. According to the methods and procedures utilized in their research, adopting an inadequate view of production appears to be one of the primary causes of poor performance. Flow and value perspectives on production were ignored. In all cases, the organization’s issues stemmed from a lack of leadership. Methodologies and practices are developed based on the flow, value viewpoints, and transformational perspective.

Social elements were proposed to oppose the purely technical understanding of design. Building design and management practices have significantly improved as a direct consequence of theory-driven interventions. Ko and Kuo (2019) studied Lean thinking in formwork design to improve design accuracy and decrease waste. A Lean formwork engineering design approach was devised, and to check for remedy design mistakes, the concept of design correctness was introduced early on in the design process. As a result, a conducive learning atmosphere was created inside the company. Their result indicates that the proposed technique may save time and money by reducing the amount of unnecessary personnel and operating time.

2.3.2. Waste in design

Based on the concept of process as a flow, Koskela (1992) proposed two methods for increasing efficiency, increasing individual activity efficiency (e.g., working harder or faster) and reducing the fraction of non-value-adding activities (Koskela, 1992; Formoso et al., 2020). The second choice is wiser (Formoso et al., 2020) since it provides more substantial benefits than the first because the potential benefits are more significant, and the amount of labour work necessary to achieve value may be reduced (Formoso et al., 2020). A resource that does not serve the customer's needs is non-value-add (Koskela, 1992). Koskela et al. (2013) have broadened the definition of waste to include non-value-adding activities and undesirable production outputs.

Waste could be spreading through the process. As manufacturing can be considered a chain of discrete events, it is anticipated to have a chain of waste through manufacturing. (Koskela et al., 2013) As a result, not only is it necessary to identify waste to remove the source of waste, but it is also necessary to break the waste chain. This form of waste, which has the potential to start a waste chain, is referred to as primary waste by some researchers. In contrast, other types of waste are referred to as secondary waste by others (Formoso et al., 2020).

The phrases "core" and "lead waste" were invented by Koskela et al. (2013). A core waste is a waste that also produces more waste. Additional waste could be removed as a consequence of removing a core waste. Lead waste is a significant core waste because of its negative influence on output (Koskela et al., 2013). Figure 9 shows these two types of waste.

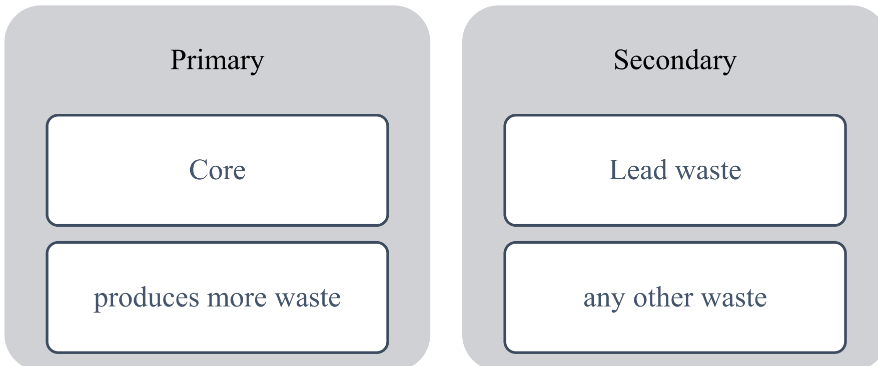


Figure 9. Types of waste adjusted from Koskela et al., 2013

Construction is an example of project-based production, a kind of manufacturing in which a temporary and unique organization develops a unique object. This procedure may be seen as a distinct process that takes place before the actual manufacture of a product. The AEC section is often believed to be riddled with waste. Despite the difficulty of rigorously measuring all sorts of waste, many studies have shown that waste accounts for a significant portion of building expenditures (Formoso et al., 2020). Waste reduction has been a substantial motivator for progress in Lean-adopted organizations.

Although Ohno's initial list of seven wastes is still widely used, many new wastes have also been suggested by other researchers, notably as a consequence of applying the concept of waste to production processes that are not exclusive to the manufacturing industry (Bølviken and Koskela, 2016). Besides Ohno's classification of waste, other types of waste also proposed by researchers include things like poor working conditions (Koskela, 2000), poorly designed goods (Womack and Jones, 1996), irrational expenditures of capital (Monden, 1983), and theft and vandalism

(Bossink and Brouwers, 1998). Formoso et al. (1999) categorized waste based on its origin, for example, the stage at which the primary root cause is most strongly linked. They suggested that overproduction, substitution, waiting time, Transportation, Processing, Inventories, Movement, and production of defective products be considered waste. They also regarded burglary, vandalism, severe weather, and accidents as waste.

Waste measurement often identifies areas of possible improvement and the root reasons for inefficiency (Ohno, 1988; Formoso et al., 2020). Waste metrics like material waste and non-value-added time (Formoso et al., 2020) are better at helping design management than traditional financial measures because they make it easier to find operational problems and give the workforce more valuable information. Figure 10 represents some of the measurements used to assess the amount of waste.

#	Measures to monitor waste	Researcher
1	Rework	Hwang et al., 2009; Love &Edwards, 2004; Zhao et al., 2010
2	Excess Material Consumption	Formoso et al., 2002
3	Production Defects	Josephson & Hammarlund, 1999
4	Unproductive Time	Horman & Kenley, 2005
5	Indirect Work	Kalsaas et al., 2014
6	Work-In-Progress	Yu et al., 2009
7	Costs	Burati et al., 1992; Ledbetter, 1994
7	Non-Value-Added Time	Forsberg & Saukkoriipi, 2007; Horman & Kenley, 2005 Kalsaas, 2010; Yu et al., 2009; Formoso et al., 2020

Figure 10. Measures to monitor waste in construction adjusted from Koskela et al., 2013

Even though waste is often recognized after production, it may be caused by activities before manufacturing, such as material manufacturing and human resource training before design, procurement, and planning. (Formoso et al., 1999)

A construction project also refers to the whole project, including design and manufacturing. Although a small percentage of construction expenses (generally 10–15%) are devoted to designing costs (Koskela et al., 2013), a fault in design could end up waste or non-value-added in construction, creating a chain of waste. In construction, the one-of-a-kind nature of both the process and the product establishes a tangled relationship between design and production where we can see design as intrinsically present in production (Koskela et al., 2013)

In product design and manufacturing, the design is completed before production. Despite this, in construction, the design is done partially before and partially in parallel with production (Bølviken et al., 2010). So, design is both a production and a creative process to create potential value. Therefore, waste and value loss are expected to be relevant to design (Koskela et al., 2013). Whenever it is not feasible to deliver all of the value that has been promised, value is lost.

The link between design errors and waste is a concern in the design process. "Any activity" drains resources but provides no value is what Womack and Jones (1996) characterize as waste in design. Time is a valuable waste indicator, particularly when determining the proportion of non-value-adding tasks. Additionally, delays, waiting, design flaws, excessive processing, and negative iteration all contribute to waste in designing (Ballard, 2000; Tzortzopoulos et al., 2020). The effect of these wastes on building projects is enormous. Design errors are the primary contributors to cost and value loss (Tzortzopoulos et al., 2020). Avoiding waste in the design process demands a focus on managing and eliminating design errors. Figure 11 shows the waste in design suggested by Ballard (2000).

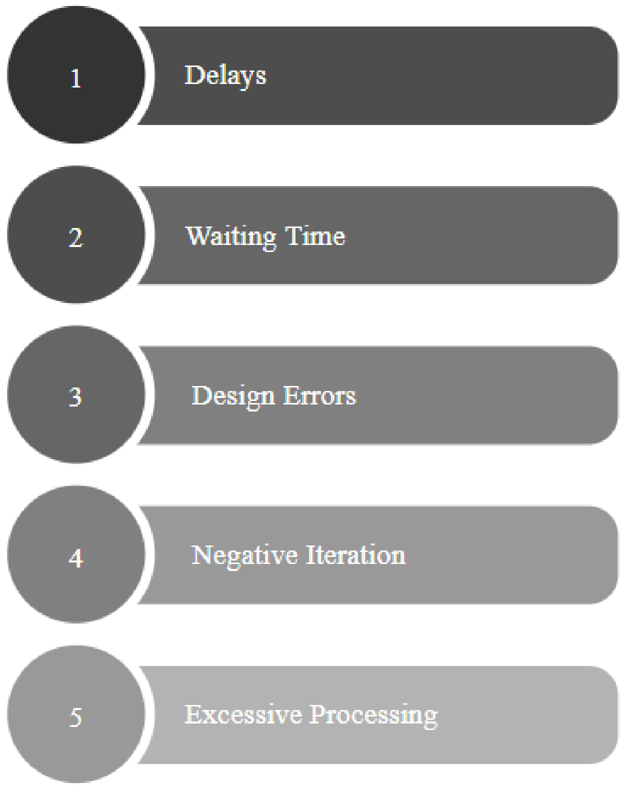


Figure 11. Waste in design adjusted from Ballard, 2000

Reducing non-value-adding operations and increasing efficiency may be achieved by seeing design as a flow of information. (Ballard & Koskela, 1998). For example, waiting for accessible information, inspecting design solutions, reworking, or going back and looking at the design solutions, may all be cut down because of this. Chachere et al. (2008) proposed the term latency in engineering. Most engineering processes are slowed down by response latency, or the time it takes for a participant to ask a question and get an answer that is good enough to allow them to continue working. A usual response time of a few days to weeks causes regular conceptual design tasks to take months or even years to complete (Chachere et al., 2008). They believed a "Just in Time approach to knowledge work" would allow design choices to be made quickly and reliably.

Actions for decreasing or eliminating waste have been studied in various ways. Some studies highlight efforts to improve industrial processes via the use of Lean approaches (Nahmens and

Ikuma, 2011), while others utilize simulation models to aid decision-making by evaluating modifications that might help reduce the percentage of nonvalue-adding activities (Park et al., 2011; Porwal & Hewage, 2011; Sacks et al. 2007; Tommelein et al. 1999).

Value stream simulation is a valuable tool for reducing waste in Lean construction. Without the need for extensive and time-consuming simulation models, it provides early insight into productivity, effectiveness, and service quality (Berndt et al., 2016). It is a static representation of the system that a VSM provides. As a descriptive model, no conclusions regarding system performance can be reached from mathematical analysis or computer experiments based on this model alone (Marvel & Standridge, 2013).

For many people, Lean thinking and simulation are inextricably intertwined, if not the same thing (Marzouk et al., 2012). Simulation may be used to effectively model and evaluate processes from a practical standpoint. As a result, Lean construction principles may be tested using simulation to assess Lean concepts before their actual application (Halpin and Kueckmann, 2002; Marzouk et al., 2012).

Laguna and Marklund (2005) listed the advantages of developing a `simulation model for controlling the design process for design organizations. The benefits they mentioned are categorized as follows:

- Simple and efficient: A consistent, consensual, and transparent model of the design process makes it simpler to identify essential changes, such as information flow simplification and step reduction.
- Increasing transparency: All participants can comprehend the process and their respective roles and responsibilities. This raises the transparency of the process and tends to facilitate communication between the parties involved.

- The flow of information: The efficacy of the information flow may be improved since the information required to complete each activity and the information that each activity must generate is officially stated. This tends to increase the design quality and the likelihood of cutting the design stage's time in half.
- Become Measurable: Developing and implementing methods for evaluating and regulating product and process performance becomes simpler.
- Real-time feedback: Effective feedback to the process is enabled because design activities are tracked and recorded systematically, including design-related tasks. The gathered information may be utilized for future project feedback, knowledge management, and the firm's strategic planning process.

Marvel and Standridge (2009) assessed the simulation-enhanced Lean design process. They provided an improved Lean approach, incorporating future state validation before deployment. The primary validation technique in their research was intended to be simulation modelling and testing. Value stream mapping is extended through simulation modelling and testing to encompass time, individual entity behaviour, structural variability, random variability, and component interaction effects. There are several ways in which the VSM model might benefit from a simulation model. Marvel and Standridge regarded them as follows (Marvel & Standridge, 2013):

- It is possible to conduct computer simulations to test the model's ability to operate under several scenarios. Incorporating time into the model allows for representing and evaluating dynamic changes in system behaviour.
- It is possible to monitor the behaviour of particular entities, such as components, inventory levels, and material handling devices, and make assumptions about the system's behaviour.

Abdulmalek and Rajgopal (2006) described the combination of VSM with simulation by creating a dynamic strategy for assessing future state maps to control system uncertainty. By including simulation in the approach, Lian and Van Landeghem (2007) addressed VSM's shortcomings and highlighted other advantages of employing simulation as a training tool besides measuring the gains. Marzouk et al. (2012) developed a framework to utilize computer simulation to examine the effect of applying Lean concepts to design processes in construction consultant businesses to help in early project decision-making. A comprehensive case study showed that using Lean construction concepts in the design process dramatically improved process efficiency in terms of decreased process durations and greater resource utilization.

Simulated entities may be recognized by one another based on their properties. Depending on these properties, entities' flow and processing times may be influenced by conditional logic. By including such information, simulation models may better mimic a system's actual behaviour (Marvel & Standridge, 2013). Simulation might contain interactions between parts of a system. These interactions may affect the system's capacity to reach its performance goals. One component's operations are likely to affect the operations of other parts and the system's overall performance.

Chapter 3: Research Methodology

3.1. Overview

This chapter introduces the research methodology. This methodology explains how the research is carried out and demonstrates how it is possible to achieve the research's goals. Afterwards, the research design process is presented, and at the end of the chapter, the methods used to collect data and their results are discussed.

3.2. Methodology

The methodology followed throughout this study is Design Science Research (DSR). This methodology aims to improve human understanding by creating new artifacts (Brocke et al., 2020). DSR includes three steps: problem identification and defining the objectives, designing the artifacts to address that problem, and evaluating the artifacts using a case study. Only by identifying problems may a solution be found and shown to be worthwhile. Both the researcher and the research's audience benefit when the worth of a solution is justified by demonstrating the researcher's thorough comprehension of the issue. DSR requires understanding the problem's current condition and the significance of a successful resolution (Brocke et al., 2020).

In previous chapters, the problem of waste and research objectives were defined. By understanding the effects of waste on the design process, the next step is to find a solution to eliminate those waste. For designing a solution, this study aims to develop a framework as a roadmap to identify waste and improve the design process. The mentioned framework is discussed in section (3.4). The case study will evaluate the proposed framework and present the results. Figure 12 shows the DSR methodology for this research.

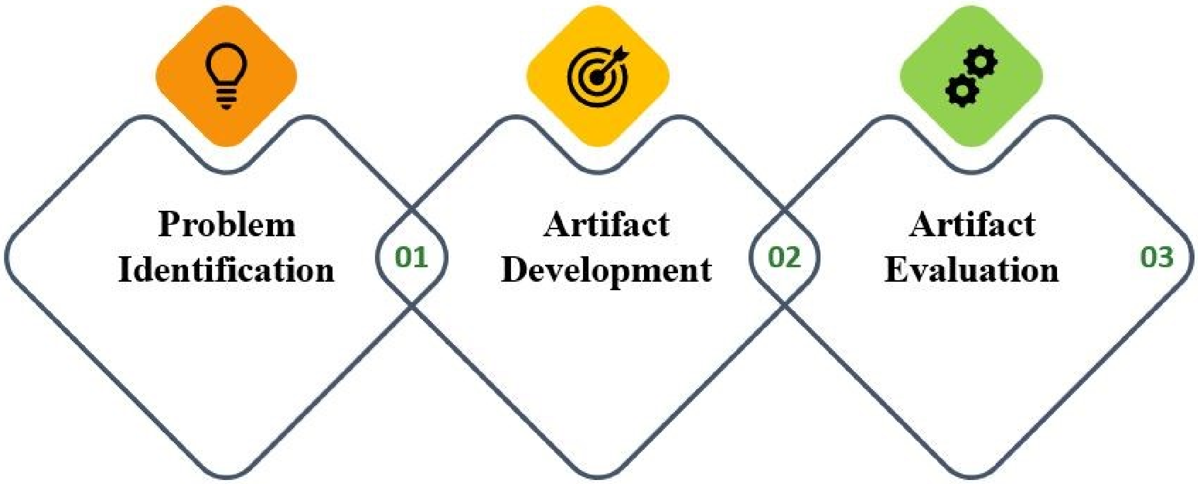


Figure 12. DSR methodology diagram for this research

Besides the principal methodology used in this research, several steps were taken throughout the research resulting in the outcome. The research comprises six phases as follows:

Phase 1. Phase one is a conceptual phase in which a thorough literature analysis is carried out to better understand the design process and Lean design management. This phase evaluates research gaps and defines the contributions to academia and industry. The method entails defining the issue in a clear and precise manner and then designing the objectives in a way that achieves the research goal.

Phase 2. This phase assesses the methodological approaches necessary to meet the study goals. This stage covers the process, what to answer, and how to respond.

Phase3. This phase introduces the case study and the data collecting methods, in which the database is developed to understand the process better. Company X, a build-to-order manufacturer, serves as the case study for this research. This facility provides design and manufacturing services, or both, to various clients. The primary purpose of this study is to evaluate the design procedure. In this regard, data relating to the design phase is presented as expert-driven and data-driven data. Expert-driven data was collected through interviews with designated experts. These individuals were chosen based on their role in the case study's design process. Extraction of data from ERP, time studies, and financial documents was utilized to collect data-driven information.

Phase4. Phase four deals with using Lean techniques to diagnose an AS-IS state. The key method utilized during this phase is value stream mapping. To validate the value stream mapping, computer simulation was used.

Phase 5. This phase includes the development of a simulation model to evaluate the results of the suggested interventions in the design process.

Phase 6. The last phase focuses on presenting the study findings following the research objectives. Figure 13 presents the diagram related to the research phases.

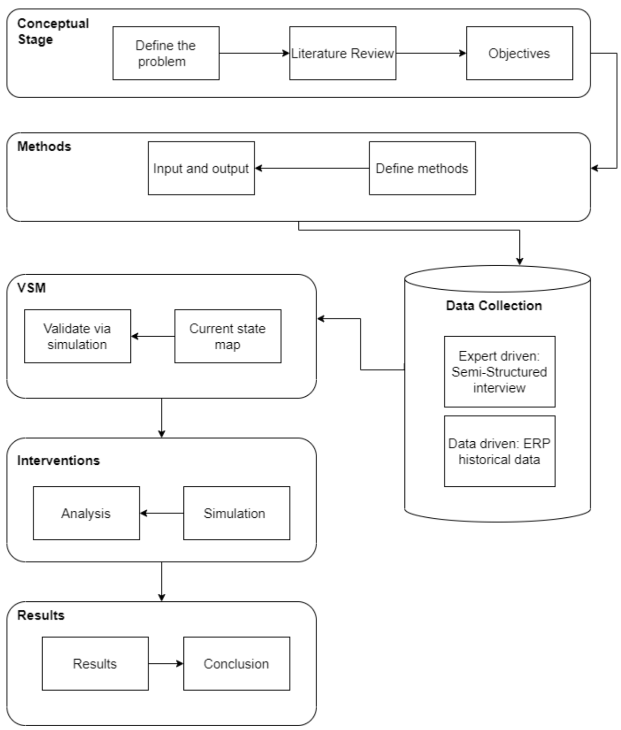


Figure 13. The methodology diagram of the research

3.3. Design Process of the case study

Manufacturing is a specialty of Company X, a build-to-order manufacturing facility in Edmonton, Alberta, which offers two key service lines. The first level is full service, in which Company X handles everything from design through production and installation. The other is the supply only when Company X only provides one of the services, which is generally manufacturing.

Company X is made up of seven different departments that collaborate. The sales/business development department obtains new jobs and expands the company's operations. A design manager, designers, and assistants work in the design department to create new cabinet designs and estimate their costs. The Order Desk department is responsible for processing orders and providing ERP system support to other departments. Customer service, scheduling, procurement, installation, and quality control are part of the operation. Accounting is concerned with financial information and invoicing. Production is in charge of making the cabinets and logistics to get the cabinet to the customer. Figure 14 shows the organizational chart in Company X.

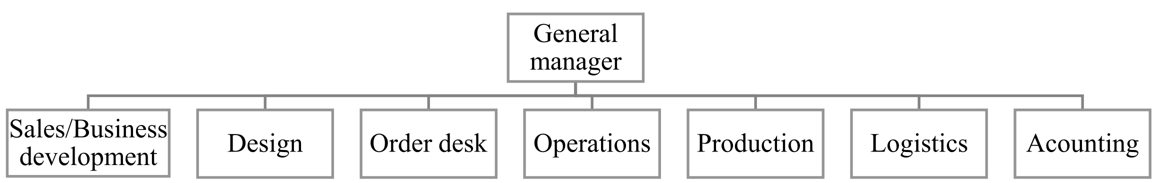


Figure 14. The organizational chart at Company X

As mentioned, this study emphasizes a case study of Company X and its design processes and procedures. In this regard, the design process is presented to get a better knowledge of the process and the challenges that may arise due to the process, which may end in waste or non-value-added to the design. The information flow throughout the process is shown in the following diagram. Three distinct stages are considered for the design process based on the kind of services and the amount of information exchanged between stakeholders. The first information flow is from the consumer to the designer and vice versa. Each iteration at this step may add to the information sent between the designer and the client. Figure 15 shows the flow of information in the design process.

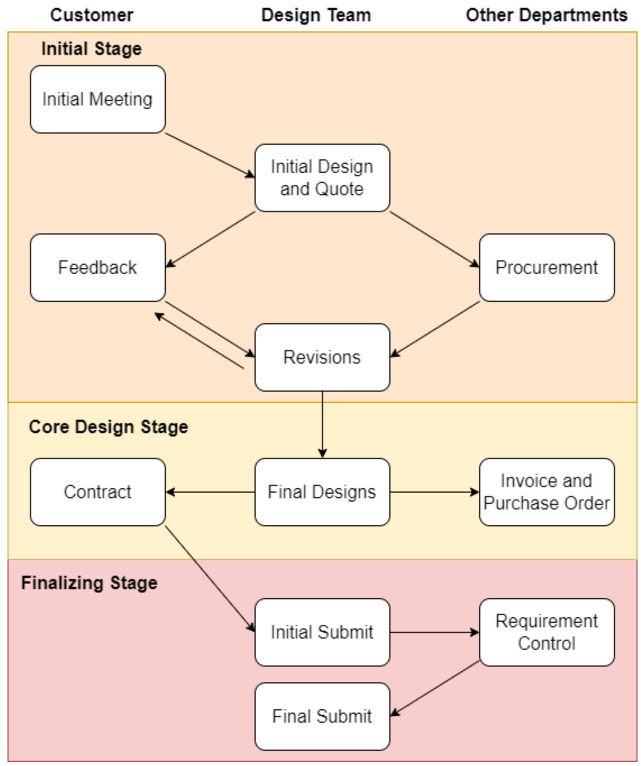


Figure 15. Current design workflow for this research

The designer is the source of knowledge at the core stage. The site mark out is the only vital information to be added to the flow of information. In the final stage, just before sending the final product to manufacture, information moves back and forth between the designer and the operation unit for quality control. There is more information on each stage in the following sections.

3.3.1. Project initiation stage

The first stage starts with a meeting with the potential client. This information exchange might take the shape of a short conversation or a long one over the phone or in person. The purpose is to collect information about the job's design, finishes, layout, appliances, and budget. Sometimes the clients are unsure about what they want. This is when the designer-client relationship becomes crucial in completing a successful transaction. The designer should concentrate on getting the most information from the customer so that they may understand what they want and create a design that reflects their preferences.

After gathering information, the designer begins work on the initial design and quote package, including sketches and 3D perspective drawings of all essential sections. Cabinetry, delivery, and installation costs are included in the quote package. During the design phase, the designer may contact the procurement unit to get information on particular materials available on the market. The package will then be provided to the customer, or a second meeting will be scheduled to evaluate the design with the client, after which the designer will wait for feedback from the client. After obtaining feedback, the designer makes any required modifications to the designs (revisions) and the quote. The designs and quotes might go through many changes. When the client requests adjustments, there might be numerous iterations for this stage. The customer is then supplied with the amended package through e-mail for first approval.

3.3.2. Core design stage

This stage starts once the customer consents to continue with the preliminary project design. Following the last modification, the designer begins putting together the final package by retrieving the work number from the Enterprise Resource Planning (ERP) system and delivering the final package for approval of the design. After that, the client must sign the contract, and the invoice or purchase order must be sent to the customer. The client may request the site mark out to ensure everything is correct and to check for any differences between the final designs and the original plan. Outside of the design team, marking out is done by specialists.

3.3.3. Finalizing stage

The project's Finalising stage is the last and final step of the design process. The designer now has all the essential information and can begin building the file. It means the designer makes any final changes, adjusts plans based on dimensions installation details, blueprints and 3D drawings, site mark out, colour board, signed drawings from clients, and prepares the job cost sheet, which includes all parts pricing, hardware and accessory costs, install and delivery fees. The designer saves these documents to a specific file on the server and in the ERP system. The task is now visible to the other departments, and the designer has sent the work number to the Order desk for processing. The Order Desk unit sends the acknowledgement to the designer to let them know whether the file is OK or if any missing information needs to be included. The designer sends the file to the Operations unit for scheduling after completing a thorough evaluation of the acknowledgement.

3.4. Proposed Framework for Waste Mitigation

The proposed framework is suggested for the design process for off-site construction. This framework was established as a best practice to help organizations reduce design waste. The framework contains four main stages: Definition, Identification, Intervention and Implementation.

According to this framework, the Definition (mathematical) stage is the first step. In this stage, the method of data collection and the kind of information that must be kept on file as input information for the procedure are defined. It is helpful to determine the metrics to understand how to reach the outputs and what types of outputs are anticipated to be controlled to find waste. The data will be collected using the defined metrics, inputs, and outputs. The suggested data collection methods include interviews and historical data. This stage aims to get as much information about the design process as possible. The Identification (analytical) stage is the next step, where data is transformed, and the current situation is analyzed to find waste using value stream mapping. In this stage, questionnaires, interviews or Lean thinking tools such as Big Room and 5S could be used to understand the standard procedures better. At the end of this stage, a simulation model will be developed to get more visibility into the design process. Figure 16 shows the proposed framework.

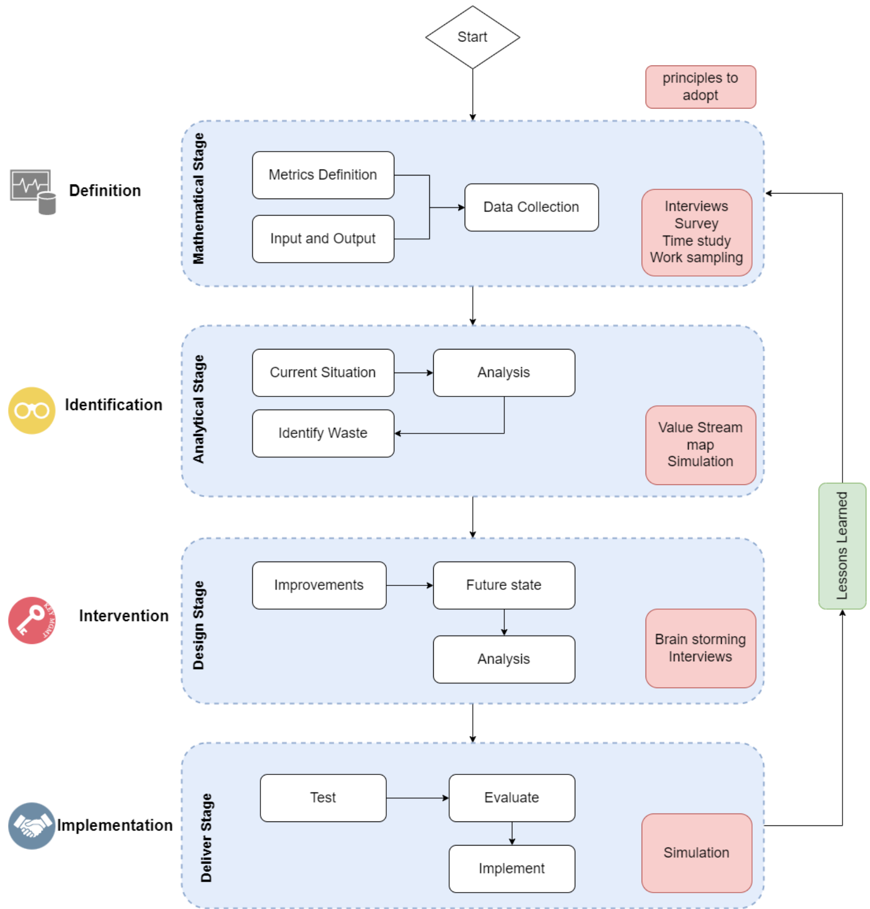


Figure 16. Proposed framework for waste mitigation

The third stage is the Intervention (design) stage, where artifacts and Lean interventions are created to reduce design process waste and enhance the process. At this stage, the improvements are determined by conducting expert interviews or conducting a brainstorming session with them to forecast how the process will develop in the future. The final stage of the suggested framework is the Implementation (deliver) stage to test the improvements and validate the effects on the process using the model developed in stage 2. Ensuring the effects of the interventions on the process and the organization can be accomplished by using simulation to verify both present and potential future conditions. The company could put their improvements into practice after they are proven to be successful.

This framework is generic and may also be used by others. This framework will aid and standardize efforts to boost productivity by reducing the number of non-value-adding activities.

3.5. Inputs, Outputs and Metrics

The data should be captured on the different criteria to know the design process. The primary data to be captured is duration. This includes the time it takes to process the information on each step of the design process and the idle times that the designs are waiting to be processed by one of the stakeholders. Defining some benchmarks to record the date and time on each benchmark in ERP or other databases helps to have a more comprehensive database on duration and time study. Also, the specifications on each job should be captured, such as the type of classification, customer segmentation, designer, number of boxes, sub-projects, and change orders. The data and criteria to collect and use as inputs in the system are presented in Table 1. More comprehensive data on the process gives a general overview and helps better understand the system's obstacles, disruptions, and waste.

Table 1. Process inputs

Inputs	Description
Processing time	The duration of each step of the design process.
Waiting times	The time between design steps that the designs sit idle.
Rework probability	The likelihood of reworking each design step.
Available time	The time available for the design process.
Units to be produced	The number of designed units in the off-site construction section.
Errors	The number of design errors in the off-site construction that cause rework
Job Classification	The class of each job based on the customer segmentation
Designers	Number of designers on the system

By knowing these inputs, there should be metrics to be used to know the system. The first one is the utilization ratio. Value stream mapping evaluates the possibility for improvement by comparing the total process time (the sum of all the times spent on the design process) with the overall lead time (The time that takes one job to move through the process or value stream, time from the initial meeting to the time sending designs to operations). Increased improvement potential may be achieved when there is an enormous difference between operational time and lead time (Berndt et al., 2016). Equation 1 defines this ratio.

Equation 1. $$Utilization\ Ratio = DPT/DLT$$

where DPT = Design Process Time and DLT = Design Lead Time.

Equation 1 offers a fair idea of how the product (information) flows through the process. The bigger the equation after the future state mapping, the more progress is made. The ratio is between 0 to one, and the closer it is to one, the more it is utilized with productivity. As mentioned, DPT stands for Design Process Time and represents the amount of time needed to complete a job from the start to the end of the design process. DLT stands for Design Lead Time and represents the total time a job completed in the design process. DLT consists of DPT, waiting time and waste time.

The German word for a rhythm or beat is Takt. Takt time meets client demand rhythm (Tapping & Shuker, 2003). Takt time displays the rate at which that demand is met. In the design process, Takt time is presented as the amount of available time in a time unit divided by the number of jobs demanded at that specific time. Equation 2 defines Takt time.

Equation 2. $$Takt\ Time = Available\ time/Number\ of\ jobs$$

Another critical element of value stream mapping is Yield. Yieldthethe proportion of process outputs, manufactured parts, assembly, analysis, transaction, and reports that do not need rework or replacement. In other words, the percent of a defect-free process is known as the Yield or the success rate, or the likelihood that it will not create any faults. The Rolled Throughput Yield (RTY) is a process performance metric that gives you an idea of how a whole process works together (Graves,2002). RTY calculates the likelihood of a defect-free unit passing through a process step by calculating the Yield for each process phase (Graves,2002). RTY gives us insight into the Yield of each process stage, allowing us to reveal the waste in design. This enables us to identify the worst-performing process stages and guides where to seek the most significant improvement possibilities. RTY is calculated by multiplying each process step's Yields, as it is shown in Equation 3.

Equation 3. $$RTY = Y_1 * Y_2 * \ldots * Y_n$$

Although, the Yield for each process stage must be calculated before computing RTY. By knowing the percent of defect per unit(dpu) in each station, the Yield is calculated as Equation 4.

Equation 4. $$Y = e^{-dpu}$$

Rework is one of the most common indicators of design defects.

The Expected value loss for yield is one indicator to help understand the system state. The primarily expected value loss formula is the probability of an event multiplied by the number of times the event happens (Glen, n.d.). The main focus in this metric is on the rework as an indicator of increasing value based on TFV theory. The expected value loss for yield is defined as Equation 5 (Glen, n.d.).

Equation 5. $$\text{Expected value loss: } P(x) * n$$

where *P(x)* is the probability of rework, and *n* is the number of reworks.

There are also other factors to consider. The total number of unfinished designs in the value stream waiting for the following action to begin is Work In Progress (WIP). WIP refers to any work that has not yet been completed or any area of a production that is not currently being worked on and falls between the beginning and ending points of the routing (Little, 2011). A system that maintains a high inventory level will experience longer lead times. In contrast, a lower inventory level system will react more quickly. So by decreasing the amount of work in progress, the cycle time will be shorter (Chin, 2009). Processes may be slow due to a large amount of work in progress in this situation; the task would likely be idle for more than 90% of its duration, resulting in severe time and money losses (George, 2003). The number of output units (goods, Jobs, designs.) can be counted to measure WIP. Following is the method used in this research to calculate the WIP. Job number 01 begins on day one and has a three-day lead time. The same may be said about work number 02, which starts on day 2. The WIP is computed by counting all the jobs each day during the period in which the jobs stay in the system. Table 2 shows how to calculate WIP.

Table 2. How to calculate WIP

		Days					
		1	2	3	4	5	6
Job Number	01	•	•	•			
	02		•	•	•		
	03			•	•	•	
	04				•	•	•
WIP		1	2	3	3	2	1

3.6. Data Collection Approaches

Each case or topic is represented by a unique data set. Statical methods gather, analyze, present, and interpret data. As this study discusses the design process, the data could be collected in various ways. Examining the time data for each activity is necessary to arrive at a statistical interpretation of how long it takes to perform that activity. The methods used to collect information are Semi-Structured Interviews and an ERP database.

The interview is one of the most powerful tools to assess the current situation and know the process (Rabionet, 2011). Three primary interview types (Alshenqeeti, 2014) can be used in collecting data. The first is a structured interview, in which the interviewer asks the interviewee a series of present questions. The interviewer and interviewees have minimal flexibility in this interview style, and the questions are usually *Yes/No.* The second kind of interview is the unstructured interview, sometimes called an open-ended discourse. It allows the interviewer and the interviewees to expand their points of view on the topic. The semi-structured interview is the last option. This form of interview is more focused on the core issue of the interview, ensuring that the interview meets its stated goal while still providing greater flexibility. Because of the benefits of semi-structured interviews, this kind was chosen to continue data collection for this study. To have a more focused conversation with the interviewees, a checklist of topics is created to cover the following topics. Table 3 presents that checklist.

Table 3. Topic checklist for the semi-structured interview.

Topics	Description
Process	questions regarding the design process to have a better understanding of the design process. For example: Can you give a complete description of the design process? - How long will it take you to finish each step of the design process? - What is the probability of getting a revision?
Contribution	questions concerning the interviewee's contribution to the design process. For example: What is your role in the design process?
Weakness	questions concerning the design process's weaknesses
Threats	questions regarding the aspects that might jeopardize the design process
Relations	questions concerning the design department's interaction with other departments. For example: What is your relationship with other departments? Do you have direct interaction with the customers?
Non-value-added	questions concerning any non-value-added activity in the design process. For example: Have you ever identified any non-value-added in the design process?

Enterprise resource planning (ERP) is an organization’s management and integration system to manage and integrate the many aspects of its operations. An ERP system is vital to a company because it records and moves financial and technical data.

One of the data to be recorded is the duration of each task in the design process. Several factors might be challenging to determine a precise task duration. Therefore, using a fuzzy form to convey preferences is simpler (Zhang et al.,2014). Capturing data in the triangular fuzzy form helps to understand the duration better. This form contains three situations optimistic time, the most probable time, and the pessimistic time to finish the tasks. Equation 6 (Zhang et al.,2014; Anand & Bharatraj,2017) shows the triangular fuzzy form's membership function.

Equation 6.

$$\mu(x) = \begin{cases} \frac{x-l}{\leq} & l \leq x \leq m \\ \frac{x-u}{m-u} & m \leq x \leq u \\ 0 & otherwise. \end{cases}$$

Where *l* is the optimistic duration of task i, *m* is the most probable duration of task i, and *u* is the pessimistic duration of task i. Also, the average of the triangular fuzzy, according to Hsieh and Chen (1999), is defined as Equation 7.

Equation 7.

$$Average = \frac{l+4m+u}{6}$$

When all of the information on the time of activities in the design process is combined, a clear picture of the current state of the design process can be obtained.

Chapter 4: Data collection

4.1. Overview

In this chapter, the data gathered from the case study is presented. As mentioned in Chapter 3, two different approaches are adopted to collect data, interviews and the use of historical data from the database. As the interview was a part of data collection, a proposal by the Study ID of Pro00121778 was submitted to the Research Ethics Office of the University of Alberta with all necessary information and sample questions for the interview. After approval by the Research Ethics Office, the data collection procedure was started.

4.2. Data Collection

The interview was the first method used to gather data. Along with the focus group interview with the design team, there were 17 rounds of interviews with the general manager, design manager, designers, production manager, order desk manager, and operations. Focus groups are a type of group interview in which participants are encouraged to interact. A focus group interview with the design team may be beneficial in obtaining additional feedback on the design process.

The interviewees were asked to estimate how long it would take them to accomplish their design tasks. The probability of each significant step in the design is another finding from the interview. These probabilities can be used to estimate the system's rework and revisions as well as the yield. Table 4 shows the results from the interviews, and Table 5 shows information about the likelihood of steps.

Table 4. Task duration results from interviews.

Task	Optimistic time	Most probable time	Pessimistic time	Average
Designing the initial designs and developing quote package (hours)	2.44	3.4	5.8	3.63
Getting the feedback for the initial package from the client (days)	2.2	4.2	10	4.83
Revising the designs based on the client's feedback the first time (hours)	1.3	2.3	4.4	2.48
Getting the feedback for the revised package	2	4	8	4.33
Revising the designs based on the client's feedback a second time (hours)	0.5	1	2	1.08
Developing final package (hours)	1.2	2.4	4.2	2.5
Reworking regarding the difference between the initial blueprint and the mark-out (hours)	1	1.7	2.8	1.77
Generating the contract (hours)	0.45	0.7	1.05	0.71
Building the file in the QB (hours)	0.3	0.45	0.85	0.49
Receiving acknowledgement from Order Desk (days)	2.8	4.2	6.6	4.37
Making final changes based on acknowledgement (hours)	0.3	0.6	1	0.61
Submitting final copy (hours)	0.35	0.55	1.1	0.60
The whole design process, from the initial meeting with the client to sending the file to Operation (days)	16.4	47.3	106.4	52

Table 5.Rework probability from interviews.

Task	Probability
The designs are being revised (first time)	95%
The designs are being revised (second time)	40 %
The designs are being revised (Third time)	10 %
Rework after initial submission	41%

It has been determined that, on average, the initial designs need 2.5 times revision. Based on Table 5, the probability of being revised for the first time is 95%, and for the second time, 45%. Moreover, the interviewees are asked about the challenges and threats in the design process that could initiate waste or non-value added to the system. Table 6 presents findings about the challenges in the design process of the case study.

Table 6. Design challenges from interviews.

Weakness	Threats
- Redundancy in process - Iteration in the design process - ERP system - Customization - Lack of sufficient primary data from marketing - Lack of coordination between drawing software and ERP - Lack of standardization - Drawing software restrictions - Lack of technical knowledge about manufacturing - Lack of improved feedback system - Lack of any short-term prediction - No Track and Trace system - Buffer and waiting time - Lack of customer satisfaction review - Lack of lesson-learned system	- Human resources - Quoting time - Variability - The time between design and material order (unstable lead time for procurement) - Balance the load and capacity - Rework and revisions

The word count chart in Figure 17 is based on the number of times the challenges mentioned above were repeated during the interviews.

Figure 17. Wordcount chart of design challenges from the interviews

Another source of data is historical data extracted from ERP. Company X is using QuickBase as an ERP system at the time of this research. QuickBase is a flexible, no-code cloud base platform that allows configurable solutions to tackle specific needs. The data from the ERP database contained 1602 rows of data in a spreadsheet, each representing one job done in 2021. Although many jobs may be connected to one primary project, each job was considered separately since it has its requirements and processes. Each job has one lead designer and is categorized in a specific classification. This classification is based on the type of customer and is different from the two lines of services (full service and supply only) mentioned before. Based on the job classification, there are four job types.

Retail: the customer is ordinary people, and the company directly deals with the customer itself.

Builder: the customers in this class are the developers and construction companies.

Dealer: the customer is usually other architecture offices or firms who designed the job and used the manufacturing services of Company X.

Project: the customers are construction companies, and the main job is related to high-rise buildings with repetitive designs.

The general information on each class is summarized in Table 7 and Figure 18.

Table 7. Available data on each job category.

class	Type of service	Frequency
Retail	Full service	134
Builder	Full service	1124
Dealer	Supply only	210
Project	Full service	134

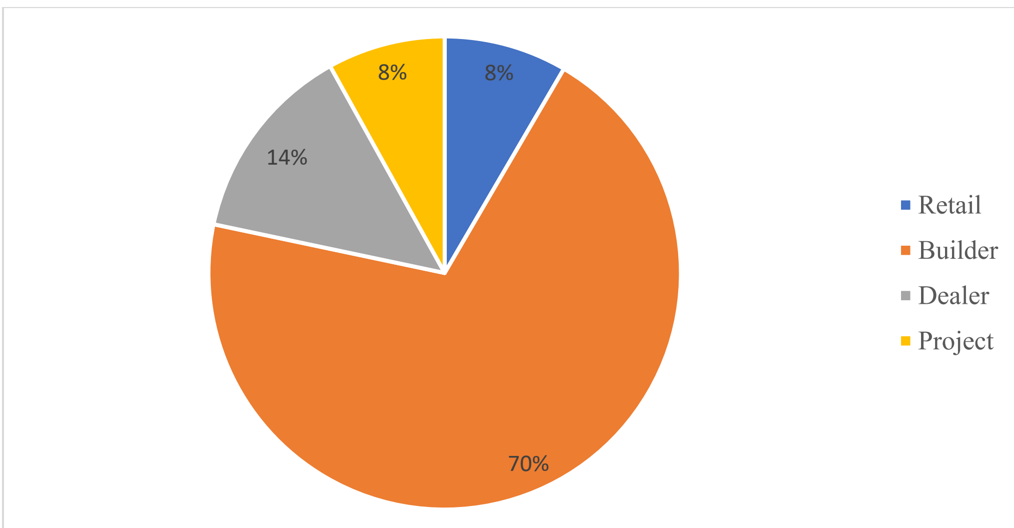


Figure 18. Job classifications.

The Type of Lead Time is the other specification. “Standard” and “Rush” delivery are the jobs based on the lead time. Standard delivery jobs are prioritized on a first-come, first-served basis; however, rush deliveries are prioritized in all circumstances, and designers begin working on these jobs as soon as possible. Rush delivery serves an extraordinary situation and is excluded from analyses. The percentage of each delivery type is shown in Figure 19.

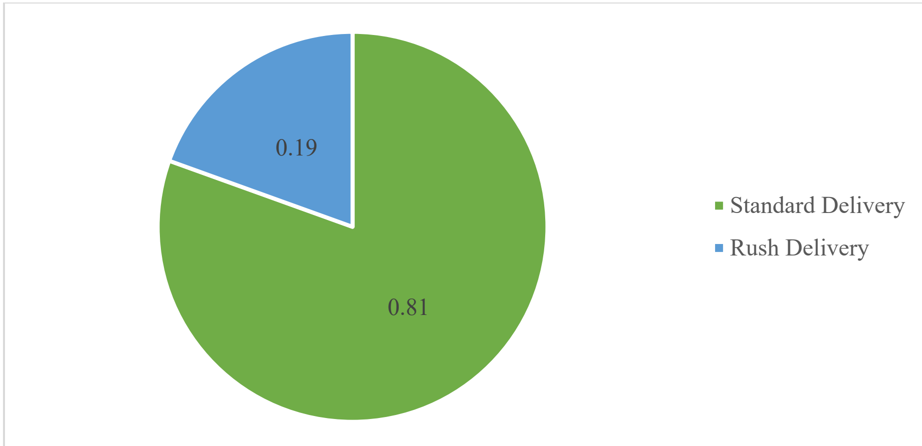


Figure 19. Type of delivery in Company X.

The number of cabinet boxes is other data collected from ERP. Figures 20, 21, 22, 23 and 24 present the cabinet box data.

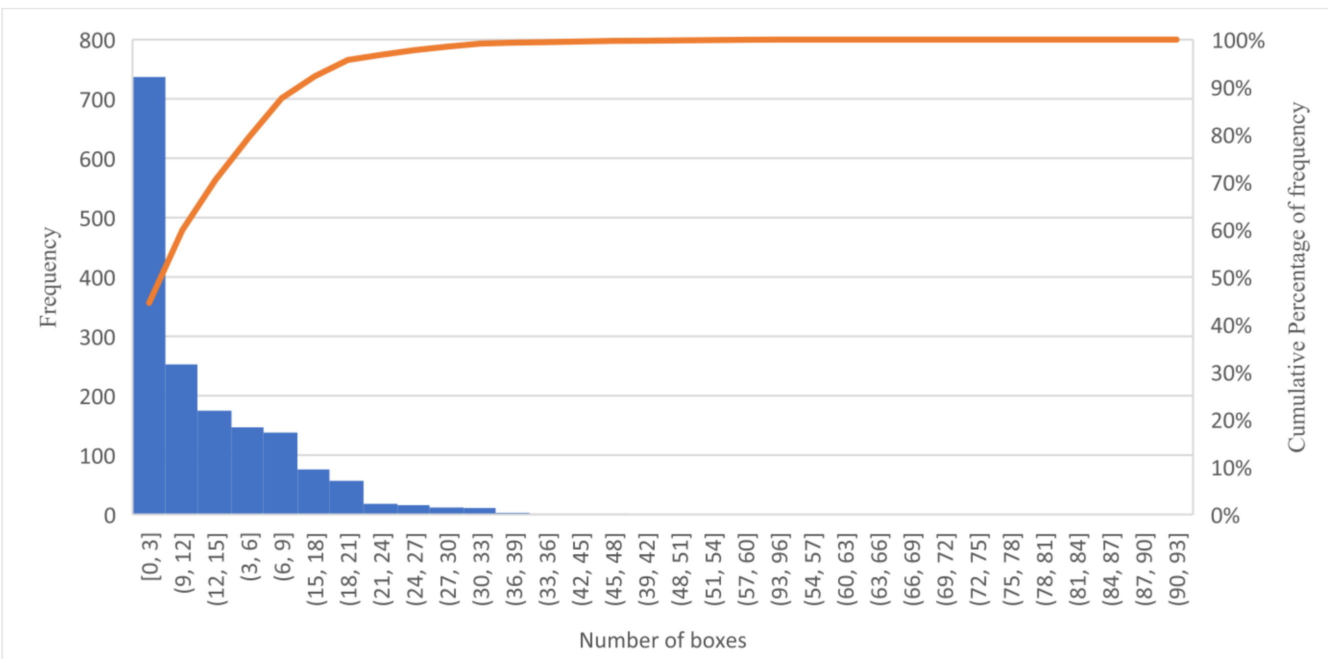


Figure 20. The number of cabinet boxes in total.

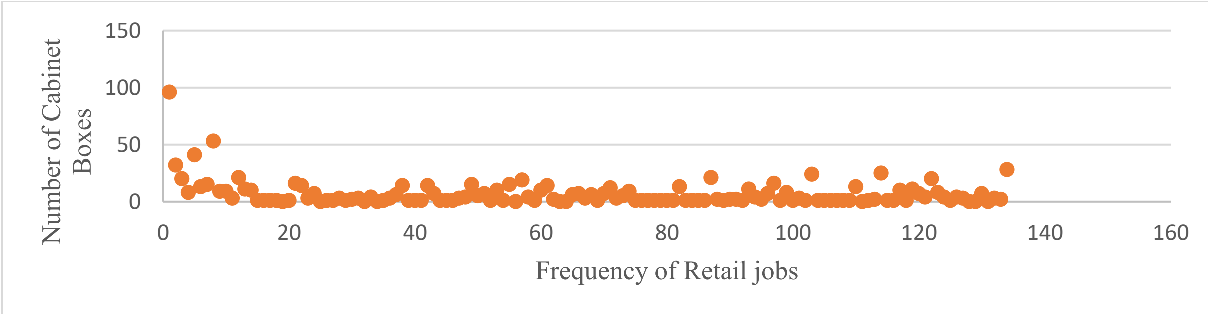


Figure 21. The number of cabinet boxes for the retail class.

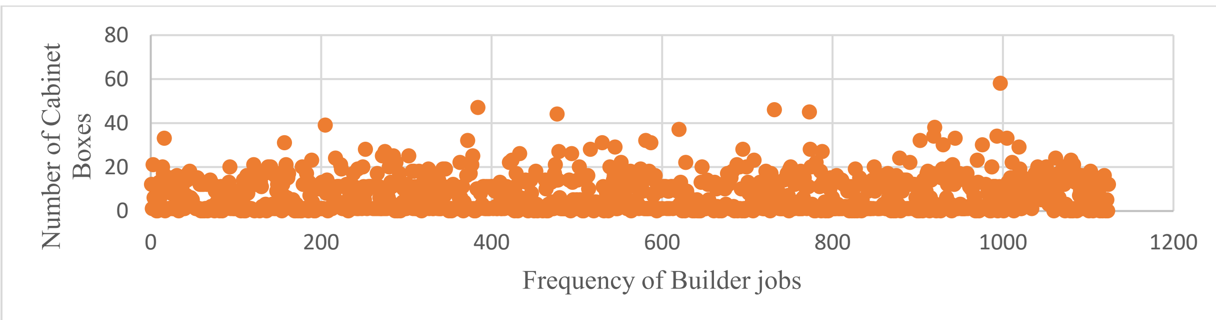


Figure 22. The number of cabinet boxes for the builder class.

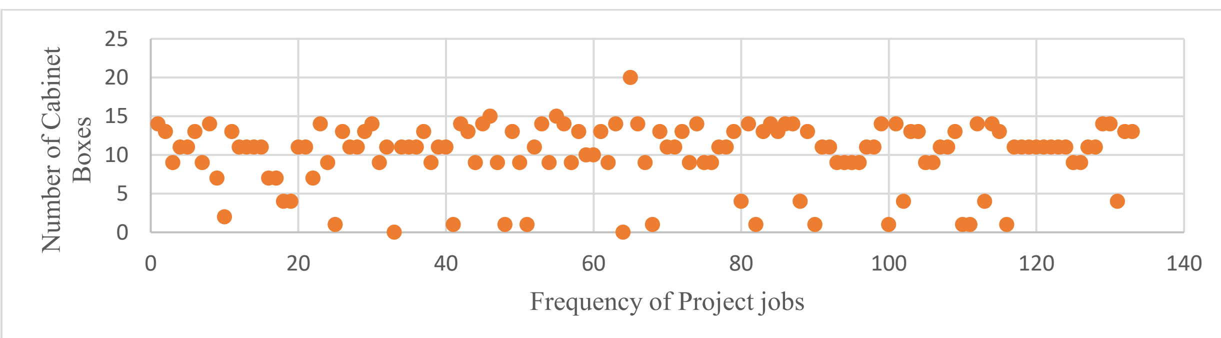


Figure 23. The number of cabinet boxes for the project class.

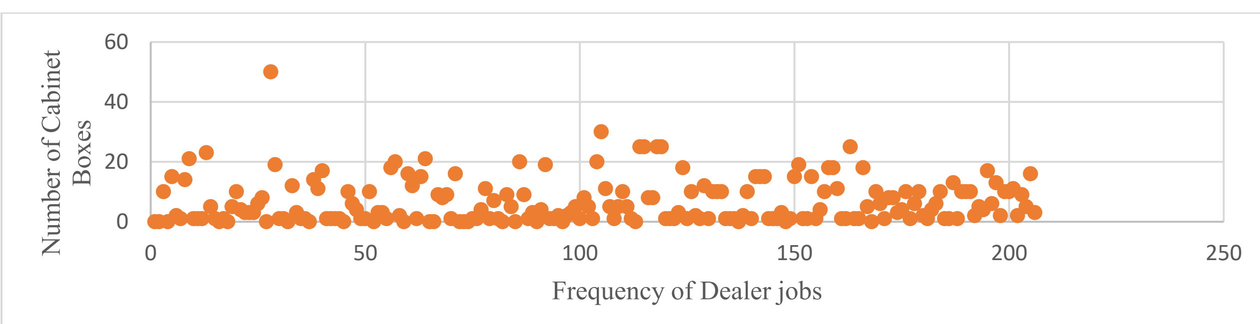


Figure 24. The number of cabinet boxes for the dealer class.

Interviews determined that Zero box of cabinets shows a change order and should be excluded from analyses. Based on the ERP database, the contract sign-off by month is shown in Figure 25.

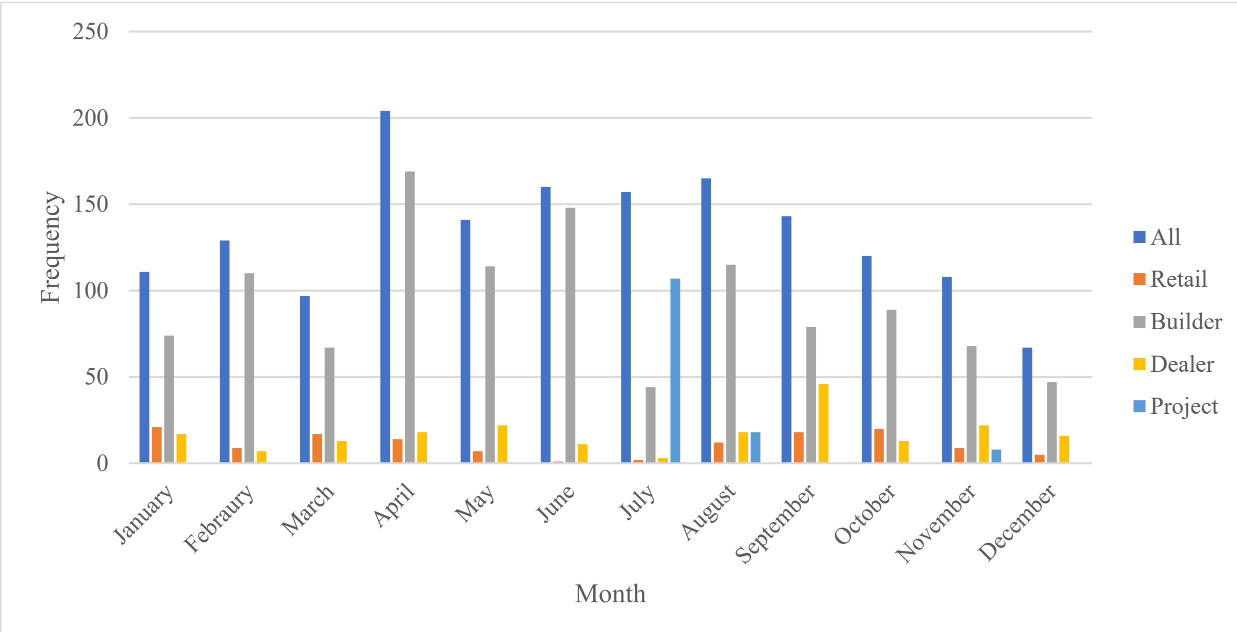


Figure 25. Contract sign-off by month.

Also, financial data for the time between invoice and payment was extracted in addition to the above information. The information is used to assess the design process's current situation. Table 8 shows this data.

Table 8.The time between sending the invoice and payment by days.

Average	Minimum	Maximum	85 % percentile	Standard deviation
5.64	0	105	11	12.49

To choose a proper job classification to proceed with the research, first was to consider that the selected class's design process must be completed. This study aims to assess the design process to improve it and reduce waste. The target class, or classes, in this case, must go through the entire design process. Among the four categories, the Dealer type of job usually does not go through the design process so it can be eliminated. Project jobs are not always available, and Company X only got jobs in this type of class in July and August last year. Considering these, Builder and Retail are the proper classifications.

The addition of processing data for each process is necessary, and each process time and queue time must be determined. As the time to finish a task varies between designers and jobs and different activities are defined at different times, the data should be fitted in certain distributions to calculate the duration of tasks. Easy Fit fitting software was used to calculate these distributions. Each distribution function will be examined using a Kolmogorov-Smirnov (K-S) test to determine the best distribution. The following sections detail the various stages of the design process and the associated data. These stages are the benchmark of the design process in which the designer works on the designs and other flow of information. The first is the initial designs and quote package when the designer begins working on designs. Using fitting software, the K-S test is used to find the most appropriate statistical model. The probability density function is presented in Figure 26, and Table 9 shows the goodness of the fit test.

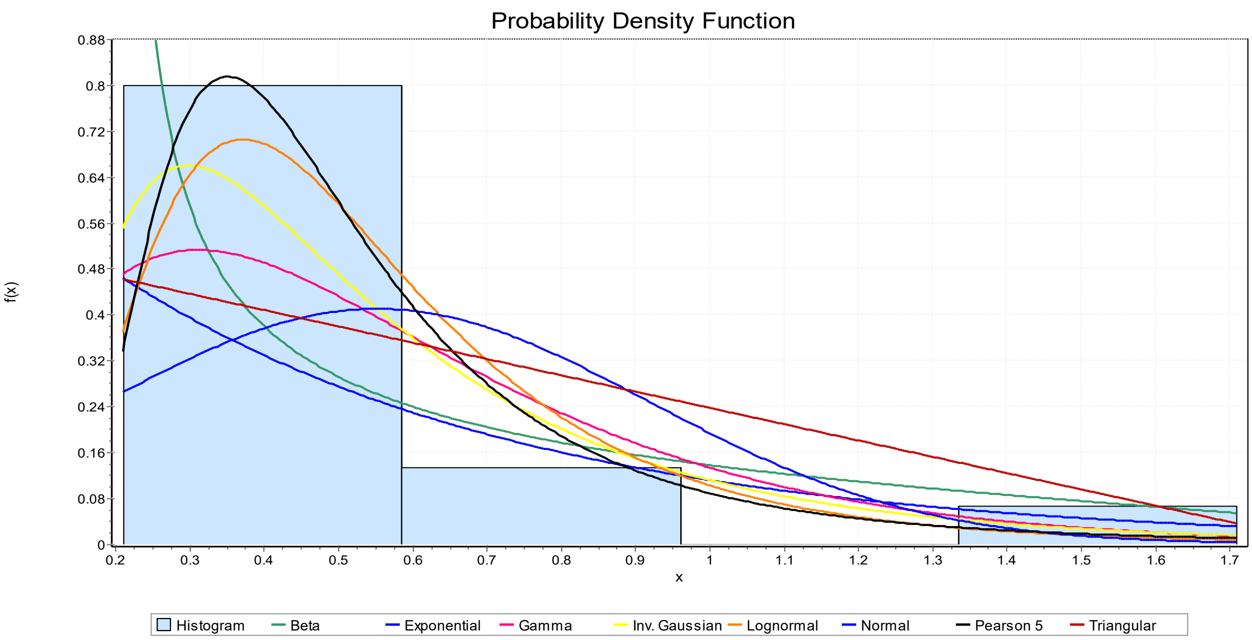


Figure 26. The Probability distributions for the initial design duration

Table 9. The goodness of fit test results for the initial design.

Distribution	Ko–mogorov - Smirnov	
	Statistic	Rank
Pearson 5	0.1351	1
Inv. Gaussian	0.16416	2
Lognormal	0.16504	3
Gamma	0.19416	4
Beta	0.23711	5

The goodness of fit test shows that Pearson 5 has the least K-S among other selected distributions, so this distribution was chosen to present the initial design and quote duration. Equation 8 shows the probability density function(pdf) for Pearson 5.

Equation 8.

$$f(x) = \frac{1}{\beta\Gamma(\alpha)} \frac{e^{-\beta/x}}{\left(\frac{x}{\beta}\right)^{\alpha+1}}$$

where α= 4.5947 and, β = 1.9672

To calculate the lead time, it is vital to see the time spent between each design stage. This gap is the queue time the designer waits for a process provided by others, a buffer time created by the designer, or a backlog time resulting from works in progress. The first stage is feedback time. The same procedure is used to fit the data to the best probabilistic distribution as the feedback time varies. Following is the result for this stage. The probability density function is presented in Figure 27, and Table 10 shows the goodness of the fit test.

Table 10. The goodness of fit test results for feedback

Distribution	Kolmogorov - Smirnov	
	Statistic	Rank
Pearson 5	0.16262	1
Inv. Gaussian	0.20181	2
Lognormal	0.20227	3
Gamma	0.22024	4
Exponential	0.23495	5

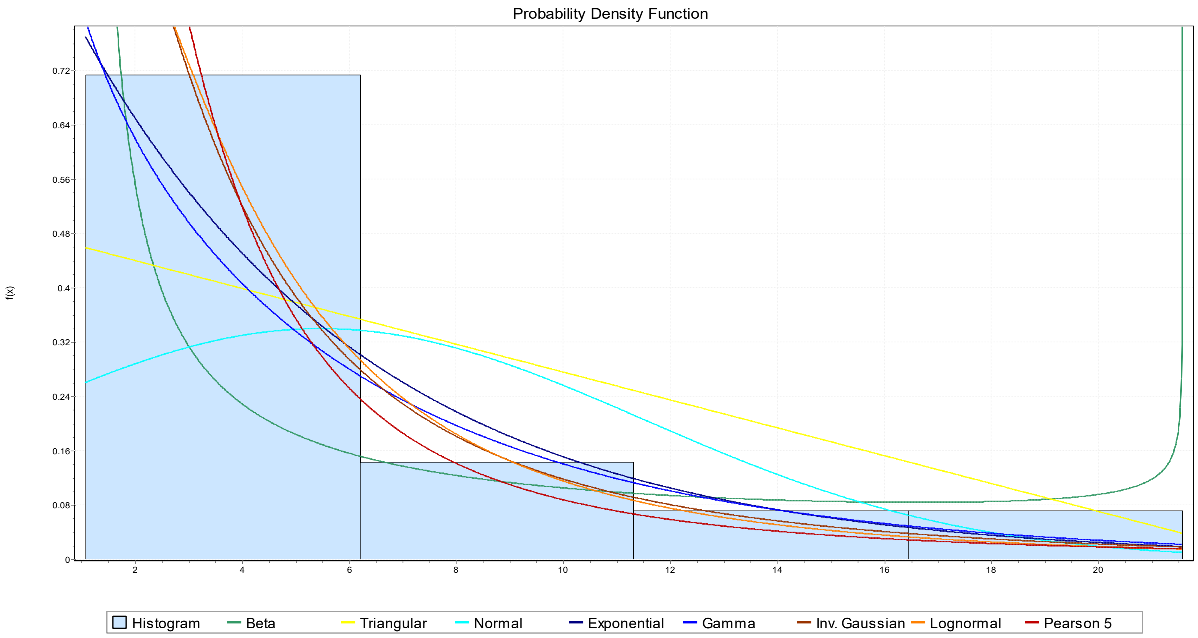


Figure 27. The probability distributions for Feedback duration.

The goodness of fit test shows that Pearson 5 has the least K-S among other selected distributions, so this distribution was chosen to represent the initial design and quote duration as Equation 8 by $\alpha = 1.5868$ and $\beta = 3.8942$.

The next benchmark is revision. The distribution has been determined for the revisions, as they are a type of rework job. Figure 28 shows the pdf, and Table 11 shows the goodness of fit for this stage.

Table 11. The goodness of fit test results for revision.

Distribution	Kolmogorov – Smirnov	
	Statistic	Rank
Gamma	0.18182	1
Inv. Gaussian	0.19895	2
Lognormal	0.20552	3
Normal	0.23295	4
Beta	0.25124	5

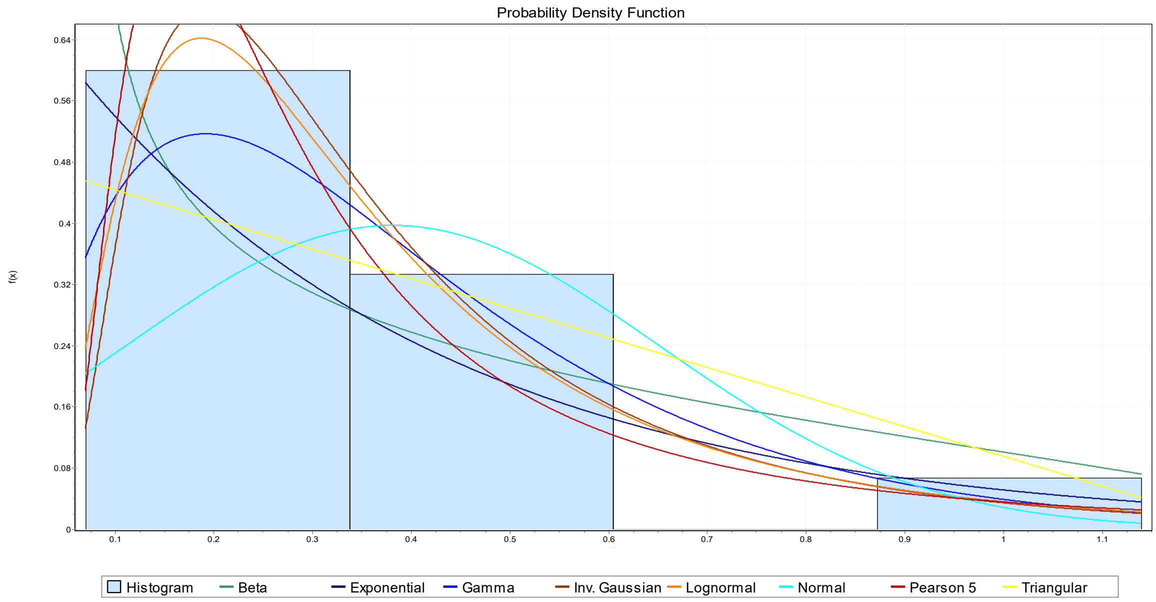


Figure 28. The probability distribution function for revision duration.

Because the Gamma distribution has minor static in terms of K-S, it is chosen to be used. Gamma's pdf equation is as Equation 9 by α = 2.0113 and, β = 0.18959, and γ = 0.

Equation 9.

$$f(x) = \frac{(x-y)^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)} exp(-(x-\gamma)/\beta)$$

After revision, the design should be returned to the customer for feedback. Table 12 and Figure 29 show this stage's goodness of fit test of the probability density function graph.

Table 12. The goodness of fit test results for receiving feedback for revisions.

Distribution	Kolmogorov - Smirnov	
	Statistic	Rank
Pearson 5	0.17949	1
Inv. Gaussian	0.22813	2
Lognormal	0.23981	3
Normal	0.31446	4
Beta	0.365	5

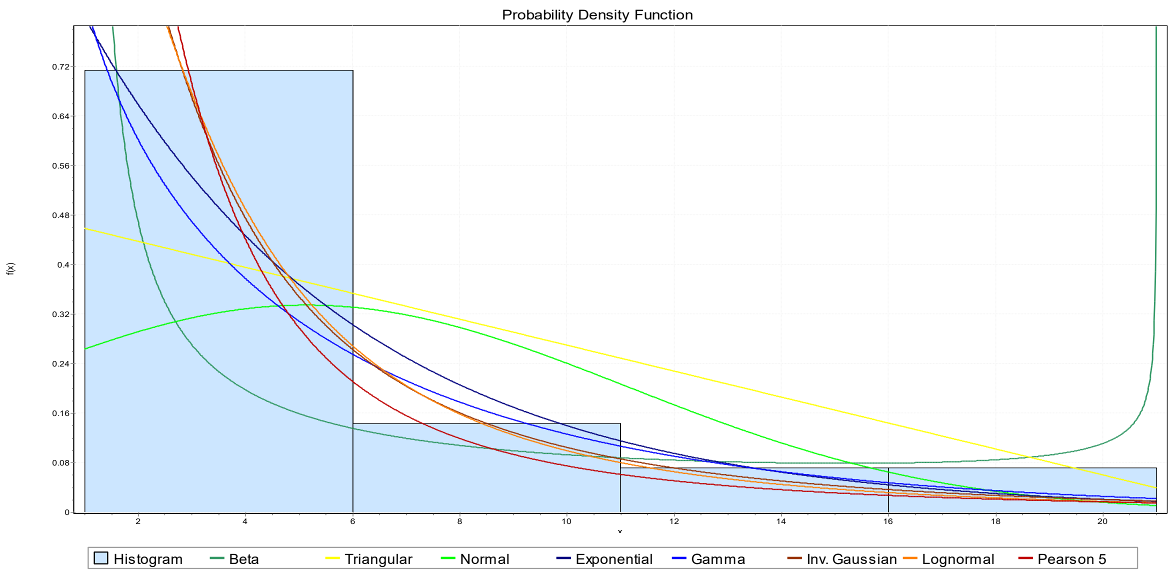


Figure 29. The probability distribution function for receiving feedback for revisions.

Pearson 5 is selected due to the distribution's most minuscule amount of K-S parameter by α = 1.1053 and β = 2.4701.

The next step is developing the designs and generating the contract. As mentioned before, after revisions, the designers start to develop the designs and complete the required document for the contract. Table 13 and Figure 30 show the goodness of fit test result and the probability density function graph for this stage.

Table 13. The goodness of fit test results for developing the designs.

Distribution	Kolmogorov - Smirnov	
	Statistic	Rank
Inv. Gaussian	0.09011	1
Lognormal	0.09036	2
Pearson 5	0.11049	3
Gamma	0.12208	4
Beta	0.19903	5
Normal	0.20125	6

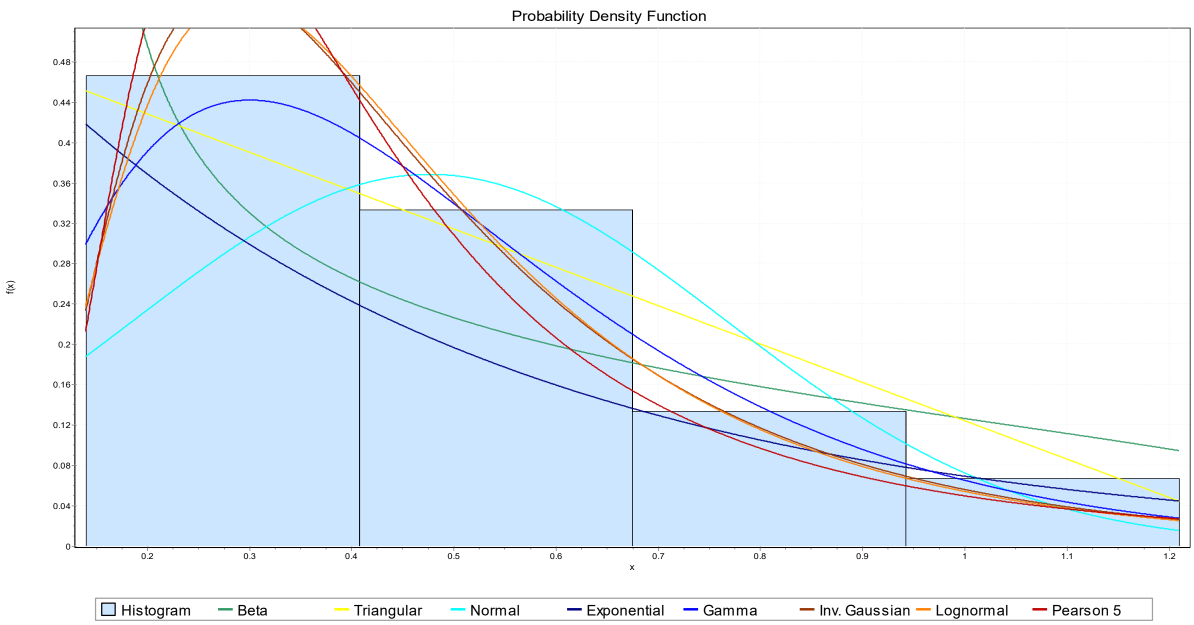


Figure 30. The probability distribution function for developing the design's duration.

The Inv. Gaussian distribution shows the least amount of K-S. The equation related to this distribution is presented as Equation 10 where λ = 1.2896, and μ = 0.47667.

Equation 10.

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} exp\left(-\frac{\lambda(x-\mu)^2}{2\mu^2 x}\right)$$

After sign-off and payment, the designer sends the complete files and designs to the Order desk for processing. Table 14 and Figure 31 result from this stage's goodness of fit test and probability density function graph.

Table 14. The goodness of fit test results for submitting the file to the order desk.

Distribution	Kolmogorov - Smirnov	
	Statistic	Rank
Normal	0.35527	1
Exponential	0.65273	2
Gamma	0.65273	3
Inv. Gaussian	0.65273	4
Lognormal	0.65273	5
Pearson 5	0.65273	6

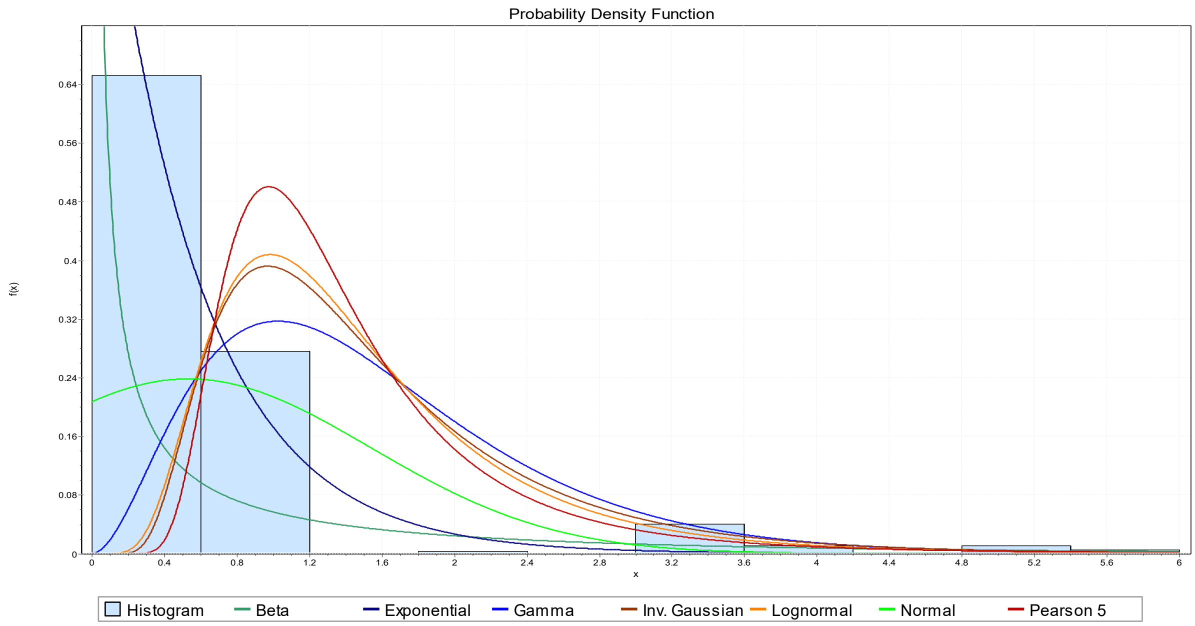


Figure 31. The probability distribution function for submitting duration.

The equation related to the normal distribution is presented as Equation 11 by σ = 0.8547 and μ= 0.38073.

Equation 11.

$$f(x) = \frac{exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)}{\sigma\sqrt{2\pi}}$$

After submitting the file to the order desk, the designer waits for the acknowledgment of the design and other documents' status.

Table 15. The goodness of fit test results for waiting for an acknowledgment.

Distribution	Ko–mogorov - Smirnov	
	Statistic	Rank
Exponential	0.16	1
Gamma	0.16	2
Normal	0.19668	3
Inv. Gaussian	0.21162	4
Lognormal	0.28209	5
Pearson 5	0.29646	6
Triangular	0.55129	7

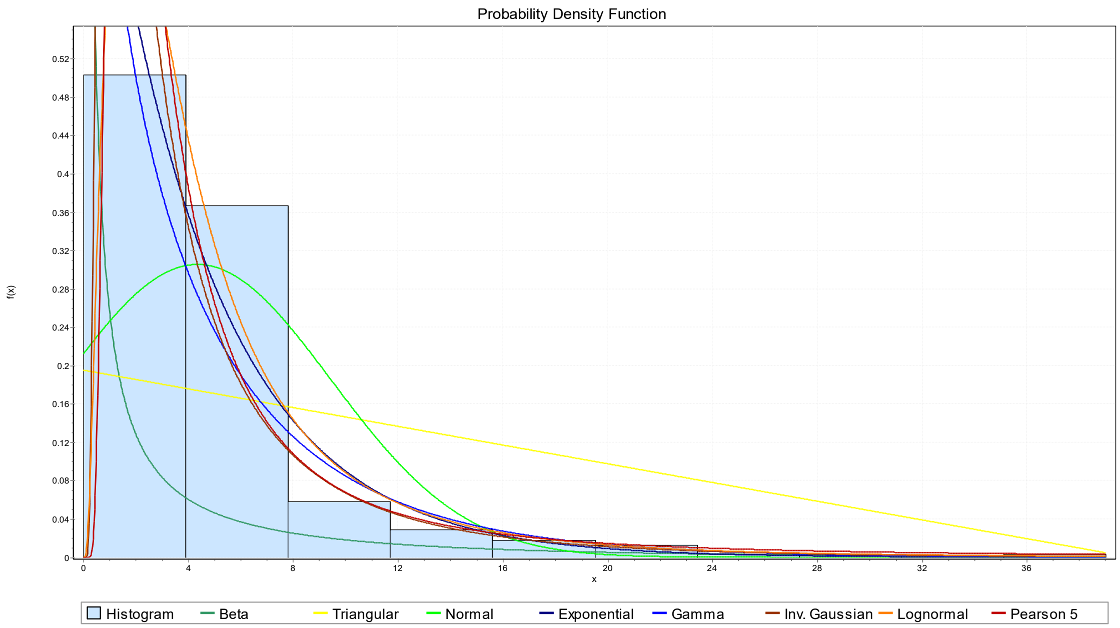


Figure 32. The probability distribution function for waiting for acknowledgment duration.

The equation related to Exponential distribution is presented as Equation 12, where λ = 0.22993.

Equation 12. $$f(x) = \lambda exp\ (-\lambda x)$$

The last process contains submitting the documents to manufacturing. Table 16 and Figure 33 show the results for the distribution fitting of this stage.

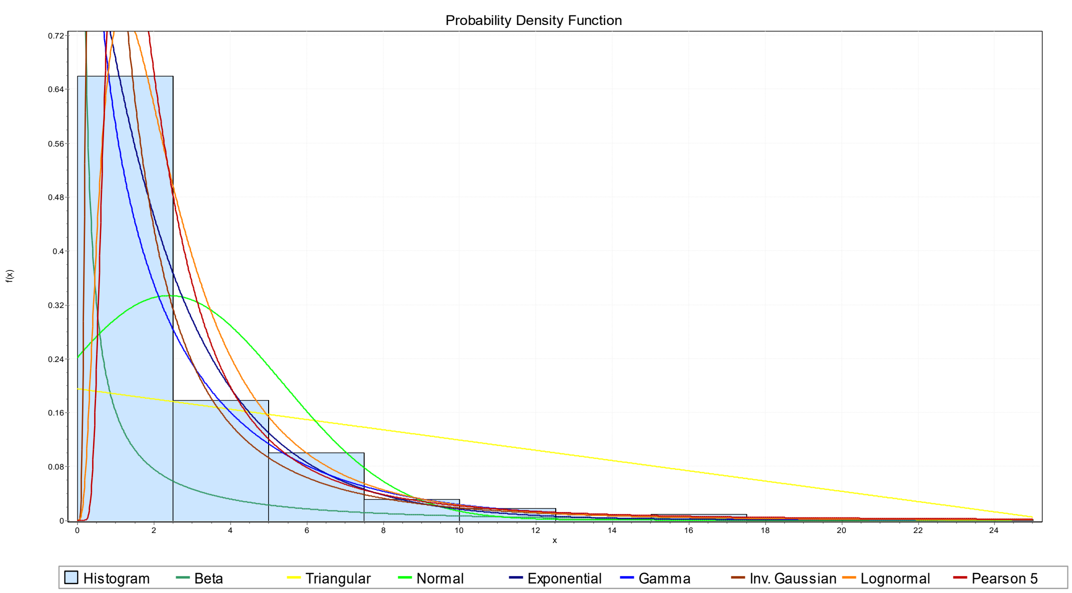


Figure 33. The probability distribution function for the final submits.

Table 16.The goodness of fit test results for the final submits.

Distribution	Ko–mogorov - Smirnov	
	Statistic	Rank
Normal	0.22807	1
Exponential	0.24909	2
Gamma	0.24909	3
Inv. Gaussian	0.24909	4
Lognormal	0.39674	5
Pearson 5	0.4106	6

The equation related to this distribution is presented as Equation 11, by $\sigma = 2.9908$ and $\mu = 2.4055$ for this stage.

After knowing all the required data about the design process and the duration of each process, it is time to analyze the current situation.

Chapter 5: Value Stream Mapping and Simulation

5.1. Overview

This chapter presents the case study's current state map associated with value stream mapping. All the data related to each task's duration is used to draw the current state map. After calculating the VSM parameters, the interventions are presented, discussed, and used to present the future state map. Simulation is being used to validate the current state situation and proposed interventions. First, simulation is used to evaluate the AS-IS situation of the current process to provide a baseline for the proposed interventions. After validation, simulation is used to evaluate the impact of different interventions and their combinations. Modelling the advantages of Lean in the design process is done using this approach to justify how the future state could be beneficial by reducing waste. Simphony.Net 4.6.0 is used to develop a simulation model to test and validate the improvements to the design process. Simphony was developed by Dr. Simaan Abourizk and his research team at the University of Alberta. The simulation models are generated based on the general template and elements of the Simphony.

5.2. Current State Map

After gathering data on the design process, it is time to develop the current state map. The way to map the current state is adopted from Rother and Shook (1999), presented in Figure 6. He suggested six steps to draw the current state map, starting with the customer and then the production process. The current value map for the design process begins with the customer who provides the information. Based on the amount of iteration between the designer and the customer, the customer is considered the operation control unit. In this way, the business development and sales department (BDM) is the supplier who provides the initial information and ends with the manufacturing process and operations as the customer for design information. The next step is to map all the processes between these two. Based on the flow of information presented in Chapter 4, a process box indicates where the information flows. Figure 34 shows the first outline for the current state map.

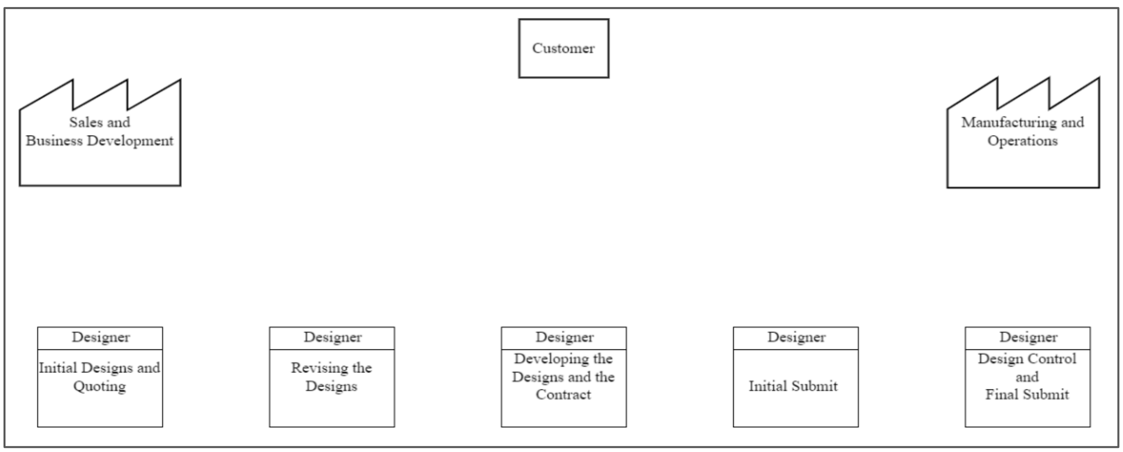


Figure 34. The first outline of the current state map

The next step is to draw the flow of information. Figure 35 shows the outline and the flow of information on the current state map.

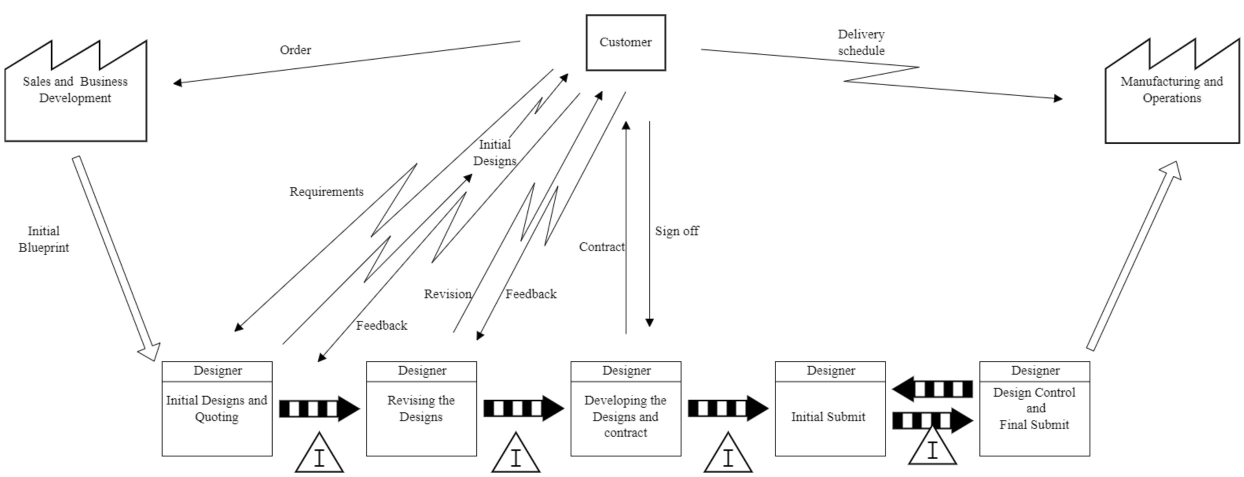


Figure 35. The flow of information on the current state map

The next step is to add process data to continue with the current state map. Although a probability distribution presents the duration for each activity, the average time for each process is considered to calculate the processing time and queue time. Figure 36 shows the process duration for VSM.

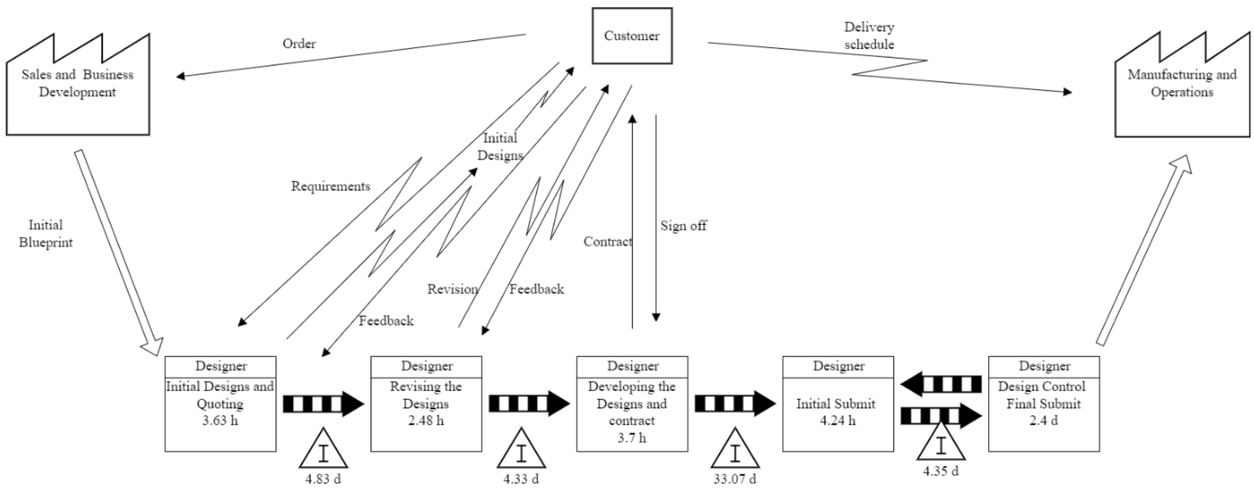


Figure 36. The process duration for the value stream current state map

The last step is to add a timeline to the value stream mapping. This timeline only considers each process's average duration. Figure 37 shows the timeline for the current state map.

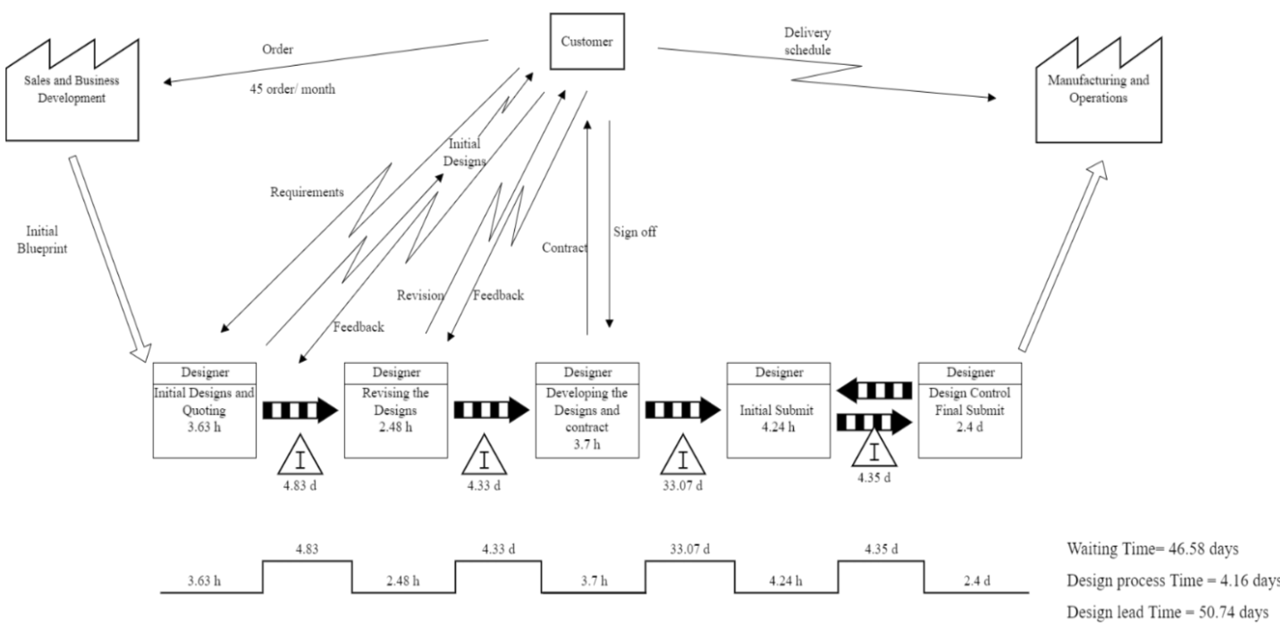


Figure 37. The timeline for the current state map

5.3. Analyzing the Current State Map

After presenting the current state map, it is time to assess the previously specified parameters for value stream mapping. The first one is the Utilization Ratio. The ratio is 8.2%, which indicates that just 8.2 % of the time spent on design is spent on the design process. Although the time buffer on the process may be due to a designer's backlog of several assignments, 8% is still too low for time utilization. The DLT is near the most probable and the fuzzy average time, which validates the VSM. The average lead time needed to complete the process is presented in Table 17.

Table 17.The average DLT from VSM vs the acceptable durations.

Task	Optimistic time	Most probable time	Pessimistic time	Fuzzy average	Value stream mapping
Design Lead time (days)	16.4	47.3	106.4	52	50.74

To meet the client's demand, a designer must finish the design process at a specific rate. To calculate the Takt time, the available design time should be divided by the number of jobs considered for VSM. Since the data is for a year, it means it has 250 working days; the Takt time for the design process may be estimated as the number of jobs = 550, and Takt time 250/550 = 0.45 job/day

If the design team wants to keep up with the Takt time, they must complete two jobs per day on average. The average interval of starting jobs in the current situation is 0.62 days. This number for submitting the jobs to manufacturing is 0.64 days. To get a better idea of the Takt time, the amount of time needed to finish one main project could b used. The data shows that the company has 2.62 jobs per project on average. By multiplying the number of jobs project by the takt time, 0.45 * 2.62 = 1.18 days. In other words, to meet the customers' demand for the selected product family, the design team should finish a project every 1.18 days, approximately four projects per week.

The other parameter to calculate is RTY. The number of reworks and revisions for each job are considered when calculating the Yield for each station. According to this number, just 13.95% of design jobs go through the process defect-free. Table 18 shows the calculation regarding RTY.

Table 18. Rolled throughput yield for each station.

Task	dpu	Yield	RTY
Revision 1	0.95	0.38	0.1556
Revision 2	0.4	0.67	
Design development	0.1	0.90	
Initial submit	0.41	0.66	
Final submits	0	1	

The expected value loss is calculated as follows using Equation 5: 0.95(1) + 0.4(2) + 0.1(3) + 0.41(1) = 2.26.

The other parameter to calculate is Work In Progress (WIP). The WIP was calculated by considering all the process jobs and their duration. Table 19 and Figure 38 show the result for WIP.

Table 19.WIP in the design process.

WIP in the design process	Average	Max	85 % Percentiles
	62	95	83

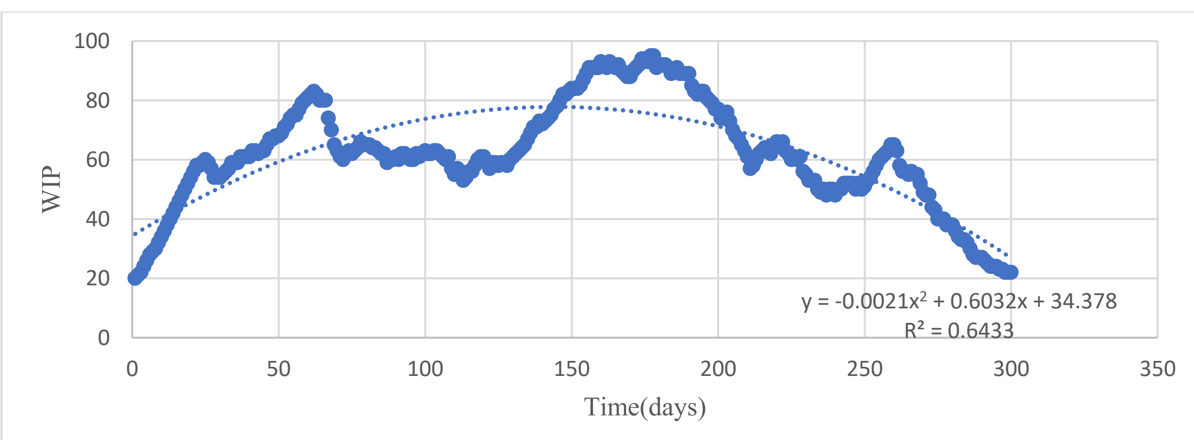


Figure 38. WIP in the design process.

Knowing which step creates value and which makes waste is essential. The step in the process map to create value is the initial design. In this step, the designer must translate the customer's needs into the designs. It has been mentioned that the activities are categorized into three different categories from a waste perspective (refer to Figure 1). Table 20 shows the same categories for the current state map.

Table 20.Category of activities in the VSM.

Non-value-adding operations	Required but non-value-adding processes	Value-adding procedures
Waiting time	Initial Submit	Initial design
Buffer	Feedback	Final submits
Revision		Developing the Designs
Iteration in the design process		

The first waste is the buffer time. Based on the current process mapping, this time is when a designer has a backlog of jobs and postpones working on the assignments. According to the current state map, there is a time frame between signing the contract and initial submitting the designs to the Order desk. This time frame is 33.07 days.

The second waste area is waiting time, when the designer waits for information or feedback from the customer or the Order desk. Based on the current state map, there are three waiting times that the designers are waiting to get the required information to continue with the process. The total duration of the waiting time is 13.04 days. The third one is design errors indicated by the number of revisions. Right now, the likelihood of a design getting revised is 95% (from interviews).

The fourth is a negative iteration in the design process, the number of acknowledgements at the design control stage. The reworks associated with iterations waste Company X's time and money. At the last step of the process, the designs were sent to the Order desk before final submission. The current probability for this iteration is 41 %.

On the other hand, some activities are considered excessive processing in the design process that does not add any value but is necessary for the procedure. Figure 39 shows the categories and their total duration.

Figure 39. The average duration for different value classifications per project.

In the current state map, two steps of feedback on the system are required for the designs to be approved. Also, the work needed to submit the file and manually import all the data in the ERP system is considered overproduction or excessive processing.

5.4. Current State Simulation

Based on the state of the value stream mapping as it stands now, the simulation model for the current state map is created. This model mimics the design process of the case study. Simphony simulation software is used to generate a block diagram after learning about the design process and gathering relevant data on the information flow discussed in previous chapters. It is necessary first to choose the model's input. The Simphony interface is depicted generally in Figure 40.

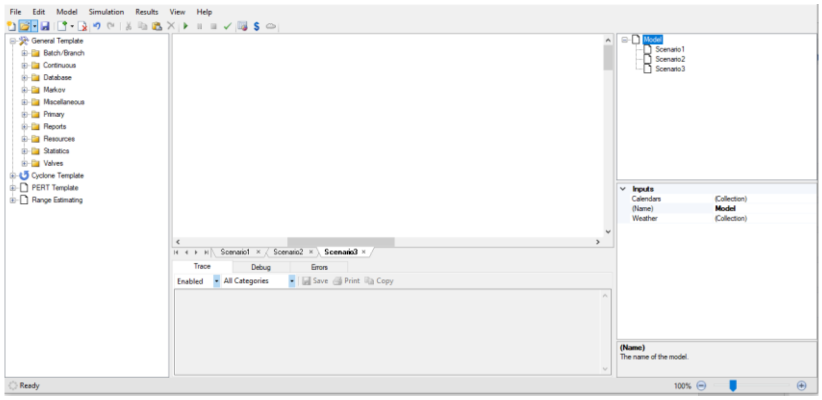
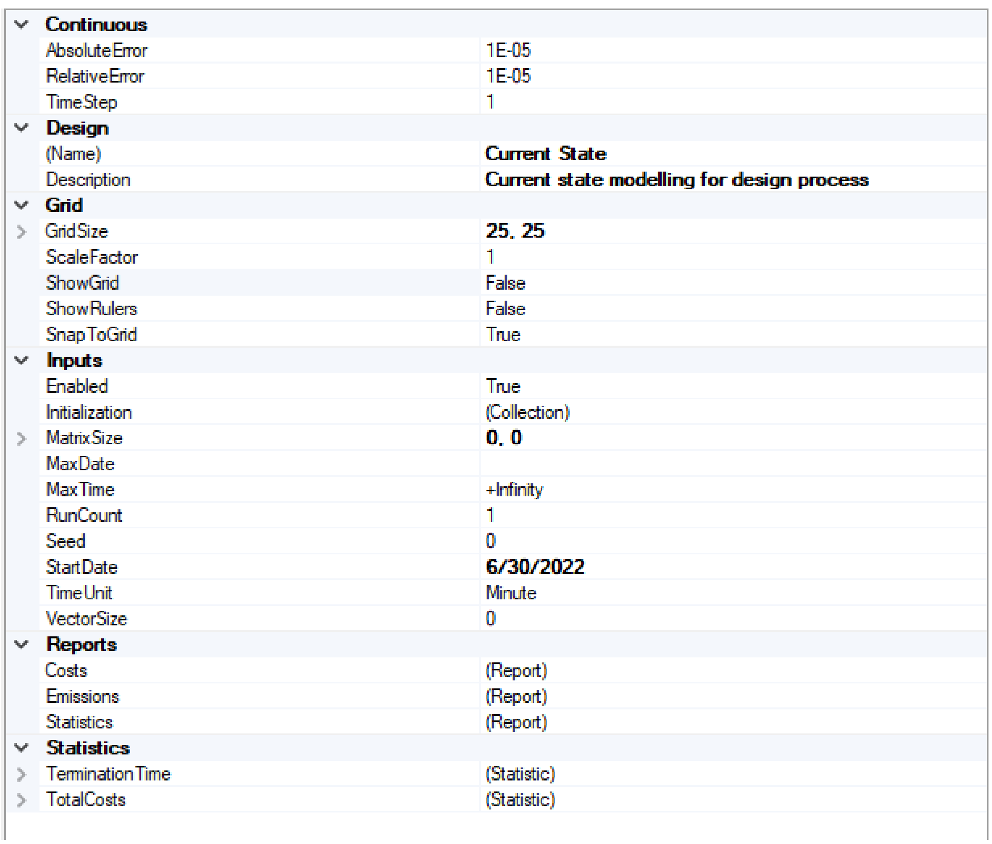


Figure 40. The general interface of Simphony.

Each Simphony model could have multiple scenarios with various inputs to compare them, or it could divide a project into smaller models for each potential outcome. Unless instructed otherwise, the Simphony simulates all the scenarios after running the model. In Figure 41, the inputs for each scenario are shown, and The description of each input is presented in Table 21.



Continuous	
AbsoluteError	1E-05
RelativeError	1E-05
TimeStep	1
Design	
(Name)	**Current State**
Description	**Current state modelling for design process**
Grid	
GridSize	**25, 25**
ScaleFactor	1
ShowGrid	False
ShowRulers	False
SnapToGrid	True
Inputs	
Enabled	True
Initialization	(Collection)
MatrixSize	**0, 0**
MaxDate	
MaxTime	+Infinity
RunCount	1
Seed	0
StartDate	**6/30/2022**
TimeUnit	Minute
VectorSize	0
Reports	
Costs	(Report)
Emissions	(Report)
Statistics	(Report)
Statistics	
TerminationTime	(Statistic)
TotalCosts	(Statistic)

Figure 41. Inputs related to each scenario.

Table 21.Input properties for each scenario.

Input name	Description	Input for the current scenario	Justification
Name & Description	The name of the scenario and the description related to it.	Current State	-
Enable	To determine whether the scenario will be simulated in that Model Run.	True	To be simulated.
Maxdate	The software will terminate the run on this date.	-	No need for this model.
MaxTime	The simulation run will be terminated if it exceeds the maximum allowable simulation time.	250	The number of working days related to the design process.
RunCount	The number of times the scenario should be run.	100	To make sure the model reaches a steady state.
StartDate	The date to start the simulation.	1/4/2021	Based on the ERP database.
TimeUnit	The time unit for the simulation scenario.	Days	Based on the methodology.

Based on the data presented in previous chapters, the number of entities to be created is 550 for the selected job classification. The average interval between jobs in the current situation of the chosen classes is 0.62 days. The general layout of the model is presented in Figure 42.

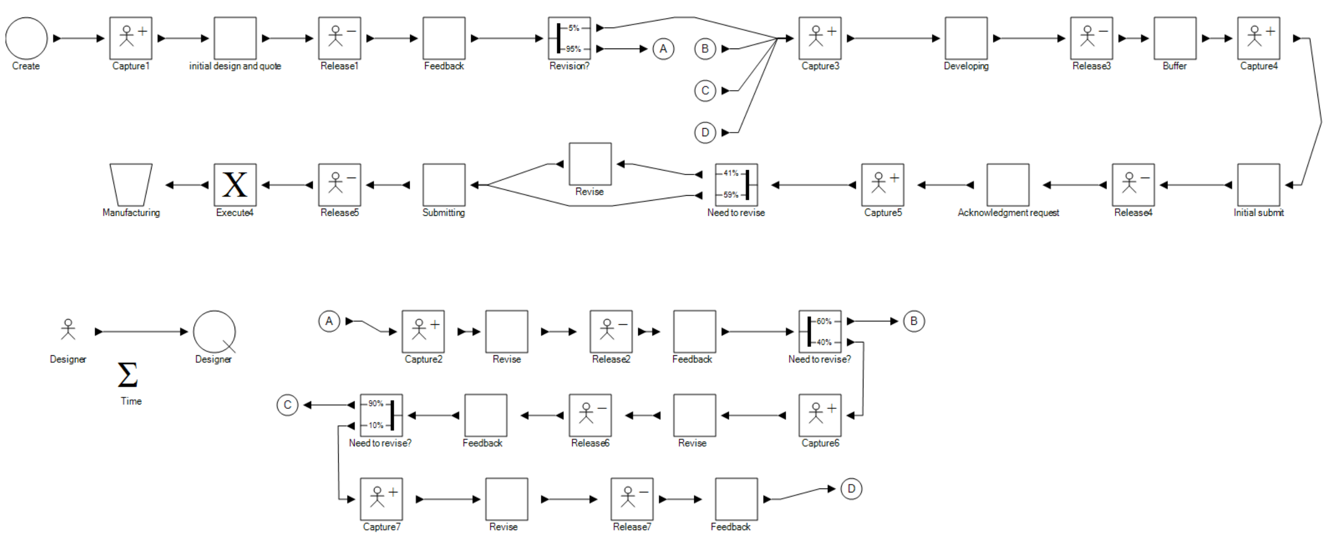


Figure 42. The general layout of the current state map simulation.

Sargent (2011) proposed some techniques to validate the models, such as Event validity, Output validity, Face or process validity, and Historical methods. Multiple approaches based on Al Hattab and Hamzeh (2018) were used to verify if the created model accurately conveys the target concept. These approaches consist of verifying the consistency of input and output data(input verification), monitoring logical model performance through basic indicators and making the appropriate modifications to ensure an accurate simulation(process validation). Monitoring these approaches showed that the model was correctly implemented. The case study model presented to experts required them to validate the model and determine whether or not it was logical, which was determined as a logical model.

Regarding the output validation, the output for the average design lead time could be used to validate the simulation. As a result, it is possible to confirm that the simulation results accurately reflect the studied real-world process. The average DLT for the simulation, value stream mapping and interviews were close to each other, which validates the model's accuracy as part of output validation. Table 22 shows the average result from the simulation of the current situation compared to the current state map of VSM.

Table 22. The current situation in VSM and simulation

	Average DLT
VSM-Current state map	50.74
Simulation-Current state map (Average of three runs)	52.7
Fuzzy average from the interviews	52

5.5. Lean Interventions

After assessing the VSM parameters, it is time to provide alternative remedies. Regarding the case study, some areas need to be improved in the system and the process to make the design more efficient. Based on the interview and value stream mapping, the four levels of improvement are Designer, Organization, Client, and Process. The designer level is the most individualized level to address waste in the design process. Improvements at the organizational level are more expensive and require a coordinated strategy to deliver them within the design team and in interaction with departments. The third level is the client level, which aims to address client waste. Table 23 shows the suggested interventions.

Table 23.Suggested improvements for the case study

#	Interventions	Related Challenge	Suggestions	Improvement Level	Expected Improvement
1	Reducing negative iteration	Insufficient information Client Indecisiveness	Develop a standard checklist with all the necessary information and ask the sales department to use it Reduce the variability	Client	More than 4 % reduction in DLT
2	Reducing the waiting time	Waiting time	Request customer feedback within a reasonable timeframe	Client	More than 4 % reduction in DLT
3	Increasing yield in the initial submission	Design errors	Assurance of quality before sending designs to the Order Desk	Designer	More than a 2 % reduction in DLT
4	Levelling the process	Workforce	Add additional designers as needed to level the process; Train other employees from downstream to be added to the design team in case of need.	Organization	More than 15 % in reducing the DLT
5	Reduce the redundancy associated with ERP	Redundancy in the process	Utilize a custom-built ERP system	Organization	More than 6 % reduction in DLT
6	Using new drawing software	Quoting time Drawing software restrictions	Develop a generative design process Integrating the ERP system with BIM	Organization	Reduction in the initial design and design development
7	Reducing acknowledgment waiting time	Waiting time	The Order Desk functions as a bottleneck; increasing its capacity by transferring some of its responsibilities to other departments would reduce waiting times.	Organization	More than 6 % reduction in DLT
8	Reduce buffer time after the contract	Buffer	Preparing the files for manufacturing in a more timely manner Reduce the invoice validation period and ask the customer to pay in a reasonable timeframe	Designer/Client	More than 4 % reduction in DLT

Regarding the wastes, Levelling the process by balancing load and capacity is essential to improve the process. As things stand, the design queue up after the contract was signed for over twenty days, which slowed down the value stream and prevented the next stage in the process from occurring. In a standard system, the designer should begin working on a design as soon as a higher authority has accepted it. However, the end goal of the design process is to have a continuous flow of information which is very hard to achieve. Maintaining a constant Number of WIP in the process could help to pace the process. In this situation, no work begins for the initial design step unless one is sent to the manufacturing. However, this might be hard to achieve due to the risk of increasing idle time for the designers.

On the other hand, it might increase the pressure from the managers on the designers, which leads to a burden on the designers. Another approach is to increase the capacity. Company X tries to make the most of its human resources by following a high-utilization strategy. When more jobs are available, employees find it more difficult to achieve maximum productivity. Even the design manager does not have time to control designs, and the designers are responsible for errors because there is no design control system. At the same load level, adding more designers decreases the design lead time with fewer WIP. This could happen by training selected employees from other departments to work as designers in case of need.

Iteration in the design process between the customer and the designers is a challenge due to client indecisiveness or a lack of sufficient primary data from marketing and between the designers and other departments due to missing information or requests for minor design changes. The business development manager (BDM) is the first to learn about customer preferences. BDM searches for leads, contacts them, and then passes the information to the designers. As a result, there is no uniform strategy for contacting customers and gathering information. BDM, the design team, and the customer are all intertwined. Sometimes, BDM acts as an intermediary or information transmitter between the designer and the client. In others, the designer and the customer are in direct communication.

As a result, there are many iterations and disruptions in the flow of information, resulting in waste. In addition, the BDM would have to repeat much of the information the customer gave to the designers. The best approach is to inform the sales manager of the various products. He would be able to gather the appropriate data and understand what is possible and what is not. Also, increasing the Yield in the initial package increases Value delivery and reduces the revisions. In the current state process, revisions are wasteful. Improving the initial design by creating more value could lead to fewer revisions. Having a pre-design meeting with the customer and increasing the early involvement of the customer could increase value and reduce the amount of rework and revisions. In the current situation, the likelihood of the design getting negative feedback and requiring rework is 95%. Reducing this by 10% only (from interviews) could improve the system. Early involvement of the customer in the design process, adopting a standard checklist with all necessary information and asking the sales department to use it before sending the leads to the design department and controlling the designs in parallel with all activities by third parties could increase the yield in the process. Increasing yield in the initial submission also could reduce the amount of rework. The current probability for negative iteration in this stage is 41%. Reducing this by 10% could improve the DLT.

Waiting time is one of the main contributors to the design process's waste. An optimized feedback system could help to improve lead time and reduce the effort required to obtain feedback from designers. The design validity and quoting reduction would pressure the customer to give feedback in less time. Currently, the average time to pay the invoice after the contract is 5.64 days.

Reducing this time even by one day could improve the process too. The same is valid for the iteration before final submission, which reduces the average time waiting to get the feedback from the Order desk by one unit and could improve the system. The Order Desk functions as a bottleneck. Increasing its capacity by transferring some of its responsibilities to other departments would reduce waiting times.

The ERP system was mentioned several times in the interviews as one of the significant challenges. The ERP system is difficult to use because of its general form and the fact that it was not designed for a cabinet manufacturing company. They must also upload everything to both the ERP and the internal server, resulting in a high level of redundancy in the process. Designers and others find it challenging to make changes to the information. The designers must manually enter everything into the ERP system, and there is no way to link the ERP system to the design and quoting software. A new and tailor-made ERP system designed for Company X and integrated with BIM would tackle this problem.

The design software's limitations bind designers. All cabinets and patterns are pre-defined, so adding a new cabinet to the software catalogue or increasing the size of an existing one requires a request email to the Order desk department. If it is not feasible to give more access using current drawing software, smother and quicker ways to ask for changes could reduce the lead time. Using new and modern approaches, such as generative design for designing the cabinet, especially for the initial design and quoting package, would benefit the organization.

Customization indicates that the product is not ordinary and that a particular operation is required to design or manufacture it. It could be a unique design the customer desires or a pattern that is difficult to produce. All departments acknowledge the difficulties that come with customization. The designers are unfamiliar with every aspect of design at this stage or do not know how to translate the customer's need or vision into a design. Finding unique materials or colours during the operation stage is difficult. Sometimes the amount of material required for that customization is only a few sheets of MDF or other material. Still, they must purchase more to obtain it from specific suppliers, and shipping a few sheets is expensive for both parties. In the production stage, the machines are designed, and the production line is laid out so that it can build cabinet parts as quickly as possible, such as doors and carcasses. Any other pattern that requires unique manufacturing would cause a manufacturing disruption. Aside from that, the workers and operators are unfamiliar with every cabinet construction method of cabinet construction, and machines cannot do the customization cannot be done by machines. In these cases, a company specialist or an external specialist should be hired to build the cabinets, which is time-consuming. Reducing variability and not accepting customization is a better approach to save time and money for the current situation.

The scenarios were constructed following the possible future state and included all of the interventions outlined in Table 23. First, individual interventions are simulated, followed by simulations of intervention combinations. The combinations are constructed by combining two interventions, three, four, and up to eight interventions. In total, 255 intervention combinations were built and simulated to evaluate the system in different situations. Regarding the improvement of design lead time, levelling the process is highly advantageous and results in a 15% improvement in DLT reduction and a 17% increase in the utilization ratio. Following that, new drawing software and generative design approaches ranked second in terms of the most remarkable improvements for DLT, with an increase of 10.4%; however, it ranked lowest in terms of improvement to the utilization ratio, at 1.9%. It is a result of the decrease in DPT as a result of the intervention. Similar to intervention 6, but with a greater improvement in utilization ratio improvement percentage, is intervention 5. Interventions 1 and 3 are the only ones that aim to reduce rework and increase yield, so they are the only ones in which RTY has improved. Additionally, the anticipated value of these two interventions has decreased to 1.56 and 1.85, respectively. The results for individual interventions are presented in Table 24.

Table 24.Simulation results for individual interventions.

Interventions	DLT (days)	Average waiting jobs	Utilization	RTY	Expected value loss	% of change compared to the current state simulation		
						DLT	Utilization	RTY
Current state simulation	52.7	63	0.079	0.156	2.26	-	-	-
1	50.1	58	0.083	0.257	1.56	4.9%	5.2%	64.9%
2	50.6	64	0.082	0.156	2.26	4.0%	4.2%	0.0%
3	51.5	60	0.081	0.235	1.85	2.3%	2.3%	50.7%
4	44.7	46	0.093	0.156	2.26	15.2%	17.9%	0.0%
5	48.9	55	0.082	0.156	2.26	7.2%	3.6%	0.0%
6	47.23	52	0.080	0.156	2.26	10.4%	1.9%	0.0%
7	48.6	61	0.086	0.156	2.26	7.8%	8.4%	0.0%
8	50.4	64	0.083	0.156	2.26	4.4%	4.6%	0.0%

To evaluate the result of combining different interventions and as an opportunity to find a way to reduce more non-value-adding activities. Although implementing different interventions simultaneously seems to be an achievement, different intervention combinations were simulated to assess each simulation's result. The results of the 255 simulations are presented in Appendix A.

Analysis of the results for 255 combinations demonstrates that adding more intervention leads to more improvements. It is anticipated to have the most significant improvement across all eight interventions. This combination ranked first in utilization ratio improvement, with a 47.3% reduction in DLT and an increase in utilization ratio to 13.7%. Table 25 displays the results for the most significant reductions in DLT ranked from 1 to 25.

Table 25.Simulation results for intervention combinations based on DLT improvements

# Combination	Interventions	DLT	Average waiting jobs	Utilization ratio	RTY	Expected value loss	DLT Reduction %	Utilization Increase %	Rank
255	1&2&3&4&5&6&7&8	27.79	34	0.137	0.39	1.15	47.3%	73.2%	1
250	1&2&3&4&6&7&8	27.99	35	0.136	0.39	1.15	46.9%	72.0%	2
252	1&2&4&5&6&7&8	28.35	35	0.134	0.26	1.56	46.2%	69.8%	3
247	1&2&3&4&5&6&7	29.64	30	0.128	0.39	1.15	43.8%	62.4%	4
237	1&3&4&6&7&8	29.65	32	0.128	0.39	1.15	43.7%	62.4%	5
249	1&2&3&4&5&7&8	30.28	39	0.132	0.39	1.15	42.5%	67.3%	6
253	1&3&4&5&6&7&8	30.3	33	0.125	0.39	1.15	42.5%	58.9%	7
223	1&2&3&4&6&8	30.4	36	0.125	0.39	1.15	42.3%	58.4%	8
254	2&3&4&5&6&7&8	30.72	38	0.124	0.29	1.45	41.7%	56.7%	9
248	1&2&3&4&5&6&8	30.83	36	0.123	0.39	1.15	41.5%	56.1%	10
232	1&2&4&6&7&8	30.93	39	0.123	0.26	1.56	41.3%	55.6%	11
229	1&2&4&5&6&7	31.25	33	0.122	0.26	1.56	40.7%	54.0%	12
178	1&2&4&6&8	31.32	37	0.121	0.26	1.56	40.6%	53.7%	13
222	1&2&3&4&6&7	31.38	34	0.121	0.39	1.15	40.5%	53.4%	14
230	1&2&4&5&6&8	31.45	36	0.121	0.26	1.56	40.3%	53.1%	15
231	1&2&4&5&7&8	31.52	43	0.127	0.26	1.56	40.2%	60.8%	16
245	2&4&5&6&7&8	31.6	41	0.120	0.16	2.26	40.0%	52.3%	17
243	2&3&4&6&7&8	31.7	40	0.120	0.23	1.85	39.8%	51.9%	18
211	2&4&6&7&8	31.85	41	0.119	0.16	2.26	39.6%	51.1%	19
235	1&3&4&5&6&8	31.9	33	0.119	0.39	1.15	39.5%	50.9%	20
234	1&3&4&5&6&7	32.5	29	0.117	0.39	1.15	38.3%	48.1%	21
177	1&2&4&6&7	32.6	34	0.117	0.26	1.56	38.1%	47.7%	22
218	4&5&6&7&8	32.6	35	0.117	0.16	2.26	38.1%	47.7%	23
220	1&2&3&4&5&7	32.6	36	0.123	0.39	1.15	38.1%	55.4%	24
100	1&2&4&6	32.8	31	0.116	0.26	1.56	37.8%	46.8%	25

Concerning the improvement in RTY and expected value loss of yield, any combination of interventions 1 and 3 (65 combinations) has the most remarkable improvement of 148% in RTY.

The value classification pr project for the current state situation and IC255 is presented in Figure 43, showing a considerable improvement in reducing non-value-adding activities.

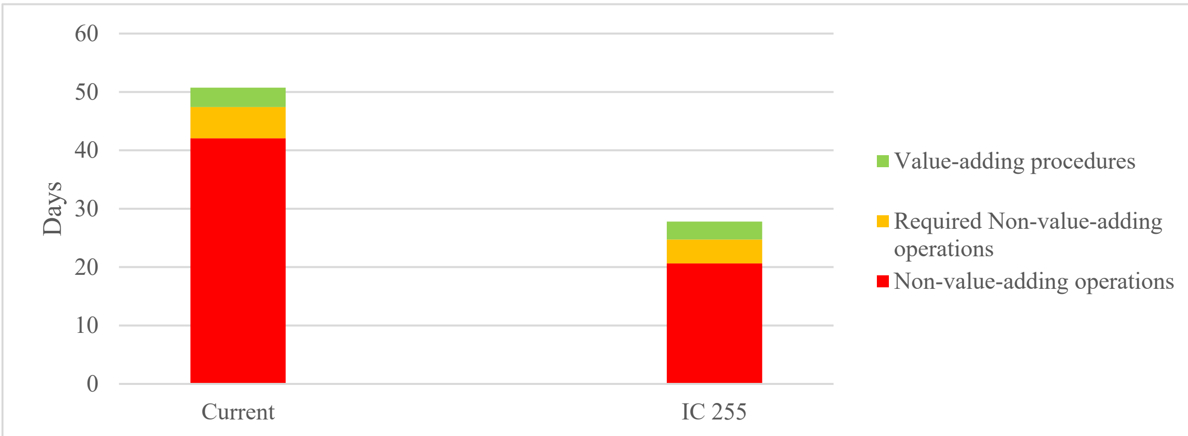


Figure 43. Value classifications per project

It is expected that by implementing all interventions, not only the non-value adding but required non-value adding and value-adding activities also have a reduction in time which is an opportunity to reduce time. Figures 44 and 45 show the DLT, and its percent of improvement, respectively. Figure 46 also shows the utilization ratio for different interventions.

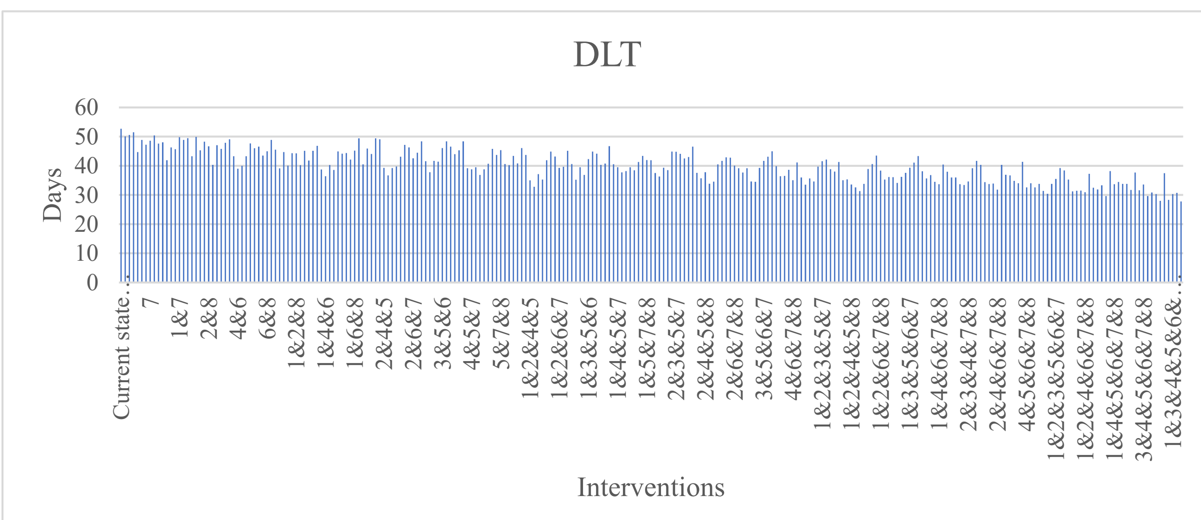


Figure 44. Design Lead Time for suggested interventions

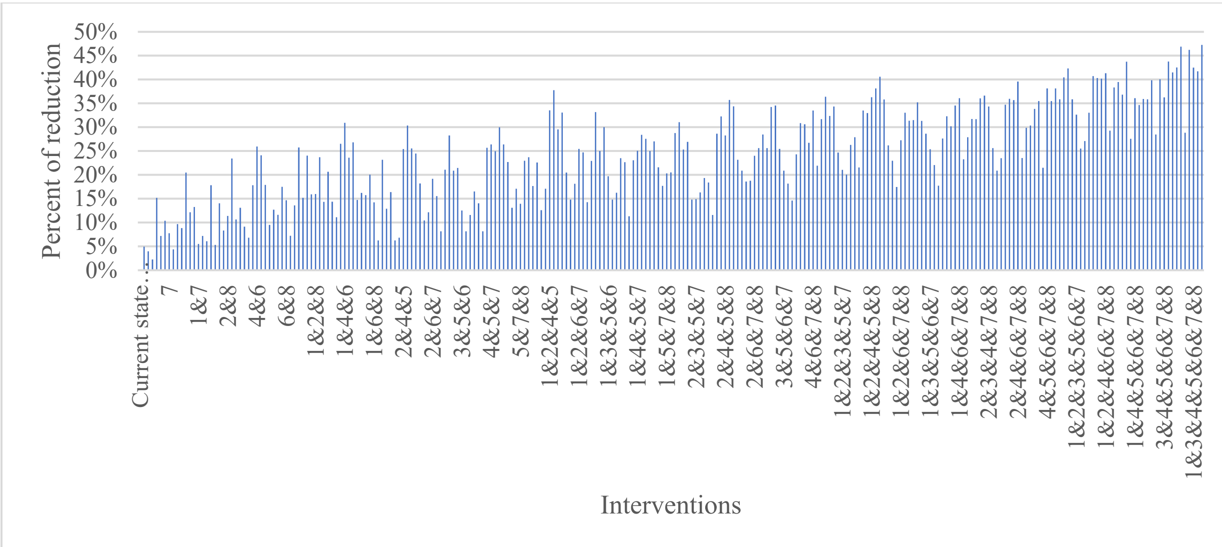


Figure 45. Percent of DLT reduction for suggested interventions compared to the current state

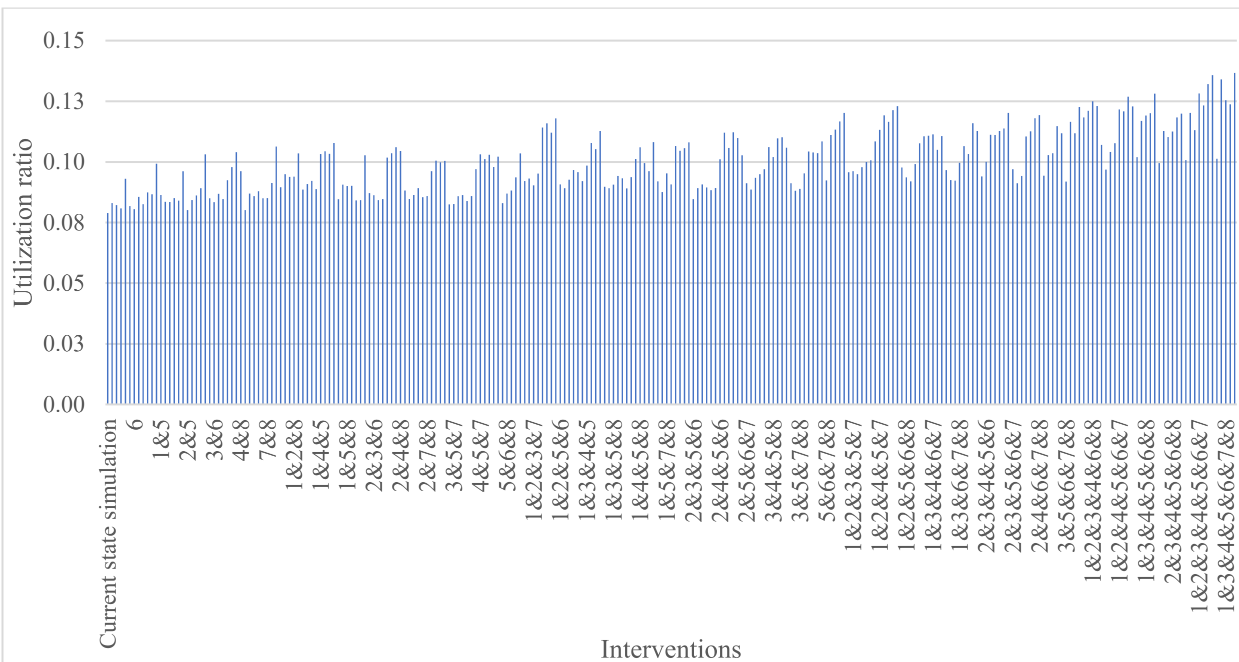


Figure 46. Utilization ratio for different interventions

The results of the future state simulation indicate an improvement in DLT. Implementing all interventions would be expected to cut the lead time in half, which is highly advantageous for a company with more than 1,000 jobs per year and saves a substantial amount of time and money. This enhancement is the result of increased productivity and decreased work in progress.

Sensitivity analysis is a method for evaluating the quality of a model or a conclusion derived from a model (Saltelli & Annoni, 2011). A sensitivity analysis of input parameters was performed to analyze the model's outputs in light of suggested interventions. A single parameter was modified and monitored to determine the outcome. The selected parameters were yield, waiting time, and buffer, represented by interventions 1,4 and 6. For the first intervention, the unit increase was accomplished by a 10% increase in yield each time. For intervention 4, the increase was the addition of more designers from downstream in order to reduce the buffer; for intervention 6, the increase was a 5% reduction in the time required to develop a design. Each intervention was simulated separately, and each time, as described previously, a single parameter was altered, and the results were recorded. Figure 47 depicts the variations in design lead time caused by a change in the simulation model's input parameter.

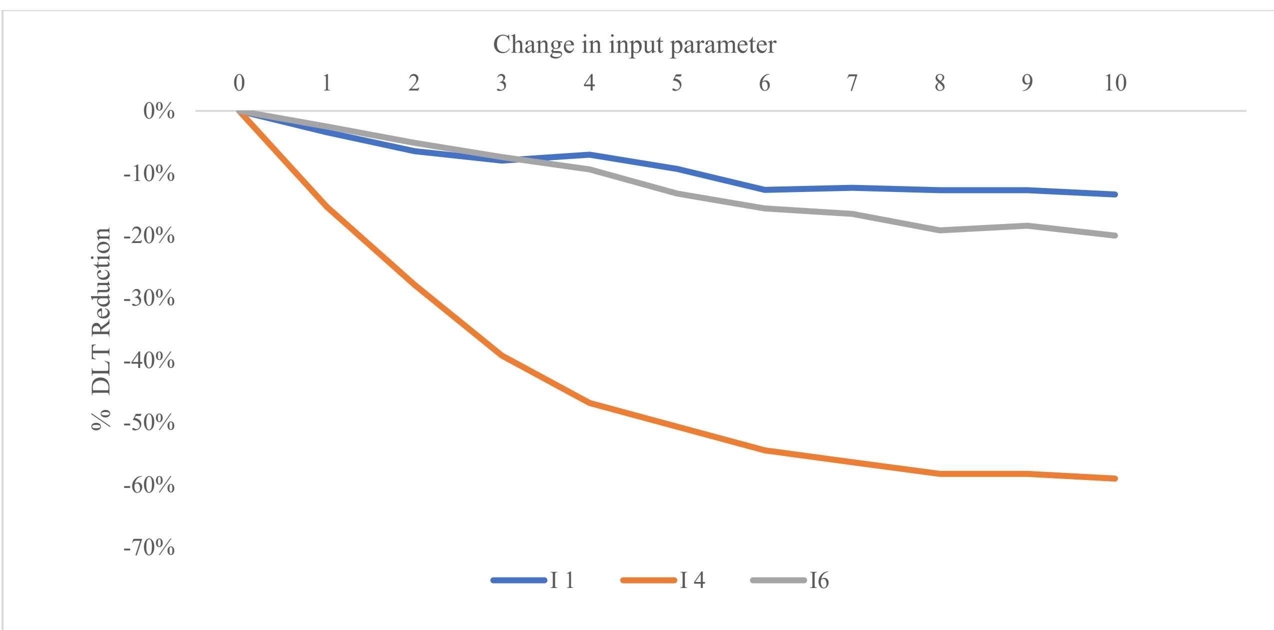


Figure 47. % of DLT reduction by the change in the input parameters

As shown in figure 47, intervention number 4 has the greatest impact on lead time changes; by modifying it by one unit, the DLT is reduced by 15%. This trend slows as more units are added and begins to stabilize after six units. By reducing the time by 5 percent each time, Intervention 6 was modified by the change in design development time. The decrease continues with a constant decline until it reaches its peak, after which the trend becomes stable. An uneven procedure may result in a 40% decrease in yield for the first intervention. Although there is a jump from 50% to 60%, the reduction remains steady.

Chapter 6: Conclusions

6.1. Conclusions

The main idea of this thesis is to adopt a methodology to improve the design process by eliminating waste and non-value-added activities. The methodology used in this research was DSR which contains value stream mapping as the main principle of investigation and then simulation to assess the suggested improvements. A Cabinet manufacturing company as part of the off-site system is investigated as a case study to validate the modifications. For the case study, different ways are adopted to collect the data on the duration of each task in the design process as well as the descriptive statics of the process. Multiple interviews were conducted to understand the design process better and collect data on missing points. It was found that dealing with an ERP system forces excessive processing time. Also, the number of revisions based on customer feedback is high. The ERP database was used to collect data too. The duration of each step of the design process was calculated as the probabilistic distribution to better conform to the actual situations.

The value stream model was built on understanding the process better and identifying waste in the process. Using the current state map, it was evident that the utilization ratio of the system is around 8 %. Based on this ratio, more than 90 % of the time for a design to exit the process is idle. One of the weaknesses in the design process of the case study was rework caused by errors in the designs or lack of value delivery. The RTY for the process is 15.56 % which shows the amount of rework caused by errors or feedback. Increasing RTY would save time and money for the system.

The proposed framework related to the research is presented in Figure 16. The main idea of this proposed framework was to create a roadmap for organizations to find waste and design remedies to mitigate the effect of waste on the process.

The introduced framework helps evaluate processes and increase efficiency during the design phases in offsite construction and built-to-order companies. In addition to creating methodologies based on statistical analysis and simulation for assessing the recommended interventions, the innovation of this framework resides in the precise procedures and direction offered to improve these phases utilizing Lean tools.

On the result of the suggested interventions, the simulation shows the estimated improvements. The simulation estimated improvements of 47.3% in design lead time and an 89% increase in utilization ratio as a result of implementing the interventions. This time reduction is significant for the cost associated with it. However, more cost reduction can be achieved by implementing Lean tools to improve the processing time.

The case study contains additional problems that call for more managerial solutions. Sometimes the amount of customer involvement in the process causes high variability, and the customer is the one who creates value. This made it hard for the designers due to lots of feedback and required rework. In these cases, it is hard to standardize the process. Reducing the variability and designing a minimum variable product helps the company to shorten the lead time and increase capacity by reducing work in progress. The good practices and the main ideas to improve the system that came from the interviews with the designers are as follows:

- Having an in-person meeting with the client before starting to design
- Training Programs

- Reducing the WIP in the system by processing the designs and sending them to manufacturing. This could be done by forcing the customers to schedule a delivery time within a month.
- Reducing the variability in the designs
- Preparing a checklist with all necessary information and asking the sales department to use it before sending the leads to the design department.
- Defining a price threshold for the compulsory design control before sending it to manufacturing
- Increasing the capacity of the design team by adding more designers. Although in this case, it only works if the number of jobs stays at the same level.
- Decreasing the number of revisions
- Clear role definitions between the design team

6.2. Evaluation of interventions and Lessons Learned

The DSR methodology concludes with a validation evaluation of the proposed framework and interventions. During the evaluation, it would assess the extent to which the artifact contributes to resolving the issue. To determine if a proposed solution fulfills its stated objectives, it is necessary to compare the stated objectives to the actual outcomes of its execution. Depending on the problem's context and the topic being assessed, a number of evaluation procedures may be employed.

In this study, the company under study were surveyed. The questionnaire was divided into three sections. The first section used a 5-point Likert scale with the following categories: 1- very poor, 2- poor, 3-neither poor nor good, 4- good, and 5- excellent to solicit feedback on the effectiveness of the interventions. Table 26 shows the result for the first section.

Table 26. Survey results section 1

Interventions	Effectiveness
1: Reducing negative iteration	4
2: Reducing the waiting time for feedback	3.5
3: Controlling the designs	4.5
4: Add additional designers as needed	4
5: Reduce the redundancy	4
6: Using new drawing software	4.5
7: Reduce waiting time for the Order desk	4.5
8: Reduce buffer time after the contract	4

According to the findings in this section, respondents believe that all proposed solutions adequately reduce waste. The lowest possible score was associated with timely customer feedback collection through follow-up.

The second section was about applicability and asked the participants to rate it as 1- not at all, 2- slightly, 3- moderately, 4- very and 5- extremely. Table 27 shows the result for this section.

Table 27. Survey results section 2

Interventions	Applicability
1: Reducing negative iteration	3
2: Reducing the waiting time for feedback	3.5
3: Controlling the designs	4.5
4: Add additional designers as needed	3.5
5: Reduce the redundancy	4
6: Using new drawing software	3
7: Reduce waiting time for the Order desk	3.5
8: Reduce buffer time after the contract	3

There appears to be some concern regarding the applicability of new approaches in design, such as new software, due to designers' unfamiliarity with other software, which could be resolved through training. Additionally, reducing the invoice validation period may be challenging to reduce the buffer time after the contract.

The Third section used the section one score scale and requested feedback on the framework's simplicity to understand, practicability to follow, sufficiency, and industry-wide applicability. Table 28 shows the result of the survey.

Table 28.Survey results section 2.

Framework	Score
The framework is simple and easy to understand	4
The framework is practicable to follow	4
The framework has sufficient steps to cover all aspects	4.5
The framework is generally applicable in the industry	3

According to the findings, participants viewed the framework as simple, implementable, and generally relevant to the field. In addition, they believed it was sufficient to cover everything they needed to know and assist in achieving the desired outcomes.

6.3. Research Objectives and Contributions

As mentioned before, the research's main idea is to utilize the design process to reduce waste and increase efficiency. Efficiency could be achieved by reducing waste and non-value added. If a more efficient or automated process is utilized, less time will be required to complete the task.

Two objectives are specified for this research, which need to be addressed at the end of the research. The followings are these objectives.

- Identify waste in the design process in the build-to-order off-site manufacturing.

This objective was accomplished by utilizing value stream mapping as a Lean tool. Design is a creative process with value delivery as its primary objective. Information flow must be captured in design even though goods can be tracked during production. Waste and non-added value are inherent to every process. Before eliminating waste from a specific process, the process must be studied and the system evaluated. Using Lean tools such as value stream mapping to evaluate the process is beneficial when confronting design challenges. Value stream mapping is utilized to map the flow of information between various stakeholders and design process stations. Another approach to this objective was doing interviews to collect the required information about the design process and get to know the process. The simulation was also used to get visibility into the process.

- Develop a framework to evaluate different methods to mitigate and eliminate waste.

This study develops a framework to guide the process of mitigating waste and recommends implementing interventions in organizations. This framework consists of four significant steps: 1) defining the deliverable and establishing metrics for it; 2) identifying challenges and information and resource waste; 3) developing interventions, and 4) implementing interventions and validating their results. This study develops waste reduction interventions using Lean principles, and by following these steps, the results are validated. Simulation is used to evaluate the state of a process before and after the implementation of interventions by calculating predetermined metrics. Simulation is a modern technique for saving money and time. It allows researchers to modify their results and monitor their progress before implementing them in the real world, which could result in time and money loss.

As a result of this research, some contributions were made to both industry and academia. The contributions achieved by doing this study are as follows:

Academic:

- Developing and validating the lean tools such as value stream mapping for the design as a creative process
- Adopting Lean approaches to Integrate the design process, and simulation into a cohesive package

Industry:

- Developing a framework to standardize identifying and eliminating waste to improve productivity
- Helping organizations to improve the design process by collecting knowledge about the design process

6.4. Research limitations and Future work

This research was not exceptional, as all research has limitations. This study had some limitations, which are discussed in the following sections.

- Several experts were interviewed to collect the necessary information about the procedure using interviews as a data collection method. The most important criterion is the role of participants in the design process. Typically, interviewing a larger group of experts would give more results about the process and evaluate the outcome.
- The study was conducted regardless of the participants' demographics. Analyzing some characteristics, such as years of experience, as a variable could help determine the efficacy of designer education programs in the workplace.
- Only a few classes were mapped regarding the process mapping with value stream mapping. This was due to the wide range of services offered to various customers.
- The metrics were chosen based on this study's research scope and key elements of comparable value stream mapping studies. Due to the nature of the available data, time and rework were the two primary waste monitors adapted and utilized in this study. Consequently, the metrics utilized in this study primarily focused on these two factors. Using other factors to monitor waste would be beneficial for locating waste that is hidden within the process.

- The framework should be validated using different approaches or another case study to compare the results.
- Additional interventions may need to be analyzed to determine their impact on the design process. These eight interventions were developed based on the interviews and the availability of technology for small and medium-sized businesses.

This study presents a method for integrating Lean tools into the design process and increasing efficiency by eliminating waste and non-value-added activities. Future research would benefit from evaluating the development of a digital platform or dashboard to integrate all design processes and tools, including enterprise resource planning (ERP) and design software. This digital twin for the design process would aid professionals in reducing waste and increasing value delivery.

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Appendix A: Simulation results for all interventions and intervention combinations.

As mentioned before, multiple combinations of interventions were generated in Symphony and simulated to collect the results. The combination of the two interventions reveals nested improvements. Intervention Combination (IC) 1&4 yields the most significant reduction in DLT, by 20,5%, and utilization rate by 25%. Combining intervention 1 with intervention 2 improves utilization by 10.7%, placing it second. Nevertheless, IC 1&3 results in a 148.4% improvement in RTY. All combinations of intervention 1 with other interventions result in a decrease in the expected value loss. However, only IC 1&3 improved from 2.26 to 1.15, whereas the expected value loss for the other combinations is 1.56. Table 29 shows combinations of intervention one with another intervention.

Table A1. *Combining two interventions (intervention 1 & others)*

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&2	47.6	0.087	0.257	1.56	9.7%	10.7%	64.9%
1&3	48.05	0.087	0.387	1.15	8.8%	9.7%	148.4%
1&4	41.9	0.099	0.257	1.56	20.5%	25.8%	64.9%
1&5	46.3	0.086	0.257	1.56	12.1%	9.4%	64.9%
1&6	45.7	0.084	0.257	1.56	13.3%	5.9%	64.9%
1&7	49.8	0.084	0.257	1.56	5.5%	5.8%	64.9%
1&8	48.9	0.085	0.257	1.56	7.2%	7.8%	64.9%

For intervention 2, similar to the first, IC2&4 yield the most remarkable improvement in utilization ratio. Again, IC 2&8 results in a significant improvement in terms of utilization ratio improvement. Regarding RTY improvement, the IC2&1 demonstrates a 64.9% improvement in

RTY, with a static expected value loss of 1.56. Table 30 shows combinations of intervention two with another intervention.

Table A2. *Combining two interventions (intervention 2 & others)*

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&2	47.6	0.087	0.257	1.56	9.7%	10.7%	64.9%
2&3	49.5	0.084	0.235	1.85	6.1%	6.5%	50.7%
2&4	43.3	0.096	0.156	2.26	17.8%	21.7%	0.0%
2&5	49.9	0.080	0.156	2.26	5.3%	1.5%	0.0%
2&6	45.3	0.084	0.156	2.26	14.0%	6.8%	0.0%
2&7	48.3	0.086	0.156	2.26	8.3%	9.1%	0.0%
2&8	46.7	0.089	0.156	2.26	11.4%	12.8%	0.0%

Like the first two interventions, Combining Intervention 3 with Intervention 4 appears to have the most excellent effect on DLT reduction and utilization rate. Regarding expected value loss and RTY, as mentioned previously, IC3&1 shows improvement, whereas combinations with other interventions produce the same results for both. Table 31 shows combinations of intervention three with another intervention.

Table A3. *Combining two interventions (intervention 3 & others)*

Interventio n combinatio	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&3	48.05	0.087	0.387	1.15	8.8%	9.7%	148.4%
2&3	49.5	0.084	0.235	1.85	6.1%	6.5%	50.7%
3&4	40.35	0.103	0.235	1.85	23.4%	30.6%	50.7%
3&5	47.08	0.085	0.235	1.85	10.7%	7.6%	50.7%
3&6	45.8	0.083	0.235	1.85	13.1%	5.7%	50.7%
3&7	47.89	0.087	0.235	1.85	9.1%	10.0%	50.7%
3&8	49.1	0.085	0.235	1.85	6.8%	7.3%	50.7%

The IC4&6 simulation reduces the DLT by approximately 12 days compared to the current state simulation. Additionally, its utilization ratio has increased by 24%. The utilization ratio is enhanced by 31.8% in IC4&7. As expected, only IC4&1 and IC4&3 have improvements in expected value loss and RTY. The combinations of intervention four and another intervention are displayed in Table 32.

Table A4. *Combining two interventions (intervention 4 & others)*

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&4	41.9	0.099	0.257	1.56	20.5%	25.8%	64.9%
2&4	43.3	0.096	0.156	2.26	17.8%	21.7%	0.0%
3&4	40.35	0.103	0.235	1.85	23.4%	30.6%	50.7%
4&5	43.3	0.092	0.156	2.26	17.8%	17.0%	0.0%
4&6	39.02	0.098	0.156	2.26	26.0%	24.0%	0.0%
4&7	40	0.104	0.156	2.26	24.1%	31.8%	0.0%
4&8	43.26	0.096	0.156	2.26	17.9%	21.8%	0.0%

Regarding intervention five and its combinations, IC5&4 has the most utilization ratio and DLT improvements; after that, IC5&7 stands second. The combinations of intervention five and another intervention are displayed in Table A5.

Table A5. *Combining two interventions (intervention 5 & others)*

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&5	46.3	0.086	0.257	1.56	12.1%	9.4%	64.9%
2&5	49.9	0.080	0.156	2.26	5.3%	1.5%	0.0%

3&5	47.08	0.085	0.235	1.85	10.7%	7.6%	50.7%
4&5	43.3	0.092	0.156	2.26	17.8%	17.0%	0.0%
5&6	47.68	0.080	0.156	2.26	9.5%	1.5%	0.0%
5&7	46	0.087	0.156	2.26	12.7%	10.2%	0.0%
5&8	46.57	0.086	0.156	2.26	11.6%	8.8%	0.0%

Regarding intervention six and its combinations, IC6&4 has the most utilization ratio and DLT improvements; after that, IC6&7 stands second. The combinations of intervention six and another intervention are displayed in Table A6.

Table A6. *Combining two interventions (intervention 6 & others)*

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&6	45.7	0.084	0.257	1.56	13.3%	5.9%	64.9%
2&6	45.3	0.084	0.156	2.26	14.0%	6.8%	0.0%
3&6	45.8	0.083	0.235	1.85	13.1%	5.7%	50.7%
4&6	39.02	0.098	0.156	2.26	26.0%	24.0%	0.0%
5&6	47.68	0.080	0.156	2.26	9.5%	1.5%	0.0%
6&7	43.48	0.088	0.156	2.26	17.5%	11.3%	0.0%
6&8	44.96	0.085	0.156	2.26	14.7%	7.6%	0.0%

Adding intervention 7 to another intervention results in a tremendous DLT and utilization ratio improvement for IC7&4. It is the same for invention 8, as IC8&4 has the most improvements. It has been stated that only the combination of interventions 1 and 3 improves the expected value loss and RTY. Table A7 shows the intervention combination of interventions 7 and 8.

Table A7. Combining two interventions (intervention 7 & others; intervention 8 & others)

Intervention combination	DLT	Utilization	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1&7	49.8	0.084	0.257	1.56	5.5%	5.8%	64.9%
2&7	48.3	0.086	0.156	2.26	8.3%	9.1%	0.0%
3&7	47.89	0.087	0.235	1.85	9.1%	10.0%	50.7%
4&7	40	0.104	0.156	2.26	24.1%	31.8%	0.0%
5&7	46	0.087	0.156	2.26	12.7%	10.2%	0.0%
6&7	43.48	0.088	0.156	2.26	17.5%	11.3%	0.0%
1&8	48.9	0.085	0.257	1.56	7.2%	7.8%	64.9%
2&8	46.7	0.089	0.156	2.26	11.4%	12.8%	0.0%
3&8	49.1	0.085	0.235	1.85	6.8%	7.3%	50.7%
4&8	43.26	0.096	0.156	2.26	17.9%	21.8%	0.0%
5&8	46.57	0.086	0.156	2.26	11.6%	8.8%	0.0%
6&8	44.96	0.085	0.156	2.26	14.7%	7.6%	0.0%
7&8	48.89	0.085	0.156	2.26	7.2%	7.8%	0.0%

Overall, combining IC4&6 has the best effect on DLT reduction, whereas IC3&4 has the greatest impact on the utilization ratio. In terms of RTY and expected value loss, IC1&3 show a tremendous improvement.

The next step is to assess the outcome by combining three interventions and then four, up to eight. Table A8 shows the combinations of three interventions.

***Table A8.** Simulation results for interventions and their combinations*

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
1	Current state simulation	52.7	0.079	0.16	2.26	-	-	-
2	1	50.1	0.083	0.26	1.56	4.9%	5.2%	64.9%
3	2	50.6	0.082	0.16	2.26	4.0%	4.2%	0.0%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
4	3	51.5	0.081	0.23	1.85	2.3%	2.3%	50.7%
5	4	44.7	0.093	0.16	2.26	15.2%	17.9%	0.0%
6	5	48.9	0.082	0.16	2.26	7.2%	3.6%	0.0%
7	6	47.23	0.080	0.16	2.26	10.4%	1.9%	0.0%
8	7	48.6	0.086	0.16	2.26	7.8%	8.4%	0.0%
9	8	50.4	0.083	0.16	2.26	4.4%	4.6%	0.0%
10	1&2	47.6	0.087	0.26	1.56	9.7%	10.7%	64.9%
11	1&3	48.05	0.087	0.39	1.15	8.8%	9.7%	148.4%
12	1&4	41.9	0.099	0.26	1.56	20.5%	25.8%	64.9%
13	1&5	46.3	0.086	0.26	1.56	12.1%	9.4%	64.9%
14	1&6	45.7	0.084	0.26	1.56	13.3%	5.9%	64.9%
15	1&7	49.8	0.084	0.26	1.56	5.5%	5.8%	64.9%
16	1&8	48.9	0.085	0.26	1.56	7.2%	7.8%	64.9%
17	2&3	49.5	0.084	0.23	1.85	6.1%	6.5%	50.7%
18	2&4	43.3	0.096	0.16	2.26	17.8%	21.7%	0.0%
19	2&5	49.9	0.080	0.16	2.26	5.3%	1.5%	0.0%
20	2&6	45.3	0.084	0.16	2.26	14.0%	6.8%	0.0%
21	2&7	48.3	0.086	0.16	2.26	8.3%	9.1%	0.0%
22	2&8	46.7	0.089	0.16	2.26	11.4%	12.8%	0.0%
23	3&4	40.35	0.103	0.23	1.85	23.4%	30.6%	50.7%
24	3&5	47.08	0.085	0.23	1.85	10.7%	7.6%	50.7%
25	3&6	45.8	0.083	0.23	1.85	13.1%	5.7%	50.7%
26	3&7	47.89	0.087	0.23	1.85	9.1%	10.0%	50.7%
27	3&8	49.1	0.085	0.23	1.85	6.8%	7.3%	50.7%
28	4&5	43.3	0.092	0.16	2.26	17.8%	17.0%	0.0%
29	4&6	39.02	0.098	0.16	2.26	26.0%	24.0%	0.0%
30	4&7	40	0.104	0.16	2.26	24.1%	31.8%	0.0%
31	4&8	43.26	0.096	0.16	2.26	17.9%	21.8%	0.0%
32	5&6	47.68	0.080	0.16	2.26	9.5%	1.5%	0.0%
33	5&7	46	0.087	0.16	2.26	12.7%	10.2%	0.0%
34	5&8	46.57	0.086	0.16	2.26	11.6%	8.8%	0.0%
35	6&7	43.48	0.088	0.16	2.26	17.5%	11.3%	0.0%
36	6&8	44.96	0.085	0.16	2.26	14.7%	7.6%	0.0%
37	7&8	48.89	0.085	0.16	2.26	7.2%	7.8%	0.0%
38	1&2&3	45.53	0.091	0.39	1.15	13.6%	15.7%	148.4%
39	1&2&4	39.13	0.106	0.26	1.56	25.7%	34.7%	64.9%
40	1&2&5	44.7	0.089	0.26	1.56	15.2%	13.4%	64.9%
41	1&2&6	40.04	0.095	0.26	1.56	24.0%	20.2%	64.9%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
42	1&2&7	44.31	0.094	0.26	1.56	15.9%	18.9%	64.9%
43	1&2&8	44.28	0.094	0.26	1.56	16.0%	19.0%	64.9%
44	1&3&4	40.2	0.103	0.39	1.15	23.7%	31.1%	148.4%
45	1&3&5	45.14	0.089	0.39	1.15	14.3%	12.3%	148.4%
46	1&3&6	41.81	0.091	0.39	1.15	20.7%	15.1%	148.4%
47	1&3&7	45.13	0.092	0.39	1.15	14.4%	16.8%	148.4%
48	1&3&8	46.84	0.089	0.39	1.15	11.1%	12.5%	148.4%
49	1&4&5	38.73	0.103	0.26	1.56	26.5%	30.8%	64.9%
50	1&4&6	36.41	0.104	0.26	1.56	30.9%	32.2%	64.9%
51	1&4&7	40.26	0.103	0.26	1.56	23.6%	30.9%	64.9%
52	1&4&8	38.57	0.108	0.26	1.56	26.8%	36.6%	64.9%
53	1&5&6	44.93	0.085	0.26	1.56	14.7%	7.1%	64.9%
54	1&5&7	44.15	0.091	0.26	1.56	16.2%	14.8%	64.9%
55	1&5&8	44.4	0.090	0.26	1.56	15.7%	14.1%	64.9%
56	1&6&7	42.14	0.090	0.26	1.56	20.0%	14.2%	64.9%
57	1&6&8	45.2	0.084	0.26	1.56	14.2%	6.5%	64.9%
58	1&7&8	49.4	0.084	0.26	1.56	6.3%	6.7%	64.9%
59	2&3&4	40.5	0.103	0.23	1.85	23.1%	30.1%	50.7%
60	2&3&5	45.9	0.087	0.23	1.85	12.9%	10.4%	50.7%
61	2&3&6	44.07	0.086	0.23	1.85	16.4%	9.2%	50.7%
62	2&3&7	49.4	0.084	0.23	1.85	6.3%	6.7%	50.7%
63	2&3&8	49.1	0.085	0.23	1.85	6.8%	7.3%	50.7%
64	2&4&5	39.3	0.102	0.16	2.26	25.4%	28.9%	0.0%
65	2&4&6	36.7	0.104	0.16	2.26	30.4%	31.2%	0.0%
66	2&4&7	39.23	0.106	0.16	2.26	25.6%	34.3%	0.0%
67	2&4&8	39.8	0.105	0.16	2.26	24.5%	32.4%	0.0%
68	2&5&6	43.1	0.088	0.16	2.26	18.2%	11.7%	0.0%
69	2&5&7	47.2	0.085	0.16	2.26	10.4%	7.4%	0.0%
70	2&5&8	46.3	0.086	0.16	2.26	12.1%	9.4%	0.0%
71	2&6&7	42.6	0.089	0.16	2.26	19.2%	13.0%	0.0%
72	2&6&8	44.5	0.085	0.16	2.26	15.6%	8.2%	0.0%
73	2&7&8	48.4	0.086	0.16	2.26	8.2%	8.9%	0.0%
74	3&4&5	41.59	0.096	0.23	1.85	21.1%	21.8%	50.7%
75	3&4&6	37.8	0.101	0.23	1.85	28.3%	27.4%	50.7%
76	3&4&7	41.7	0.100	0.23	1.85	20.9%	26.4%	50.7%
77	3&4&8	41.4	0.100	0.23	1.85	21.4%	27.3%	50.7%
78	3&5&6	46.1	0.082	0.23	1.85	12.5%	4.4%	50.7%
79	3&5&7	48.4	0.083	0.23	1.85	8.2%	4.7%	50.7%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
80	3&5&8	46.6	0.086	0.23	1.85	11.6%	8.7%	50.7%
81	3&6&7	44	0.086	0.23	1.85	16.5%	9.4%	50.7%
82	3&6&8	45.3	0.084	0.23	1.85	14.0%	6.3%	50.7%
83	3&7&8	48.39	0.086	0.23	1.85	8.2%	8.9%	50.7%
84	4&5&6	39.16	0.097	0.16	2.26	25.7%	22.9%	0.0%
85	4&5&7	38.8	0.103	0.16	2.26	26.4%	30.6%	0.0%
86	4&5&8	39.53	0.101	0.16	2.26	25.0%	28.2%	0.0%
87	4&6&7	36.9	0.103	0.16	2.26	30.0%	30.5%	0.0%
88	4&6&8	38.8	0.098	0.16	2.26	26.4%	24.1%	0.0%
89	4&7&8	40.73	0.102	0.16	2.26	22.7%	29.4%	0.0%
90	5&6&7	45.8	0.083	0.16	2.26	13.1%	5.1%	0.0%
91	5&6&8	43.7	0.087	0.16	2.26	17.1%	10.2%	0.0%
92	5&7&8	45.35	0.088	0.16	2.26	13.9%	11.7%	0.0%
93	6&7&8	40.6	0.094	0.16	2.26	23.0%	18.6%	0.0%
94	1&2&3&4	40.2	0.103	0.39	1.15	23.7%	31.1%	148.4%
95	1&2&3&5	43.4	0.092	0.39	1.15	17.6%	16.8%	148.4%
96	1&2&3&6	40.8	0.093	0.39	1.15	22.6%	18.0%	148.4%
97	1&2&3&7	46.06	0.090	0.39	1.15	12.6%	14.4%	148.4%
98	1&2&3&8	43.7	0.095	0.39	1.15	17.1%	20.6%	148.4%
99	1&2&4&5	35.03	0.114	0.26	1.56	33.5%	44.7%	64.9%
100	1&2&4&6	32.8	0.116	0.26	1.56	37.8%	46.8%	64.9%
101	1&2&4&7	37.13	0.112	0.26	1.56	29.5%	41.9%	64.9%
102	1&2&4&8	35.27	0.118	0.26	1.56	33.1%	49.4%	64.9%
103	1&2&5&6	41.9	0.091	0.26	1.56	20.5%	14.9%	64.9%
104	1&2&5&7	44.9	0.089	0.26	1.56	14.8%	12.9%	64.9%
105	1&2&5&8	43.15	0.093	0.26	1.56	18.1%	17.4%	64.9%
106	1&2&6&7	39.29	0.097	0.26	1.56	25.4%	22.5%	64.9%
107	1&2&6&8	39.68	0.096	0.26	1.56	24.7%	21.3%	64.9%
108	1&2&7&8	45.17	0.092	0.26	1.56	14.3%	16.7%	64.9%
109	1&3&4&5	40.62	0.098	0.39	1.15	22.9%	24.7%	148.4%
110	1&3&4&6	35.23	0.108	0.39	1.15	33.1%	36.6%	148.4%
111	1&3&4&7	39.51	0.105	0.39	1.15	25.0%	33.4%	148.4%
112	1&3&4&8	36.89	0.113	0.39	1.15	30.0%	42.9%	148.4%
113	1&3&5&6	42.32	0.090	0.39	1.15	19.7%	13.8%	148.4%
114	1&3&5&7	44.9	0.089	0.39	1.15	14.8%	12.9%	148.4%
115	1&3&5&8	44.14	0.091	0.39	1.15	16.2%	14.8%	148.4%
116	1&3&6&7	40.32	0.094	0.39	1.15	23.5%	19.4%	148.4%
117	1&3&6&8	40.76	0.093	0.39	1.15	22.7%	18.1%	148.4%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
118	1&3&7&8	46.73	0.089	0.39	1.15	11.3%	12.8%	148.4%
119	1&4&5&6	40.54	0.094	0.26	1.56	23.1%	18.7%	64.9%
120	1&4&5&7	39.5	0.101	0.26	1.56	25.0%	28.3%	64.9%
121	1&4&5&8	37.73	0.106	0.26	1.56	28.4%	34.3%	64.9%
122	1&4&6&7	38.17	0.100	0.26	1.56	27.6%	26.1%	64.9%
123	1&4&6&8	39.51	0.096	0.26	1.56	25.0%	21.8%	64.9%
124	1&4&7&8	38.46	0.108	0.26	1.56	27.0%	37.0%	64.9%
125	1&5&6&7	41.32	0.092	0.26	1.56	21.6%	16.5%	64.9%
126	1&5&6&8	43.37	0.088	0.26	1.56	17.7%	11.0%	64.9%
127	1&5&7&8	41.99	0.095	0.26	1.56	20.3%	20.7%	64.9%
128	1&6&7&8	41.89	0.091	0.26	1.56	20.5%	14.9%	64.9%
129	2&3&4&5	37.54	0.107	0.23	1.85	28.8%	35.0%	50.7%
130	2&3&4&6	36.33	0.105	0.23	1.85	31.1%	32.5%	50.7%
131	2&3&4&7	39.36	0.106	0.23	1.85	25.3%	33.9%	50.7%
132	2&3&4&8	38.51	0.108	0.23	1.85	26.9%	36.8%	50.7%
133	2&3&5&6	44.9	0.085	0.23	1.85	14.8%	7.2%	50.7%
134	2&3&5&7	44.84	0.089	0.23	1.85	14.9%	13.0%	50.7%
135	2&3&5&8	44.09	0.091	0.23	1.85	16.3%	14.9%	50.7%
136	2&3&6&7	42.5	0.089	0.23	1.85	19.4%	13.3%	50.7%
137	2&3&6&8	43.01	0.088	0.23	1.85	18.4%	11.9%	50.7%
138	2&3&7&8	46.6	0.089	0.23	1.85	11.6%	13.1%	50.7%
139	2&4&5&6	37.6	0.101	0.16	2.26	28.7%	28.0%	0.0%
140	2&4&5&7	35.7	0.112	0.16	2.26	32.3%	41.9%	0.0%
141	2&4&5&8	37.8	0.106	0.16	2.26	28.3%	34.1%	0.0%
142	2&4&6&7	33.87	0.112	0.16	2.26	35.7%	42.1%	0.0%
143	2&4&6&8	34.59	0.110	0.16	2.26	34.4%	39.2%	0.0%
144	2&4&7&8	40.5	0.103	0.16	2.26	23.1%	30.1%	0.0%
145	2&5&6&7	41.69	0.091	0.16	2.26	20.9%	15.5%	0.0%
146	2&5&6&8	42.89	0.089	0.16	2.26	18.6%	12.2%	0.0%
147	2&5&7&8	42.8	0.093	0.16	2.26	18.8%	18.4%	0.0%
148	2&6&7&8	40.05	0.095	0.16	2.26	24.0%	20.2%	0.0%
149	3&4&5&6	39.2	0.097	0.23	1.85	25.6%	22.8%	50.7%
150	3&4&5&7	37.7	0.106	0.23	1.85	28.5%	34.4%	50.7%
151	3&4&5&8	39.2	0.102	0.23	1.85	25.6%	29.3%	50.7%
152	3&4&6&7	34.65	0.110	0.23	1.85	34.3%	38.9%	50.7%
153	3&4&6&8	34.5	0.110	0.23	1.85	34.5%	39.5%	50.7%
154	3&4&7&8	39.29	0.106	0.23	1.85	25.4%	34.1%	50.7%
155	3&5&6&7	41.69	0.091	0.23	1.85	20.9%	15.5%	50.7%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
156	3&5&6&8	43.13	0.088	0.23	1.85	18.2%	11.6%	50.7%
157	3&5&7&8	45	0.089	0.23	1.85	14.6%	12.6%	50.7%
158	3&6&7&8	39.89	0.095	0.23	1.85	24.3%	20.7%	50.7%
159	4&5&6&7	36.44	0.104	0.16	2.26	30.9%	32.1%	0.0%
160	4&5&6&8	36.57	0.104	0.16	2.26	30.6%	31.6%	0.0%
161	4&5&7&8	38.61	0.104	0.16	2.26	26.7%	31.2%	0.0%
162	4&6&7&8	35.05	0.108	0.16	2.26	33.5%	37.3%	0.0%
163	5&6&7&8	41.14	0.092	0.16	2.26	21.9%	17.0%	0.0%
164	1&2&3&4&5	36	0.111	0.39	1.15	31.7%	40.8%	148.4%
165	1&2&3&4&6	33.53	0.113	0.39	1.15	36.4%	43.6%	148.4%
166	1&2&3&4&7	35.65	0.117	0.39	1.15	32.4%	47.8%	148.4%
167	1&2&3&4&8	34.6	0.120	0.39	1.15	34.3%	52.3%	148.4%
168	1&2&3&5&6	39.7	0.096	0.39	1.15	24.7%	21.3%	148.4%
169	1&2&3&5&7	41.6	0.096	0.39	1.15	21.1%	21.8%	148.4%
170	1&2&3&5&8	42.14	0.095	0.39	1.15	20.0%	20.2%	148.4%
171	1&2&3&6&7	38.84	0.098	0.39	1.15	26.3%	23.9%	148.4%
172	1&2&3&6&8	38	0.100	0.39	1.15	27.9%	26.7%	148.4%
173	1&2&3&7&8	41.34	0.101	0.39	1.15	21.6%	27.5%	148.4%
174	1&2&4&5&6	35.05	0.108	0.26	1.56	33.5%	37.3%	64.9%
175	1&2&4&5&7	35.33	0.113	0.26	1.56	33.0%	43.4%	64.9%
176	1&2&4&5&8	33.57	0.119	0.26	1.56	36.3%	50.9%	64.9%
177	1&2&4&6&7	32.6	0.117	0.26	1.56	38.1%	47.7%	64.9%
178	1&2&4&6&8	31.32	0.121	0.26	1.56	40.6%	53.7%	64.9%
179	1&2&4&7&8	33.83	0.123	0.26	1.56	35.8%	55.8%	64.9%
180	1&2&5&6&7	38.9	0.098	0.26	1.56	26.2%	23.8%	64.9%
181	1&2&5&6&8	40.6	0.094	0.26	1.56	23.0%	18.6%	64.9%
182	1&2&5&7&8	43.49	0.092	0.26	1.56	17.5%	16.5%	64.9%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
183	1&2&6&7&8	38.33	0.099	0.26	1.56	27.3%	25.6%	64.9%
184	1&3&4&5&6	35.3	0.108	0.39	1.15	33.0%	36.4%	148.4%
185	1&3&4&5&7	36.18	0.111	0.39	1.15	31.3%	40.1%	148.4%
186	1&3&4&5&8	36.1	0.111	0.39	1.15	31.5%	40.4%	148.4%
187	1&3&4&6&7	34.14	0.111	0.39	1.15	35.2%	41.0%	148.4%
188	1&3&4&6&8	36.2	0.105	0.39	1.15	31.3%	33.0%	148.4%
189	1&3&4&7&8	37.6	0.111	0.39	1.15	28.7%	40.2%	148.4%
190	1&3&5&6&7	39.33	0.097	0.39	1.15	25.4%	22.4%	148.4%
191	1&3&5&6&8	41.07	0.093	0.39	1.15	22.1%	17.2%	148.4%
192	1&3&5&7&8	43.36	0.092	0.39	1.15	17.7%	16.9%	148.4%
193	1&3&6&7&8	38.14	0.100	0.39	1.15	27.6%	26.2%	148.4%
194	1&4&5&6&7	35.68	0.107	0.26	1.56	32.3%	34.9%	64.9%
195	1&4&5&6&8	36.8	0.103	0.26	1.56	30.2%	30.8%	64.9%
196	1&4&5&7&8	34.49	0.116	0.26	1.56	34.6%	46.9%	64.9%
197	1&4&6&7&8	33.69	0.113	0.26	1.56	36.1%	42.9%	64.9%
198	1&5&6&7&8	40.43	0.094	0.26	1.56	23.3%	19.1%	64.9%
199	2&3&4&5&6	37.99	0.100	0.23	1.85	27.9%	26.7%	50.7%
200	2&3&4&5&7	35.98	0.111	0.23	1.85	31.7%	40.8%	50.7%
201	2&3&4&5&8	36	0.111	0.23	1.85	31.7%	40.8%	50.7%
202	2&3&4&6&7	33.7	0.113	0.23	1.85	36.1%	42.8%	50.7%
203	2&3&4&6&8	33.4	0.114	0.23	1.85	36.6%	44.1%	50.7%
204	2&3&4&7&8	34.6	0.120	0.23	1.85	34.3%	52.3%	50.7%
205	2&3&5&6&7	39.2	0.097	0.23	1.85	25.6%	22.8%	50.7%
206	2&3&5&6&8	41.7	0.091	0.23	1.85	20.9%	15.4%	50.7%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
207	2&3&6&7&8	40.32	0.094	0.23	1.85	23.5%	19.4%	50.7%
208	2&4&5&6&7	34.4	0.110	0.16	2.26	34.7%	39.9%	0.0%
209	2&4&5&6&8	33.76	0.113	0.16	2.26	35.9%	42.6%	0.0%
210	2&4&5&7&8	33.9	0.118	0.16	2.26	35.7%	49.5%	0.0%
211	2&4&6&7&8	31.85	0.119	0.16	2.26	39.6%	51.1%	0.0%
212	2&5&6&7&8	40.3	0.094	0.16	2.26	23.5%	19.5%	0.0%
213	3&4&5&6&7	36.95	0.103	0.23	1.85	29.9%	30.3%	50.7%
214	3&4&5&6&8	36.7	0.104	0.23	1.85	30.4%	31.2%	50.7%
215	3&4&5&7&8	34.86	0.115	0.23	1.85	33.9%	45.4%	50.7%
216	3&4&6&7&8	34	0.112	0.23	1.85	35.5%	41.6%	50.7%
217	3&5&6&7&8	41.37	0.092	0.23	1.85	21.5%	16.4%	50.7%
218	4&5&6&7&8	32.6	0.117	0.16	2.26	38.1%	47.7%	0.0%
219	1&2&3&4&5&6	34	0.112	0.39	1.15	35.5%	41.6%	148.4%
220	1&2&3&4&5&7	32.6	0.123	0.39	1.15	38.1%	55.4%	148.4%
221	1&2&3&4&5&8	33.8	0.118	0.39	1.15	35.9%	49.9%	148.4%
222	1&2&3&4&6&7	31.38	0.121	0.39	1.15	40.5%	53.4%	148.4%
223	1&2&3&4&6&8	30.4	0.125	0.39	1.15	42.3%	58.4%	148.4%
224	1&2&3&4&7&8	33.8	0.123	0.39	1.15	35.9%	55.9%	148.4%
225	1&2&3&5&6&7	35.5	0.107	0.39	1.15	32.6%	35.6%	148.4%
226	1&2&3&5&6&8	39.25	0.097	0.39	1.15	25.5%	22.6%	148.4%
227	1&2&3&5&7&8	38.42	0.104	0.39	1.15	27.1%	31.9%	148.4%
228	1&2&3&6&7&8	35.29	0.108	0.39	1.15	33.0%	36.4%	148.4%
229	1&2&4&5&6&7	31.25	0.122	0.26	1.56	40.7%	54.0%	64.9%
230	1&2&4&5&6&8	31.45	0.121	0.26	1.56	40.3%	53.1%	64.9%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
231	1&2&4&5&7&8	31.52	0.127	0.26	1.56	40.2%	60.8%	64.9%
232	1&2&4&6&7&8	30.93	0.123	0.26	1.56	41.3%	55.6%	64.9%
233	1&2&5&6&7&8	37.27	0.102	0.26	1.56	29.3%	29.2%	64.9%
234	1&3&4&5&6&7	32.5	0.117	0.39	1.15	38.3%	48.1%	148.4%
235	1&3&4&5&6&8	31.9	0.119	0.39	1.15	39.5%	50.9%	148.4%
236	1&3&4&5&7&8	33.3	0.120	0.39	1.15	36.8%	52.2%	148.4%
237	1&3&4&6&7&8	29.65	0.128	0.39	1.15	43.7%	62.4%	148.4%
238	1&3&5&6&7&8	38.18	0.100	0.39	1.15	27.6%	26.1%	148.4%
239	1&4&5&6&7&8	33.69	0.113	0.26	1.56	36.1%	42.9%	64.9%
240	2&3&4&5&6&7	34.45	0.110	0.23	1.85	34.6%	39.7%	50.7%
241	2&3&4&5&6&8	33.78	0.112	0.23	1.85	35.9%	42.5%	50.7%
242	2&3&4&5&7&8	33.8	0.118	0.23	1.85	35.9%	49.9%	50.7%
243	2&3&4&6&7&8	31.7	0.120	0.23	1.85	39.8%	51.9%	50.7%
244	2&3&5&6&7&8	37.7	0.101	0.23	1.85	28.5%	27.7%	50.7%
245	2&4&5&6&7&8	31.6	0.120	0.16	2.26	40.0%	52.3%	0.0%
246	3&4&5&6&7&8	33.6	0.113	0.23	1.85	36.2%	43.3%	50.7%
247	1&2&3&4&5&6&7	29.64	0.128	0.39	1.15	43.8%	62.4%	148.4%
248	1&2&3&4&5&6&8	30.83	0.123	0.39	1.15	41.5%	56.1%	148.4%
249	1&2&3&4&5&7&8	30.28	0.132	0.39	1.15	42.5%	67.3%	148.4%
250	1&2&3&4&6&7&8	27.99	0.136	0.39	1.15	46.9%	72.0%	148.4%
251	1&2&3&5&6&7&8	37.5	0.101	0.39	1.15	28.8%	28.4%	148.4%
252	1&2&4&5&6&7&8	28.35	0.134	0.26	1.56	46.2%	69.8%	64.9%
253	1&3&4&5&6&7&8	30.3	0.125	0.39	1.15	42.5%	58.9%	148.4%
254	2&3&4&5&6&7&8	30.72	0.124	0.29	1.45	41.7%	56.7%	84.0%

#	Interventions	DLT	Utilization Ratio	RTY	Expected value loss	% of DLT the reduction compared to the current state	% of the increase in the Utilization ratio compared to the current state	% of the increase in the RTY compared to the current state
255	1&2&3&4&5&6&7&8	27.79	0.137	0.39	1.15	47.3%	73.2%	148.4%