Analysing Warehouse Material Flow using a Lean Framework

A Case Study of an Engineer-to-Order Company

Master's thesis in Quality and Operations Management

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Abstract

Warehouse operations in Engineer-to-Order (ETO) manufacturing environments face distinctive challenges due to high product variability, project-based production, and complex material flows. Despite this, limited research has addressed warehouse operations in ETO settings. This study examines how Lean principles can be used to analyse warehouse material flow and identify inefficiencies contributing to lead time in an ETO context.

A qualitative single-case study was conducted at a European defence manufacturer operating under an ETO production strategy. Data were collected through semi-structured interviews and analysed using thematic analysis. In addition, a process flowchart was developed to visualise and support the analysis of the warehouse material flow. Womack and Jones (1997) five core Lean principles – value, value stream, flow, pull, and perfection – were applied together with the ETO context as an analytical framework.

The findings reveal a range of inefficiencies, including batch-based material reservations, consolidation delays, fluctuating workloads, limited system support, and normalised reliance on an express flow mechanism. These inefficiencies are explained as the result of disrupted material and information flow, the absence of effective pull mechanisms, and the interaction between waste (muda), unevenness (mura), and overburden (muri). The ETO context amplifies these challenges through high variability, late engineering changes, and siloed working practices.

The study concludes that Lean principles provide a productive diagnostic framework for ETO warehouse environments, though their applicability is differentiated. The seven wastes transfer directly, while the principles of flow, pull, and perfection require contextual adaptation given the structural variability inherent to ETO production. The findings contribute to the empirical understanding of Lean application in non-repetitive manufacturing environments and offer guidance for improving warehouse performance based on Lean theories under conditions of high customisation and growth.

Keywords: Lean, Engineer-to-Order, warehouse operations, material flow, waste, internal logistics

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Fanny Ekeblom and Noa Sjöstrand, Gothenburg, May 2026

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1
Introduction

Many of today's markets are characterised by a high demand for customised products. Products often need to be tailored to specific operational requirements and integrated with existing platforms and technologies. As a result, manufacturers must deliver specialised solutions based on detailed customer specifications.

This production strategy is commonly referred to as Engineer-to-Order (ETO). Olhager (2003) defines ETO as a production strategy in which the customer order decoupling point is located at the design phase, meaning that both engineering and production activities are directly triggered by specific customer orders. In ETO environments, products are therefore designed and manufactured according to unique customer requirements, and each order may involve new drawings, modified components, and customised assembly processes. Unlike repetitive manufacturing systems, ETO production is characterised by high variability and limited standardisation.

The high degree of customisation, complex product structures, and the overlap between design and manufacturing activities contribute to substantial internal supply chain complexity in ETO companies (McGovern et al., 1999). If this complexity is not effectively managed, it can result in extended lead times and inefficiencies. Since customers in ETO contexts are already exposed to long lead times because design, procurement, manufacturing, assembly, and testing activities begin only after an order is placed (McGovern et al., 1999), reducing time deficiencies in internal processes becomes critical to ensure on-time-delivery.

Within this context, improving internal efficiency without altering product design or core production strategies becomes increasingly important. In particular, warehouse operations and internal material flow play a critical role in enabling production performance in complex ETO systems.

Previous research has explored the application of Lean principles in Engineer-to-Order manufacturing environments, e.g. Strandhagen et al. (2018) and Jünge et al. (2023). However, limited focus has been placed on warehouse operations and internal material flow, despite their importance for supporting production scalability and responsiveness.

Consequently, this study explores how Lean principles can be used to analyse warehouse material flow within an ETO manufacturing company through an in-depth case study. More specifically, the study examines the material and information flow within the warehouse and its interaction with production and planning from a Lean perspective, with the aim of identifying inefficiencies and sources of waste affecting operational performance. By doing so, the study seeks to provide practical insights for the case company while contributing to the empirical understanding of Lean application in ETO warehouse contexts.

1.1 The Case Company and Warehouse Context

The case company operates within the European defence industry and applies an ETO production strategy. The company develops and manufactures customised defence systems. As a result, products are characterised by high variability, complex structures, and strict requirements related to quality, flexibility, and traceability.

In recent years, the operating context for European defence manufacturers has changed significantly. Following the war in Ukraine and the increased political and economic integration within the European Union (Anghel, 2025; Håkansson, 2024; Petit, 2025), military spending has risen from 1.3% of EU GDP in 2015 to 1.9% in 2024 (World Bank Group, n.d.). These developments have altered demand conditions across the European defence industry, increasing pressure on manufacturers to expand production capacity. As a result, the case company has experienced a substantial increase in demand, necessitating a rapid expansion of production activities and placing considerable pressure on its existing production system and internal logistics. Managing this growth while sustaining required performance levels has therefore emerged as a key operational challenge.

The warehouse facility plays a central role in the company's production system, serving as the interface between inbound material flows and downstream manufacturing operations. The company operates one warehouse at the main production site in addition to two external warehouse facilities. Together, these warehouses are responsible for receiving, storing, and supplying materials to production. This role is further complicated by the Engineer-to-Order (ETO) context, more specifically an RTO environment where project novelty primarily lies in adaptation and reconfiguration rather than fundamental innovation (Alfnes et al., 2021). High levels of customisation, project-specific deliveries, and limited information regarding incoming materials increase the complexity of material handling, storage management, and coordination with production.

Furthermore, the warehouse is constrained by limited available space at the company site and has been unable to expand its capacity in proportion to the increasing production volumes. As a result, the time required to supply materials to production has increased.

Against this background, the warehouse facility represents a suitable context for investigating how internal material flow can be improved in an ETO manufacturing environment. Focusing on warehouse operations allows for the examination of operational improvements that support production scalability without fundamentally altering product design or core manufacturing strategies.

1.2 Purpose

This thesis aims to analyse warehouse material flow in an ETO manufacturing company in order to identify inefficiencies affecting the warehouse's ability to supply materials to production. Beyond identifying these inefficiencies, the thesis seeks to explain them through both Lean principles and the structural characteristics of the ETO context, examining how the ETO environment shapes and constrains material flow and what this means for the applicability of Lean principles in non-repetitive manufacturing environments. As an extension of this analysis, potential improvement opportunities grounded in Lean principles are also touched upon.

1.3 Scope

This study focuses on the analysis of internal material flow within the warehouse operations of an ETO manufacturing company. The study is conducted within a single production facility comprising several production areas and The scope is limited to the warehouse material flow and associated activities directly affecting the warehouse's ability to supply material to production, including planning and production activities. Procurement activities, upstream suppliers, and downstream flows to customers are excluded to allow for a more focused and in-depth investigation of warehouse processes. The scope is further restricted to material flow associated with picking operations for shop orders, excluding supporting processes such as inventory audits and scrap handling. This delimitation enables an in-depth and context-specific investigation of the selected flow, while also allowing for the development of detailed process understanding within a defined part of the system.

The analysis aims to identify inefficiencies and factors affecting the warehouse's ability to supply materials to production efficiently, using Lean principles as an analytical framework. While the study identifies improvement opportunities based on Lean principles, it does not include the design, implementation, or evaluation of specific solutions. The focus remains on analysing the current state and developing theoretically grounded insights into the warehouse material flow.

1.4 Research Questions

The research questions should capture both the operational focus of the investigation and its theoretical framing. Rather than treating Lean principles as prescriptive improvement tools, the study applies them as an analytical and diagnostic framework for understanding current practices and identifying operational inefficiencies. Based on this purpose, the study is guided by three research questions.

The first research question establishes the empirical foundation of the study by identifying inefficiencies and sources of waste in the current warehouse material flow:

RQ 1: *What inefficiencies and sources of waste can be identified in the current warehouse material flow?*

The second research question builds directly on the first. Once inefficiencies have been identified, Lean principles and the structural characteristics of the ETO context are used to explain their underlying causes and interpret how they emerge within a non-repetitive manufacturing environment:

RQ 2: *How can the identified inefficiencies be explained through Lean principles and the ETO context?*

The third research question extends the analysis to a broader theoretical reflection:

RQ 3: *What might the analysis suggest about the applicability of Lean principles as a diagnostic tool in non-repetitive manufacturing environments?*

Together, the three research questions support a structured investigation that moves from empirical identification to theoretically grounded explanation and finally to broader analytical reflection. RQ 1 is addressed in Chapter 4, where interviews and observations are used to map the current state of the warehouse material flow and identify inefficiencies. RQ 2 is addressed in Chapter 5, where the identified inefficiencies are analysed through Lean principles and the ETO context. Finally, RQ 3 is discussed in Chapter 6, where the findings are reflected upon in relation to the applicability of Lean principles in non-repetitive manufacturing environments.

1.5 Outline of the Thesis

The thesis is structured into seven chapters that together address how Lean principles can be applied to analyse warehouse material flow in an ETO environment.

Chapter 1 contextualises the study by introducing the case company and its warehouse environment, and establishes the research purpose, scope, and questions that guide the investigation.

Chapter 2 develops the theoretical foundation, presenting key concepts and frameworks related to Engineer-to-Order manufacturing and Lean thinking, with particular attention to the five core Lean principles, the concept of flow, and the three Ms.

Chapter 3 elaborates on the methodological approach, including the choice of research design, the data collection and analysis procedures employed, and the ethical considerations that informed the conduct of the study.

Chapter 4 presents the empirical findings by mapping the current state of the warehouse material flow and systematically identifying inefficiencies and sources of waste across the studied processes.

Chapter 5 constitutes the analytical core of the thesis, applying the five Lean principles and the structural characteristics of the ETO context as complementary analytical lenses to explain the underlying causes of the identified inefficiencies.

Chapter 6 synthesises the findings into a broader discussion of Lean applicability in non-repetitive manufacturing environments, and addresses sustainability implications, theoretical contributions, and the limitations of the study.

Finally, Chapter 7 concludes the thesis by summarising the principal findings and their implications for both theory and practice. A complete list of references follows.

2

Theoretical Frame of Reference

This chapter presents the theoretical concepts that form the foundation of the study. It introduces the key definitions and theories used to analyse the case company and its warehouse material flow. The chapter concludes with a synthesised analytical framework illustrating how the theoretical concepts guided the analysis and overall study design.

2.1 Engineer-to-Order (ETO)

ETO is a production strategy in which the customer order decoupling point is positioned at the design stage. Engineering, design, and production activities are initiated only after a customer order has been received. Unlike repetitive production systems, ETO companies develop and manufacture customised products tailored to customer specifications (Strandhagen et al., 2018).

ETO environments are characterised by high product complexity and variability. Products are often large, highly customised, and complex with deep product structures. At product level, volume is low and variety is high. From a process perspective, manufacturing is typically organised as projects in fixed-position layouts, where engineering and production activities overlap and are tightly integrated. Frequent changes and focus on flexibility further increase operational complexity (Strandhagen et al., 2019).

These characteristics create substantial internal supply chain complexity which, if not managed correctly, can result in long lead times and increased costs (Strandhagen et al., 2018). Effective coordination of material and information flows is therefore critical, and tailored management approaches are required to ensure efficient manufacturing operations (Strandhagen et al., 2019).

2.1.1 Degree of ETO: from ITO to RTO

Although ETO is often treated as a single category, Alfnes et al. (2021) show that ETO supply chains can be differentiated based on the position of the customer penetration point within the engineering process. Their empirical studies identify two main types: Innovate-to-Order (ITO) and Redesign-to-Order (RTO).

In pure ETO or ITO settings, customer involvement extends deeply into the engineering phase. Orders may originate from research and development initiatives or from new codes and standards, requiring innovative design solutions. These situations demand significant engineering effort to develop new product concepts (Alfnes et al., 2021).

In contrast, RTO situations arise when customer requirements are addressed after an initial product design or template already exists. Engineering activities focus primarily on modifying or adapting established designs rather than creating entirely new solutions (Alfnes et al., 2021).

As previously established, the case company in this study can predominantly be classified as an RTO company. Although products are customised to meet customer requirements, they are generally based on established product platforms and prior engineering solutions. Project novelty lies primarily in adaptation and reconfiguration rather than in fundamental innovation.

This distinction has important implications for uncertainty management. Alfnes et al. (2021) conceptualise uncertainty through the "uncertainty circle," which comprises four interrelated categories: process uncertainty related to internal activities, supply uncertainty linked to suppliers, demand uncertainty associated with customers, and control uncertainty concerning planning and coordination. Engineering projects are particularly exposed to uncertainty due to their complexity and interdependencies. In RTO systems, where novelty is concentrated in engineering adaptation, uncertainty is typically higher in the process and control dimensions (Alfnes et al., 2021).

2.1.2 Challenges

A primary challenge for ETO companies concerns production lead times, since production is often designed to prioritise flexibility over flow efficiency. Manufacturing is organised as projects, often with limited capacity buffers and reliance on specialised competencies. Consequently, long build times and bottlenecks are frequent, particularly when engineering and production activities overlap (Alfnes et al., 2021; Strandhagen et al., 2018).

High customisation also increases the complexity of production planning. The unique nature of each product makes it difficult to forecast required materials, resources, and space accurately. Internal logistics in ETO environments are especially challenging due to project-based execution and the absence of standardised, repetitive material flows. Unlike serial production systems, ETO companies cannot depend on stable inventories or predefined replenishment patterns. Materials typically arrive in project-specific load units which reduces visibility regarding arrival times, load characteristics, and handling requirements, complicating warehouse capacity planning and storage layout design (Braglia et al., 2024).

Previous literature identifies internal logistics issues in ETO settings, including congestion in receiving areas, inefficient use of storage space, excessive storage times, and difficulties in material identification and traceability. When deliveries are not synchronised with production schedules, materials accumulate in production areas, leading to cluttered workspaces and increased risk of damage. Inadequate information about load unit dimensions and handling constraints further complicates storage and handling system design (Braglia et al., 2024). These conditions generate unnecessary internal movements, poor space utilisation, and increased handling complexity. Overall, the lack of structured planning mechanisms for internal logistics creates systemic challenges in managing material flow between receiving, storage, and production.

Another critical challenge concerns cross-functional coordination. Close collaboration between functions is essential to manage changes that arise during project execution. Ineffective communication can amplify uncertainty and disrupt schedules, further increasing operational complexity (Braglia et al., 2024; Strandhagen et al., 2018).

2.2 Lean

Lean production has been a dominant manufacturing paradigm for several decades and originates from the Toyota Production System (TPS), which is widely recognised for achieving high levels of quality and efficiency (Liker, 2004). At its core, Lean focuses on creating customer value, continuously improving processes, and systematically eliminating waste. Although elements of Lean thinking can be traced back to the late nineteenth century, the term “Lean Production” emerged in the 1980s following the international success of Japanese manufacturing. During this period, European and American industries grew increasingly concerned about declining competitiveness and began investigating the practices underlying Japanese production systems (Dave, 2020).

2.2.1 Lean as an Integrated Management System

Lean is commonly described as a holistic system rather than a set of isolated methods. According to Liker (2004), the Lean system consists of four interrelated elements: philosophy, processes, people, and problem solving. The philosophical dimension emphasises long-term, systems-oriented thinking, where sustainable value creation is prioritised over short-term financial gains. The process dimension focuses on delivering customer value through built-in quality, transparency, balanced workloads, standardisation, and pull-based production systems designed to prevent overproduction. The people dimension highlights respect for individuals and partners, as well as leadership responsibility for developing people and fostering learning. Finally, the problem-solving dimension stresses scientific thinking and continuous improvement as means of moving the organisation toward a desired future state.

This systemic perspective is also emphasised by Langstrand and Drotz (2016) who argue that the full benefits of Lean can only be realised when its elements are implemented in an integrated manner. As a result, Lean is often portrayed less as a collection of tools and more as a management philosophy. According to Langstrand and Drotz (2016) research suggests that the universality of Lean lies primarily in its underlying principles rather than in specific methods or techniques.

2.2.2 The Five Core Principles of Lean

From a process-oriented perspective, Womack and Jones (1997) proposes five principles: value, value stream, flow, pull, and perfection are applied as a process-oriented analytical lens.

Womack and Jones (1997) first principle, value, emphasises that value must be defined from the customer's perspective; only activities that directly contribute to what the customer is willing to pay for are considered value-adding, while all others are regarded as waste.

The second principle, value stream, involves identifying all activities required to bring a product or service from concept to delivery, enabling organisations to distinguish between value-adding and non-value-adding activities. Mapping the value stream is useful for analysing and optimising processes by distinguishing between value-adding and non-value-adding activities in both the material flow and information flow (Womack & Jones, 1997). A Value Stream Mapping (VSM) is a Lean Management tool used to identify waste and streamline production processes. It is considered one of the core pillars of Lean philosophy, as it systematically maps and integrates material and information flows in order to identify and measure sources of non-value-adding activities arising from process inefficiencies (Womack & Jones, 1997). Making waste visible is a prerequisite for coordinating and improving the value stream and creates a foundation for continuous improvement initiatives (Liker, 2022; Ohno, 1988).

The third principle, flow, aims to ensure that value-creating activities proceed in a continuous sequence without interruptions, delays, or bottlenecks, promoting process-oriented rather than functionally siloed structures (Womack & Jones, 1997).

The fourth principle, pull, implies that production is driven by actual customer demand rather than forecasts, thereby reducing overproduction and excess inventory. Central to this is the idea that materials are pulled through the flow by clear signals of need from downstream processes, rather than being pushed forward based on schedules or assumptions. This creates a customer-supplier relationship at each stage of the process, where upstream activities are only triggered when a genuine demand signal is received from the stage below (Womack & Jones, 1997).

The fifth principle, perfection, is tightly linked to Liker (2004) problem solving element and reflects the pursuit of Kaizen (continuous improvement), emphasising that Lean is an ongoing process rather than a one-time initiative. Kaizen aims to make small, incremental improvements in processes and systems, leading to significant long-term benefits. Achieving this requires structured problem identification, standardised processes, and a shared organisational commitment to learning and improvement. Standardisation is a prerequisite for continuous improvement, as it enables a common understanding of performance and facilitates systematic identification of deviations (Liker, 2004; Ohno, 1988; Womack & Jones, 1997).

Together, these perspectives allow Lean to be analysed both as an overarching management philosophy and as a practical framework for evaluating and improving material flow (Langstrand & Drotz, 2016).

2.2.3 Lean and the Concept of Flow

Flow is a central concept in Lean management and is closely linked to the principles of waste reduction, lead time minimisation, and value creation. Flow refers to the continuous and uninterrupted movement of materials and information through processes in a way that supports timely delivery of customer value (Liker, 2022).

One-Piece Flow

According to Liker (2022, pp. 94–97), the pursuit of continuous flow constitutes one of the most central principles of Lean. The ideal expression of continuous flow is described as one-piece flow, meaning that products move through the production process one unit at a time without becoming trapped in intermediate buffers or queues between process steps.

Liker argues that it is within such a flow that the core of Lean thinking is realised. When products move through the value stream without interruption, lead times are minimised, quality improves, costs are reduced, and delivery performance is strengthened. One-piece flow therefore represents a process in which value creation can occur with reduced waste, while simultaneously making process problems more visible.

Importantly, one-piece flow does not in itself solve problems, however, it exposes existing problems more clearly and more immediately (Liker, 2022, pp. 95–97). In systems characterised by large inventories and buffers, downstream processes are shielded from upstream disturbances. Liker (2022) illustrates this through a metaphor in which inventory levels correspond to the water level, while problems represent rocks on the riverbed. When the water level is high, the boat passes without striking the rocks, allowing problems to remain hidden. As inventory levels are reduced, problems become exposed and must be addressed.

From this perspective, it is the increased visibility of problems that makes one-piece flow valuable. When disturbances have direct consequences for the flow, a strong incentive is created to analyse root causes and stabilise the process. Flow thus becomes a mechanism for learning and continuous improvement rather than merely a means of increasing efficiency.

Pull System

Liker (2022, p. 115) emphasises that it is not always possible to achieve complete one-piece flow. For certain processes, inventory is a necessary condition for creating a stable and predictable flow. In such cases, pull systems are described as a practical compromise between one-piece flow and traditional forecast-driven production.

A pull system is characterised by the relationship between two parties: a customer and a supplier. The customer signals its demand to the supplier, who then produces and delivers only what is requested and when it is requested. This mechanism is commonly referred to as Kanban, a Japanese term commonly translated as ‘sign,’ ‘card,’ or ‘signal’, which in this context denotes a method for regulating demand within the flow (Liker, 2022, p. 116).

According to Liker (2022, p. 116), Kanban decentralises planning by shifting demand signalling to each customer within the value stream. Each downstream process requests what is needed from its upstream supplier, creating greater flexibility and responsiveness. The faster a process can adapt to changes in customer demand, the smaller the required inventory buffers between processes.

The defining characteristic of a pull system is that demand is initiated downstream and subsequently "pulls" material and information through the value stream. This contrasts with forecast-driven systems, where production is initiated based on planned volumes and where material, capacity, and labour requirements are calculated in advance. In pull-based systems, actual customer demand becomes the primary driver of the flow (Liker, 2022).

2.2.4 Three Ms

According to Liker (2022, pp. 125–127), achieving a stable and efficient production flow requires addressing three fundamental sources of inefficiency: Muda, Mura, and Muri. Muda refers to waste, Mura to unevenness or variability in the flow, and Muri to overburdening of people or resources. Both Liker (2022) and Pienkowski (2014) emphasises that the 3Ms are closely interrelated and cannot be addressed in isolation; all must be managed simultaneously to create an efficient flow in accordance with the Lean philosophy.

Muda

Womack and Jones (1997) highlight Muda as a central concept in Lean thinking and describe it through the seven wastes originally identified by Toyota executive Taiichi Ohno. These wastes are transportation, inventory, motion, waiting, over-processing, overproduction, and defects. Rawabdeh (2005) and Pienkowski (2014) further synthesise the concept of Muda by emphasising the interdependencies between different types of waste, arguing that the presence of one often leads to the emergence or amplification of others.

Transportation waste refers to unnecessary movement of materials or products between processes that does not add value from the customer's perspective (Pienkowski, 2014; Rawabdeh, 2005). Moreover, Rawabdeh (2005) argues that long transportation distances increase the risk of additional waste, particularly defects, as frequent handling and transport raise the likelihood of damage to materials and products.

Excess inventory results in more capital being tied up in unfinished or unsold products, increased lead times, greater space requirements, over-production, and defects, while simultaneously concealing underlying problems in the production system (Rawabdeh, 2005). Ohno (1988) argued that the first step toward eliminating waste is making it visible. Problems hidden behind buffers and inventory are never confronted, and the system therefore has no incentive to resolve them.

Unnecessary motion includes inefficient or ergonomically poor movements performed by workers, which reduce productivity and often result in quality issues. Poor ergonomics can cause fatigue, increasing the likelihood of errors and defects, and may also generate additional waste such as waiting time when workers need recovery periods (Rawabdeh, 2005).

Waiting occurs when no value-adding work is performed on materials or products. This type of waste is considered particularly impactful, as waiting time strongly influences other forms of waste, especially over-production, excess inventory, and defects. Idle time disrupts flow and reduces overall process efficiency (Rawabdeh, 2005).

Overproduction, according to Rawabdeh (2005) and Pienkowski (2014), is the waste with the greatest impact on other waste categories. Pienkowski (2014) defines over-production as producing output before it is requested by the downstream process. Rawabdeh (2005) argues that overproduction leads to increased inventory levels, longer lead times, and greater space requirements, while also discouraging smooth flow and negatively affecting quality and productivity.

Over-processing occurs when a process performs more work than necessary or applies incorrect methods, often due to poor process design or inappropriate tool selection (Pienkowski, 2014). Rawabdeh (2005) notes that over-processing is less influenced by other types of waste compared to other categories. However, its primary consequence is reduced product quality.

Defects result in products requiring rework, repair, scrapping, or reordering, and may also lead to additional inspection activities. All of these consequences consume time, energy, and resources without creating value for the customer (Liker, 2022).

Mura and Muri

According to Liker (2022, pp. 124–127), most production systems experience variability in workload over time. Periods arise in which the volume of work exceeds the capacity of available machines and personnel, followed by periods with insufficient work. This variability is often caused by uneven production scheduling or large fluctuations in production volumes. Such fluctuations are, in turn, frequently driven by internal disturbances, including defects, missing components, or other disruptions in the production flow. Liker (2022, pp. 124–127) argues that this unevenness forces organisations to dimension personnel and resources to handle peak workloads, which subsequently leads to underutilisation during periods of lower demand. This imbalance represents a typical manifestation of mura (unevenness), which undermines both efficiency and flow.

A central mechanism for addressing mura is production levelling, commonly referred to as Heijunka. Production levelling involves moving away from large batches andirregular product mixes toward smaller batches and a more evenly distributed pro-duction plan that is guided by actual customer demand (Liker, 2022, pp. 128–133). By smoothing production over time, Heijunka aims to reduce variability and create more predictable and stable flows.

Liker (2022, pp. 124–127) argues that if mura (unevenness) is not properly managed, it may give rise to both muri (overburden) and muda (waste). High levels of mura imply significant variability in workload, which inevitably results in periods where machines and personnel are overburdened. Such overburdening reduces operational efficiency, as neither equipment nor workers can perform optimally under sustained excessive load.

Furthermore, Liker (2022, pp. 124–127) notes that overburdened personnel are more prone to errors, which increases the occurrence of muda. Mistakes such as handling errors or dropped materials become more likely when work is performed under stress or time pressure.

Liker (2022, pp. 124–127) also emphasises that responsibility for addressing the three Ms differs within the organisation. While muda should primarily be identified and improved by workers closest to the process, mura and muri should be addressed at the managerial level.

2.3 Analytical Framework

Figure 2.1 synthesises the theoretical concepts presented in this chapter into an integrated analytical framework that guides the study's empirical analysis. The framework illustrates how the three theoretical layers interact to support the identification and explanation of inefficiencies in warehouse material flow within an Engineer-to-Order (ETO) environment.

The outermost layer represents the ETO context, which establishes the structural conditions under which the comapny's operations take place. High product variability, project-based production, overlapping engineering and manufacturing activities, and elevated uncertainty do not invalidate Lean thinking, but they shape and constrain how Lean principles can be applied in practice.

Within this context, the five Lean principles (Womack & Jones, 1997) constitute the primary analytical lens of the study. The principles provide a structured approach for examining warehouse material flow and identifying areas of inefficiency. Each principle highlights a different dimension of operational performance, including customer value, value stream efficiency, flow continuity, pull-based material release, and continuous improvement.

Observed inefficiencies within each Lean principle are subsequently diagnosed through the Three Ms: muda (waste), mura (unevenness), and muri (overburden). Following (Liker, 2022) and (Pienkowski, 2014), the Three Ms are treated as interconnected rather than independent categories. In particular, mura and muri are understood as underlying conditions that generate and amplify muda. The Three Ms therefore function as diagnostic categories that help explain the nature and root causes of inefficiencies identified within the Lean principles.

Together, the three theoretical layers form the analytical basis of the study by linking the operational characteristics of the ETO environment with Lean-based analysis and diagnostic interpretation. The framework thereby guides how warehouse material flow inefficiencies are identified, categorised, and explained.

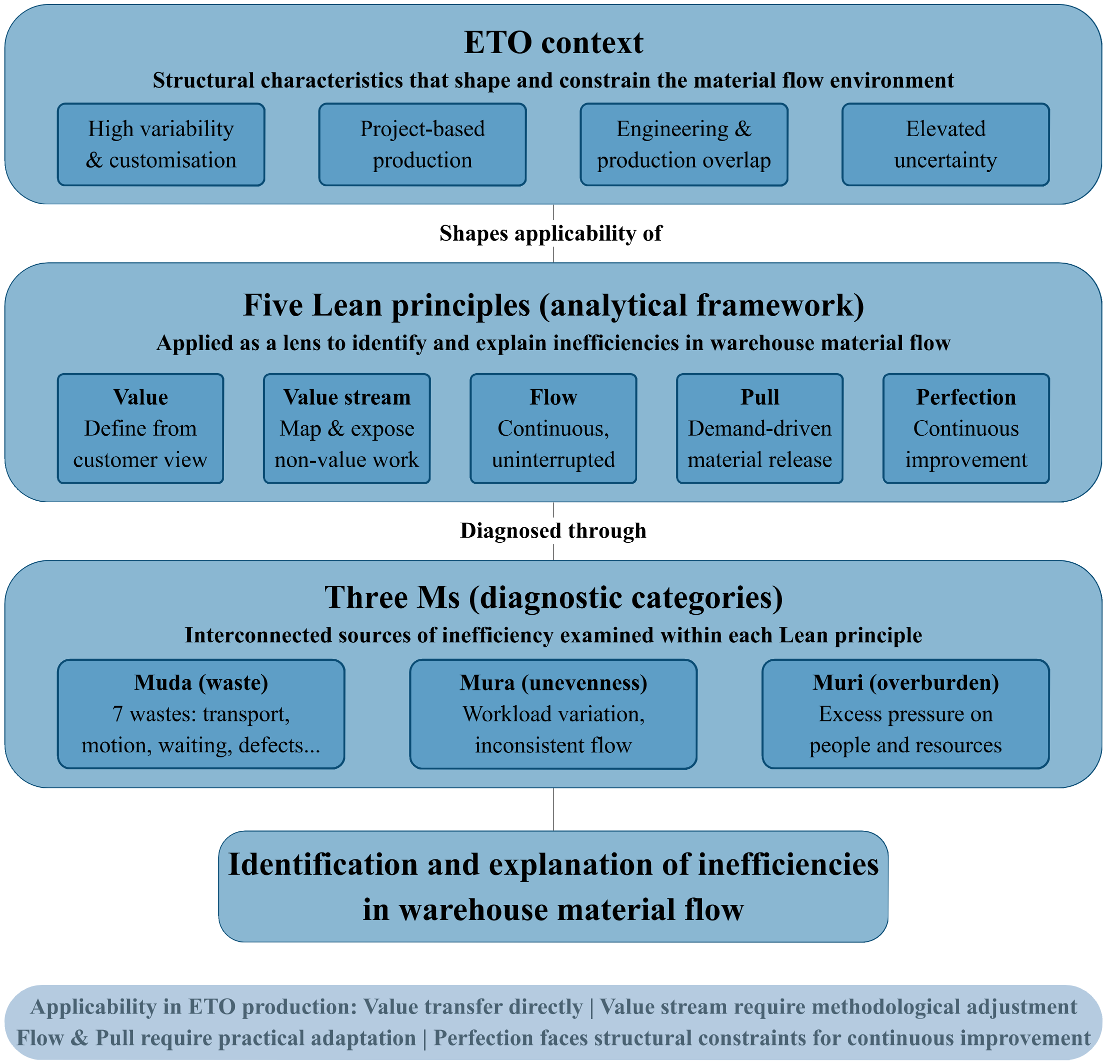

Figure 2.1: Analytical framework: ETO context, Lean principles, and three Ms.

3

Methodology

This chapter aims to describe the chosen methodology and how research was conducted. First the research design will be presented, followed by sections explaining the literature reviewing process, how data was collected and analysed, and ethical considerations.

3.1 Research Design

This study adopts a qualitative single-case study design. A case study approach is particularly relevant when addressing "how" or "why" questions when exploring a contemporary phenomenon within its real-world context, where the phenomena of interest are embedded in organisational processes and cannot be isolated (Yin, 2018). Because material flow in ETO warehouse operations involves multiple interacting variables (e.g., human practices, information systems, regulatory requirements), case study research enables comprehensive analysis adapted to the context that would not be possible through experimental or purely quantitative methods.

According to Yin (2018) case studies are especially relevant when the goal is to generate deep understanding of a phenomenon as it naturally occurs, rather than to test isolated variables under controlled conditions. The case company is an ETO firm characterised by high variation in customer specifications, strict quality and traceability requirements, and complex material handling processes. This context presents unique challenges and opportunities for Lean implementation, making it a suitable and illustrative case for studying material flow optimisation. Additionally, given that the study aims to understand how Lean principles manifest in an internal operational ETO logistics context, a case study design supports both descriptive and explanatory insights.

Initially, the study focuses on building an understanding of the current warehouse material flow at the case company. This was done through pre-study observations and semi-structured interviews with relevant warehouse and production personnel, enabling a contextualised representation of how the process is performed in practice.

The analysis was then conducted through thematic analysis guided by Lean theory. Thematic analysis is a structured method for identifying, analysing, and reporting patterns within qualitative data. In parallel, a flowchart was developed to support the understanding of the material flow by visualising process interactions, inefficiencies and non-value-adding activities. Finally, the findings were discussed in relation to the applicability of Lean principles in ETO environments.

The chosen research design enabled the identification of key factors affecting warehouse material flow and provided a structured link between empirical observations and theoretical concepts. To illustrate how the study progressed from the initial pre-study to the final analysis and discussion, an overview of the research process is presented in Figure 3.1.

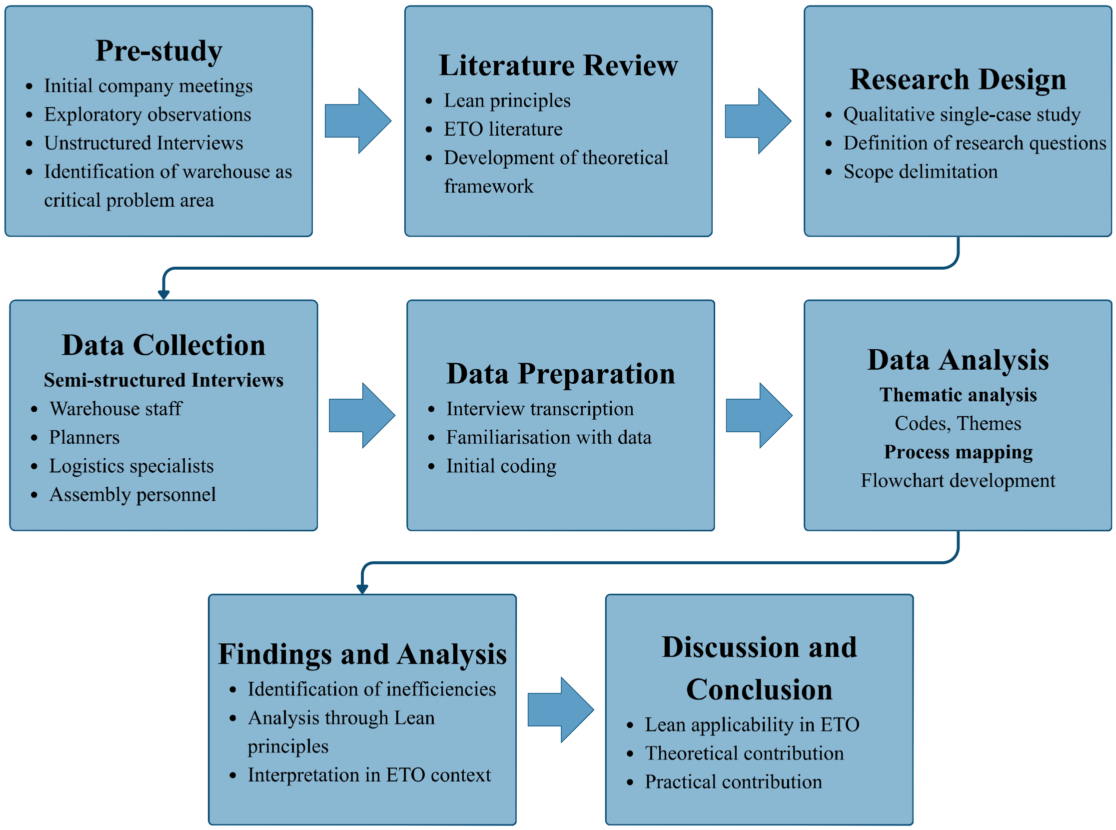

Figure 3.1: Overview of the methodological research process.

3.2 Literature Review

A qualitative study should be grounded in relevant literature, and the theoretical framework should be aligned with the objectives of the study (Maxwell, 2008). Conducting the literature review served two main purposes. It provided the theoretical foundation used for identifying key subject areas and form initial research questions during the pre-study. In the later stages of the study, the reviewed literature provided the analytical framework used to interpret the empirical findings from interviews.

Knopf (2006) emphasises that caution should be exercised when selecting sources from the internet. Therefore, theory used throughout this research was primarily peer-reviewed scientific articles and academic publications identified through Google Scholar and the databases provided by Chalmers University Library.

Keywords connected to central concepts relevant for the study, such as Lean, ETO

(Engineer-to-Order), HVLV (High Variety Low Volume), internal logistics, and material flow optimisation will be used to find relevant literature.

3.3 Data Collection

This section outlines the data collection methods employed in the study, including pre-study observations and interviews, as well as the sampling strategy used to ensure relevant and reliable empirical data. The purpose of the data collection was to develop a detailed understanding of the current warehouse material flow and to identify inefficiencies within the studied processes.

3.3.1 Observations

Besides interviews, observations at the production sites and the warehouse were carried out during the pre-study. These observations were largely unstructured and exploratory, allowing flexibility in identifying relevant processes, behaviours, and problem areas. This exploratory approach supported the development of an initial understanding of the system, how processes interact, how material flows through the system, and how product structures influence handling and storage activities. Together with pre-study interviews, the observations supported the establishment of the current state and the formulation of the research problem.

The observations were primarily focused on warehouse material flow. Particular attention was paid to workflow sequences, handover points, and waiting times. Observation was considered a good complement to interviews as it enabled the direct study of workflows and interactions as they occur, thereby reducing reliance on self-reported information and increasing contextual understanding (Kumar, 2023).

Overall, observation served two key functions in this study: first, to create an initial understanding of the current operational state, and second, to validate findings derived from interviews.

3.3.2 Interviews

Interviews were conducted during the pre-study to create an understanding of the current situation and a direction for the study. These interviews were unstructured, which is explained by DiCicco-Bloom and Crabtree (2006) as more guided conversations in order for the researcher to obtain information and learn about the context.

In total, the pre-study consisted of four interviews with personnel involved in different operational areas: production technician, logistics specialist, production planning, and project planning. The purpose was to develop an overall understanding of key activities, process interactions, and perceived challenges within the organisation, thereby forming an initial problem formulation.

During the interviews, the warehouse consistently emerged as a critical problem area, with several interviewees highlighting inefficiencies and extended lead times. Consequently, the focus of the study was narrowed to the warehouse facility.

Building on the initial pre-study interviews, additional interviews were conducted in later stages of the study to develop a deeper understanding of the current state and to collect empirical data for answering the research questions. These interviews were semi-structured, as DiCicco-Bloom and Crabtree (2006) identify this as the most commonly used format in qualitative research. The approach is based on guiding the conversation through predefined themes while allowing for open-ended responses and follow-up questions when needed.

The interview topics and questions were adapted to the role of each respondent, meaning that the interview guides varied across departments. The questions were developed based on the Lean theory presented in Section 2.2 and aimed to capture aspects related to muda, mura, and muri by exploring operational inefficiencies, workload and process variation, and how work was experienced in practice, including stress and operational pressure. Respondents were also asked to describe the picking process and their specific role within it to support the mapping of the value stream, understand how material and information flow through the system, and identify the presence of pull-related mechanisms. The interview guides for the different respondent groups are presented in Appendix A, while an overview of the pre-study and semi-structured interviews is provided in Appendix B.

Conducting semi-structured rather than fully structured interviews allow room to explore new areas that may emerge during the course of the interview (Wildemuth, 2016). The approach is well suited for this study, as an overly structured interview guide could limit the emergence of important or otherwise interesting information, potentially affecting the results. However, maintaining a reasonably consistent interview structure is important to ensure that interviews keep to the same topics, so that results can be analysed with the understanding that the interviews were conducted under comparable conditions.

Selection of interview participants

The initial selection of interviewees was done using a purposive approach in consultation with a supervisor at the case company and respondents who participated in the pre-study. These individuals were considered knowledgeable regarding organisational responsibilities and areas of expertise within the company and were therefore able to suggest relevant participants for the study. Purposive sampling is a form of non-probability sampling in which researchers select participants according to specific criteria, such as expertise in the study domain or the ability and willingness to take part in the research (Jupp, 2006). Jupp (2006) explains that case study research often requires purposive sampling because the selection of the case and its participants is driven by the relevance of the context rather than representativeness in a statistical sense. In accordance with Jupp (2006) potential participants were chosen based on their roles, responsibilities, and involvement in the studied processes, ensuring access to data that is both contextually grounded and analytically valuable. Roles chosen were warehouse staff, warehouse manager, logistics engineer/specialist, project planners, production planners etc. (see Appendix B).

Purposive sampling increases the likelihood of obtaining rich, detailed, and relevant data, essential for in-depth qualitative analysis. However, this sampling strategy also involves inherent limitations. The primary risk of purposive sampling lies in the subjectivity of the researcher's selection decisions, which introduces a risk of selection bias and may threaten the validity of the study's conclusions (Jupp, 2006). To mitigate these risks, purposive sampling was complemented with snowball sampling. After each interview, respondents were asked to suggest additional potential participants, who were subsequently interviewed and invited to recommend further respondents. This process was repeated until sufficient data had been collected, in accordance with Jupp (2006).

3.4 Data Analysis

The data collected from interviews were analysed using thematic analysis. In parallel, the empirical material was used to map the process through an activity flowchart. Combining these approaches enabled both an in-depth interpretation of qualitative data and a structured visual representation of material flow. While thematic analysis supported the identification of patterns, inefficiencies, and underlying causes, the flowchart complemented this by illustrating interactions across process steps.

3.4.1 Thematic Analysis

Thematic analysis is described as a structured method for identifying, analysing, and reporting patterns (themes) within qualitative data. This method enables researchers to organise and describe a dataset in detail while also allowing interpretation of underlying meanings and patterns relevant to the research questions (Bell et al., 2019; Braun & Clarke, 2006). Because this study relies on semi-structured interviews and observational notes to understand operational practices in a real-world organisational setting, thematic analysis provides an appropriate analytical approach.

The thematic analysis has been conducted in an inductive manner, which Braun and Clarke (2006) explain as allowing patterns to emerge from the empirical data. However, the interpretation of these themes was guided by the study's theoretical framework on Lean principles. This approach enabled the empirical findings to be systematically related to established Lean concepts such as waste and flow, thereby linking observed operational issues to the analytical framework used in the study.

The first phase of the thematic analysis involved familiarisation with the data. In this study, this included transcribing interview recordings using OpenAI's transcription tool. The audio recordings were first transcribed into raw text by the AI model, after which the researchers reviewed the transcripts separately while listening to the recordings, making necessary corrections and adding headers to different sections, such as process descriptions or role-related discussions.

The researchers then repeatedly reviewed and discussed the interview transcripts and observation notes together. Braun and Clarke (2006) emphasise the importance of engaging with the entire dataset before formal coding begins, as initial impressions and potential themes often emerge during this stage. Accordingly, coding did not start until all interviews had been transcribed and the dataset was complete.

The second phase involved generating initial codes which represent the most basic segment of raw data that appear relevant to the research question (Braun & Clarke, 2006). The interview transcripts were split between the two researchers to, separately, code half each. It was conducted manually by going through interview transcripts and highlighting relevant data segments (quotes). These quotes were then transferred into an Excel table to support the organisation of codes. Each quote were then given a code based on these considerations suggested by Bell et al. (2019):

- Of what general category is this item of data an instance?
- What does this item of data represent?
- What is this item of data about?

In addition, each quote was assigned to a key process. This column identified the process to which the quote was most closely related, such as assembly, picking, planning, etc. This is not a defined step of the thematic analysis; rather the purpose of this was to facilitate the structuring of the findings in the report by enabling the researchers to filter the data by process in the Excel table.

This process resulted in an extensive Excel table of quotes and codes that captured recurring operational issues across the data set. When all interviews had been coded, the researchers went through the table together, reviewing, explaining, and sorting through the codes. Since the coding was conducted separately by the researchers, a joint review of the codes was necessary to ensure coherence.

The third phase involved identifying themes. The researchers re-examined the codes and grouped them into broader themes relevant to the research question, capturing recurring patterns and insights within the interview data, in line with Bell et al. (2019). These were recorded in an additional table column labelled “theme”. Notably, the significance of a theme is not determined solely by the frequency with which it appears in the dataset. Instead, its importance is evaluated based on whether it captures something meaningful in relation to the research problem. A theme may therefore appear in a limited portion of the dataset yet still be analytically significant (Braun & Clarke, 2006). This was an important consideration in this study, given that only a small number of participants from each role were interviewed.

At the end of this phase, a set of candidate themes and potential sub-themes had been identified. At this stage, the table contained the columns “respondent code”, “key process”, “quote”, “code”, “theme”, and, where applicable, “sub-theme”, as illustrated in Figure 3.2, which presents a limited extract from the thematic analysis table.

Resp. code	Key Process	Quote	Code	Theme
R9	Picking	*"It could be that even if something is supposed to be picked tomorrow, it still gets sent to an external site because we don't know any better. Then we end up sending it away and bringing it back a few days later."*	Excessive transport	Muda
R2	Consolidation	*"Consolidation has historically really been a source of frustration, because it's such a small area, and sometimes there's an huge amount of boxes and pallets that need to be consolidated. "*	Space constraints	
R2	Planning	*"It really is ups and downs. We don't have any maximum capacity limits in the planning, so the planners can schedule picking tasks that would normally take an entire week to complete, in just one day. And some days, it can be zero."*	Variation in the inflow	Mura
R1	Management	*"Everyone has such different preferences regarding which KPIs and metrics should be used, and so on. More and more is being measured, but nothing is actually done with the results."*	Data and metrics	Perfection

Figure 3.2: A limited extract from the thematic analysis table illustrating the coding and categorisation of interview data.

The fourth phase involved reviewing the themes. In this stage, the candidate themes were evaluated to determine whether they accurately represent the coded data and the dataset as a whole. Braun and Clarke (2006) emphasise the importance of ensuring internal homogeneity and external heterogeneity, meaning that data within each theme should meaningfully relate to each other, while clear distinctions should exist between different themes. With this in mind, not all candidate themes were deemed as actual themes because there was not enough data to support them or the data was too diverse. Thus, some candidate themes had to be refined, combined, or broken up into separate themes.

Once the themes worked in relation to the coded extracts and the entire data set, the fifth phase involved defining and naming themes. This includes clearly identifying the underlying essence of each theme and determining which aspect of the data it captures (Braun & Clarke, 2006). The identified themes were interpreted in relation to Lean principles. The Excel table was once again reviewed and the researchers added a column linking themes to different Lean concepts such as muda, muri, and mura. Through this interpretation, the thematic analysis supports the identification of non-value-adding activities and inefficiencies affecting material flow in the warehouse.

3.4.2 Process Mapping

The process was mapped using an activity flowchart, developed to support the understanding of the empirical findings. A flowchart is a visual representation of a process that illustrates the sequence of activities and the flow of materials or information between them, where each operation is represented by standardised symbols or functional blocks. This provides a clear visual overview of both the operational sequence and the system structure (M. Carter, 2021).

Initially, the study aimed to construct a Value Stream Map (VSM), as it is a commonly used Lean tool for analysing material and information flows. However, due to long manufacturing cycles, high variability, and lack of stable and standardised processes, it was not feasible to collect sufficiently reliable quantitative data required for a VSM during the study's time period. The project-based nature of production, frequent changes in priorities, and variability in material handling processes limited the applicability of a traditional VSM approach. Consequently, a flowchart was chosen as a more suitable method to capture the sequence of activities and identify inefficiencies in a qualitative and context-sensitive manner. Given that ETO environments involve complex, interconnected activities from goods reception to production supply, a visual representation supports clearer understanding than text alone, making relationships and bottlenecks more visible and thereby strengthening the analytical foundation of the study (M. Carter, 2021). The resulting flowchart provides a structured representation of the current warehouse process and helps the reader visualise how the different activities fit together and integrate.

3.5 Triangulation

According to Yin (2018) a case study should rely on multiple data sources that ideally point to the same conclusions, also known as triangulation. Triangulation is a common principle for qualitative studies, used to validate findings, increase credibility and reduce biases arising from the use of a single method or a single observer (N. Carter et al., 2014; Noble & Heale, 2019).

In this study, themes identified from the interview data were compared with insights from the pre-study observations. This triangulation enabled the convergence of multiple sources of evidence and supported a robust understanding of the warehouse material flow (Yin, 2018). This approach is especially important given the complexity of material flow in an Engineer-to-Order context, where operational practices, information systems, and organizational routines interact.

3.6 Ethical Considerations

This section outlines the ethical considerations relevant to the study, including the handling of interview data and the use of AI tools during the research and writing process.

Interviews

The report has taken appropriate steps to ensure that both the interviews and the report itself adhere to the ethical frameworks commonly applied in qualitative research. Recording an interview requires the respondent's consent (Wildemuth, 2016). At the start of each interview, participants were asked to give consent to have the conversation recorded using the built-in voice-recording function on the laptop.

In accordance with DeMarrais and Lapan (2003) respondents may be contacted after the interview to verify that the report accurately reflects their statements. Once the report was finalised, both the case company and the respondents received a copy to confirm that the information concerning the company and their contributions has been accurately represented.

In a qualitative, interview-based study, respecting participants' privacy is essential (DiCicco-Bloom & Crabtree, 2006). To safeguard this, all data presented in the report is anonymised; only general, non-personal information about each participant is disclosed. For ease of reference, each interview has been assigned an identifier.

AI declaration

This thesis utilised AI tools for two main purposes. First, OpenAI's transcription tool, Whisper, was used to transcribe interview recordings (OpenAI, n.d.-b). Second, AI was used during the writing process to improve the clarity and readability of the text. After drafting sections of the thesis, the researchers prompted large language models (LLMs) with instructions such as "improve readability" or "simplify the explanation." The suggested revisions were then reviewed, and relevant parts were incorporated where appropriate. In some cases, parts were written in Swedish and translated into English using LLMs.

The primary tool used was an internal chatbot at the case company, based on the open-source model GPT-OSS-120B by OpenAI (OpenAI, n.d.-a).

AI was not used to generate results or conduct analysis. Its use was limited to supporting the transcription process, as well as language refinement and translation.

4

Identification of Inefficiencies in the Current State

Insights from the interview study are presented in this chapter in order to answer research question one: *What inefficiencies and sources of waste can be identified in the current warehouse material flow?* First, a flowchart was developed based on the process descriptions provided by the respondents. Second, the findings are structured according to different process steps. Each step is described, followed by the associated challenges. Some challenges were identified by the process owners themselves, while others were highlighted by respondents from other areas.

4.1 Flowchart

The flowchart in Figure 4.1 presents an overview of the material and information flow as described by the respondents. It illustrates the main process steps from planning and order release to picking, consolidation, and final assembly, as well as key decision points and interactions between functions. The purpose of the flowchart is to provide a structured representation of the current state process, highlighting how activities are sequenced and how materials and information move through the system.

The flowchart is based on the combined descriptions of multiple respondents and therefore represents a consolidated view rather than a single individual's perspective. While the figure captures the general process flow, it does not reflect all variations and exceptions in detail. These are instead addressed in the subsequent sections, where each process step is analysed in relation to identified challenges.

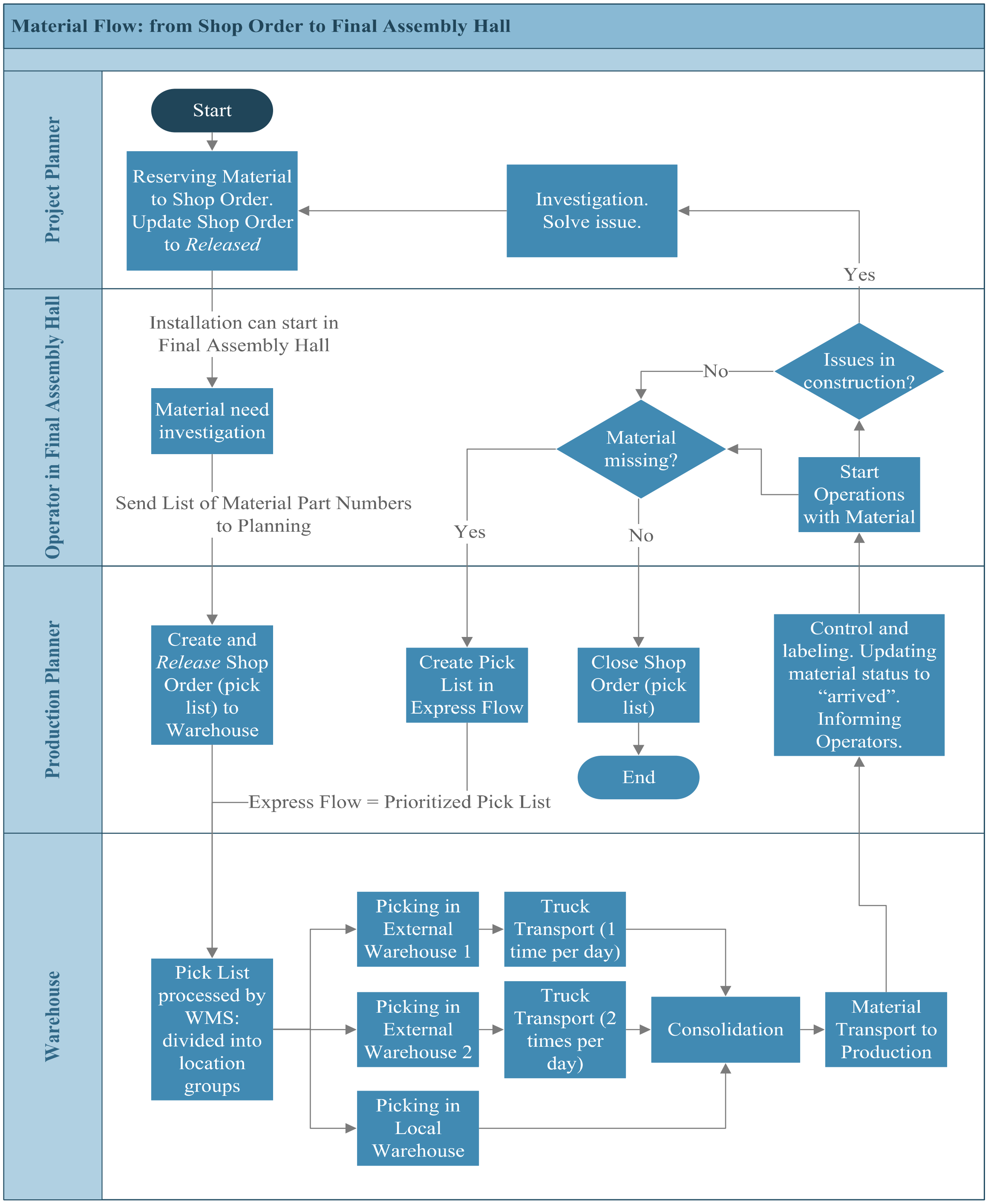

Figure 4.1: Flowchart visualising the material flow from shop order to final assembly hall.

4.2 Planning Process

Interviews were conducted with three production planners, R4, R5 and R12, which offered valuable insights into the case company's planning process. Additionally, other respondents provided further insights into how various functions and processes are affected by the planning process.

R4 explains that the planning process begins with a material availability check to ensure that all required materials are available (in storage and not allocated to other projects). If materials are available, the planner can either manually reserve specific batches or use an auto reserve function that automatically finds available batches and reserves them. Material is reserved on a shop order for each project.

When the required materials have been reserved, the shop order is released to production. R4 outlines that a shop order consists of multiple installation levels that are built progressively by operators in the final assembly hall. R4 explains that when an operator intends to start a particular installation level, they inform the planner. This notification must be given at least two weeks before production of that level begins. Planners use the two-week notice to ensure that necessary material is available and reserved for the upcoming production period. If the planner does not receive this notice, there is a risk that production will stop because of material shortage.

Reserving material on batch

At the company, material is reserved on batch numbers. Both R4 and R8 note that, regardless of whether the reservation is performed manually or automatically, the system allocates material to specific batches and does not support reservation based solely on volume.

The practice of reserving on batch is driven by the need for strict traceability. Several respondents (R3, R4, R8 and R10) explain that, as a defense-sector supplier, the company must be able to identify exactly which components are installed in each product to guarantee quality and to diagnose problems in the field.

Reservation procedures differ between production stages. In the final assembly hall, where R4 works, planners typically reserve material about one month before production begins. For earlier stages such as pre-assemblies, reservations can be made up to six months in advance. R4 explains that planners aim to reserve materials as early as possible. However, frequent changes and reprioritisations in the final assembly hall often require materials to be unreserved and re-reserved multiple times before production begins. Both R4 and R12 further describe how materials previously reserved for one project may be released and reassigned when higher-priority projects arise.

The timing of reservations therefore involves a trade-off. R4 notes that reserving too early may tie up material needed by other projects and increase the workload associated with reallocation. Conversely, R5 argues that reserving too late risks material shortages for the project itself.

According to R8, batch reservation practices create several operational challenges. Because different batches may be stored in separate locations, pickers must repeatedly move across the warehouse and between shuttle systems, making the picking process more time-consuming. Furthermore, when a stock error occurs or reserved batches have already been consumed, warehouse personnel must manually reallocate material to alternative batches, creating a substantial amount of administrative work. R8 suggests that reserving material based on volume rather than specific batch numbers could reduce this administrative workload.

Variation in picklist release and volume

There is no maximum capacity imposed on the number of picklists that can be released from planning. Consequently, a full week's worth of picklists may be issued on a single Monday, making the warehouse having to work throughout the week to clear the backlog (R2). Respondents report considerable day-to-day variation in the inflow of picklists from production (R2, R3, R9). It is also observed that demand is unevenly distributed throughout the week, with higher volumes from Monday to Thursday and comparatively lower volumes on Fridays. R6, R7 and R9 also note that the current daily volume of pick-lists is higher than it was a few years ago.

According to R9, the size of the picklists differs between production areas. Picklists from the final assembly hall could contain hundreds of items, whereas picklists from other production areas usually comprise fewer items. R9 emphasises that picklists with more items increase the risk of picking errors.

Communication across departments

Respondents also talked about cross-functional communication. There is no formal communication channel between planning and the warehouse, leaving staff to rely on informal exchanges (R2). Respondent R5 exemplifies this by saying that the most reliable way to obtain up-to-date material status is through a face-to-face visit to the warehouse and direct conversation with warehouse personnel.

Late changes to product structure

Late changes to the product structure can lead to significant rework for both planning and production, as noted by respondents R4 and R10. For instance, changing cable lengths after production has started involves several tasks, including batch changes, reallocation of materials, additional picking operations and require physical labor to remove and reinstall the new cables.

4.3 Assembly Process

One interview was conducted with a worker at the final assembly hall, R10. Furthermore, a tour of the site was done together with R11 where the process was explained by several workers. These respondents among others provided insight into inefficiencies related to the assembly site.

When the shop order has been released by the planning team, operators can start building the first installation levels. R10 notes that currently there is no prescribed order for constructing the products; operators may choose whichever installation they feel is appropriate. The company is, however, working towards an operation-driven planning approach that will provide a predetermined, step-by-step sequence.

When a new installation level begins, the required material must be ordered from the warehouse. The operator does this by sending a notice to the planners. R10 explains that the system does not generate an automatic signal to indicate when material should be ordered, so operators must physically inspect the storage area and estimate how long the available material will last. Planner R4 has highlighted the issue that ordering material from the final assembly hall is dependent on the individual operator because there is no support from the system.

R5, R10 and R11 describe a special express flow for material that is urgently needed on the shop floor. This flow shortens the time from four days down to 20-30 minutes and is used when production stops due to an unexpected issue, such as a missing screw or broken components. The assembly line makes frequent use of this express flow to minimise downtime.

Operators moving between projects adds delays and create risk

R5 responded that operators frequently move between projects. R10 confirms that it creates variation in the work performed and causes delays because with every switch between projects the operator needs to assess the project status and determine the next steps before continuing work.

Furthermore, when operators switch projects there can be material-related problems. Some product structures are planned with position-specific picking, meaning that each screw is assigned to a specific position (e.g., screw 1 for hole 1, screw 2 for hole 2), even though the screws are physically identical. While some assemblers follow these instructions strictly, others focus only on using the correct type and batch of screw, regardless of position.

This can create issues later in the process. For example, if a screw assigned to one position is used in another, an operator might think that the required screw is missing, even though it has already been installed. As a result, a new screw may be requested through the express flow, causing unnecessary delays and additional work for the warehouse.

An internal storage area would increase efficiency

R10 suggests that the assembly site should have an internal storage area for common material such as screws and cable ties. R10 explains that the reason for not having this internal storage could be because of traceability concerns. However, strict traceability requirements sometimes lead to quality issues. R10 gives an example: screws may only be reinserted once before they must be replaced due to quality standards. Lack of on-site storage means operators must order a new screw from the warehouse through the express flow, which is time consuming.. As a result, operators in this situation are likely to reinsert the screw rather than risk the delay.

4.4 Picking Process

In the warehouse interviews were conducted with a maintenance technician, R2, two logistics specialists R3 and R8, and two warehouse workers R6 and R7. These interviews gave insights regarding the picking process and its efficiency.

The picking operation begins the moment a shop-order is entered into the warehouse management system. The order can contain just a few lines or hundreds of different part numbers. Once it is received, picklists are generated and assigned to location-groups. These groups may be an automated shuttle rack, a pallet area, external warehouse sites, or other specialised zones such as chemical- or ESD material. When the picklist is released, it appears on the operator's screens at different pick locations (R6 and R7).

R6, R7 and R8 describe the different location groups. The shuttle rack is the fastest location for picking and operators are supported by the system with a laser beam showing operators the correct compartment for picking. In the pallet area operators use forklifts to move pallets up and down the racks and retrieve items. R6 and R7 explain that the specialised zones are more complex and not suitable for people who have just started working at the warehouse. The process here differs a lot depending on what items are picked. At the external sites material is stored in pallets. R3 adds to this by saying that the external sites do not have the same security level and that some materials are not allowed to be stored and picked there.

As introduced earlier, the express flow exists for unplanned, urgent material needs. Using this express flow, picklists are generated automatically and pushed up the queue to be picked immediately. All other picks are interrupted, and the warehouse workers shift their focus to the express flow. Only when this urgent order has been picked may the workers continue with the interrupted picklists.

Variation depending on location-group

R2, R8 and R9 all pointed out that the time required to pick varies a lot across different location-groups. R2 and R3 highlighted the pallet area and the specialised zones as the slowest parts of the process, whereas every respondent who discussed picking times agreed that the shuttle-rack is by far the most efficient. R3 and R8 believe that adding more shuttle-racks would therefore shorten overall picking times.

The pallet area is repeatedly described as a bottleneck. R2 explained that space for the forklifts is very limited. Usually only one forklift can operate, with two forklifts it becomes difficult to move around. R3 complained that the system offers no route optimisation for pallet picking, which means workers often retrieve pallets (for example A, B and C) for one pick-list and then immediately repeat the same trips for a second pick-list because the system does not group those orders together. R3 also mentioned the problem of having mixed pallets. When many different items share the same pallet, operators waste time searching for the correct part. R1 added that mixing metal components with circuit boards on the same pallet creates a risk of damaging the circuits when the pallet is lifted, potentially leading to defects.

When a pick-list contains items stored at external warehouse sites, the transportation from those sites adds one to two days to the process, depending on which site holds the material, the transport schedule and the moment the pick-list is released. R2 and R3 point out that this extra handling lengthens the lead time before the material reaches production. R8 expands on this by noting that nothing can be released to production until all items from each location group (including those from the external sites) have been consolidated, meaning all pick lists must wait for the transport from the external warehouses.

Unnecessary transportation create delays

R9 observes that a considerable amount of unnecessary transportation occurs, resulting in delays and transportation costs. Material sometimes arrives at the company only to be sent straight to an external site, and when it is needed in production the next day it is immediately shipped back. According to R9, the root cause is the system's inability to indicate when a particular item will be required in production, leading to back-and-forth transport.

The express flow is resource heavy and interruptive

A second major issue is the express flow. R2, R3 and R9 all said that handling express orders is very resource-intensive. Currently, there is a need to have a dedicated resource handling only express work. R9 added that most urgent orders are not caused by warehouse errors but by problems in production, such as missing screws or broken items. R6, R7, and R8 claimed that the express flow is very disruptive to the picking process, creating delays and increasing the likelihood of mistakes.

Picking mistakes creates risk and is a costly quality concern

Faulty picking is another identified concern. R1 explained that picking errors, such as selecting screws of incorrect length or volume, occur relatively frequently. These mistakes often force production to request replacement material through the express flow and, in the worst case, may remain undetected until the product reaches the customer, resulting in faulty assemblies. According to R1, the costs associated with such picking errors are significant. The underlying causes are described as limited system support for warehouse operators, a heavy reliance on manual work, and processes that depend strongly on individual experience.

Furthermore, R1 explains that these picking errors create additional work in the assembly hall. When material is delivered from the warehouse, operators sometimes feel compelled to verify the entire pick before starting production to ensure that all items are correct. According to R1, this practice is highly time-consuming, as reviewing a complete pick list may take more than an hour.

Position picking adds unnecessary work

The warehouse faces challenges related to position-specific picking requirements. In certain product structures, screws are assigned to designated installation positions according to the blueprint (e.g., screw 1 in hole 1, screw 2 in hole 2), despite being physically identical. R2 and R8 explain that this practice forces the warehouse to put the same type of screws into separate bags and label them according to their exact position. Consequently, an operation that requires 40 screws could require 40 separate bags, which R6 and R7 consider a waste of time. R8 agrees, adding that the practice also wastes plastic bags.

4.5 Consolidation

Throughout the interview process several operational challenges related to the consolidation process could be identified. Particularly concerning manual handling, lack of system support, and the impact of workload and order release practices.

R3, R6 and R7 describe the consolidation process as follows: once a pick list has been picked, put in a box, and completed, it is transported to the consolidation area, scanned, and put on a shelf. The scanner provides a notification indicating whether the picklist belongs to a new order or whether material from the same shop order is already stored on the shelf. In the latter case, the operator must manually locate the shelf position, so that the newly picked material can be consolidated together with the other picklists belonging to the same shop order.

Furthermore, the respondents explain that consolidation relies heavily on manual handling, as there is no system support indicating when an order is complete and ready for dispatch. Instead, completion must be verified by checking labels and ensuring that all boxes are present. The risk of labels detaching further complicates the identification and retrieval of orders that are stored across multiple locations.

Finally, R6 and R7 note that consolidation is one of the most difficult tasks for new employees to learn, which increases the likelihood of such procedural deviations.

High workload increases the risk of errors

R3 mentions that many issues arise due to high workload and stress among warehouse personnel. Boxes are sometimes placed directly on the shelf without being scanned. Instead, they are placed in the first available location to allow the worker to quickly proceed to the next task. When a box is not scanned, subsequent operators picking other parts of the same order are not informed that items are already stored on the shelf. As a result, the order becomes dispersed across multiple locations and remains incomplete.

Order release and system limitations

R3 explains that issues related to dispersed orders often also originate from how picking orders are initially released. Administrative staff are responsible for monitoring how many orders have already been released and ensuring that only a manageable volume is issued. Releasing all orders simultaneously results in a large number of partially completed picks remaining in the consolidation area, awaiting the final pick list before they can be delivered to production. This creates difficulties in locating specific shop orders, as material belonging to the same order may be stored on different shelves. There is no system support to track this effectively, therefore, orders must be released in smaller batches on a continuous basis to maintain control over the process.

Challenges related to partial deliveries

Partial deliveries are not made unless agreed upon with the assembly department, for example due to material size constraints or prioritisation needs. R3, R6 and R7 emphasise that releasing only part of an order can create challenges. A shop order is divided into multiple pick lists depending on picking zones. For instance, if an order consists of five pick lists, the number “5” is displayed on the header label attached to the boxes. This number remains unchanged even if one of the pick lists has been prioritised and therefore released separately, earlier than the other four. Consequently, when the remaining pick lists are printed, the label will still indicate five items, even though there are only four left. This requires manual tracking, often resulting in the remaining four pick lists waiting for the fifth, which has already been delivered. This is one of the most frequent issues associated with consolidation and may cause goods to remain in storage for several days, occupying space before reaching production.

Space constraints and capacity limitations

Consolidation is not performed within the production area due to space limitations. Therefore, items are only transported to production once all picking activities are finished and the order is complete (R8). However, this means that large orders may occupy significant space in the consolidation area while awaiting completion, for example when awaiting transport from an external warehouse.

R2 and R3 explain that during periods of high inbound flow of picklists, the consolidation area risks becoming overloaded. In practice, there is often no immediate solution other than allowing accumulation, leading to pallets being stacked on top of each other. Consolidation has historically been, and continues to be, a source of frustration due to space limitations. The process becomes inaccurate, disorganised, and time-consuming, ultimately causing delivery delays. According to R3, the actual picking process itself is not necessarily the main source of delay. Instead, delays primarily arise when consolidation problems, shortage handling, and related disruptions occur:

> *“If it’s an error-free pick list, I’d say it can be done in one day, to dispatch it. But as I said, if consolidation takes a long time or shortage handling and things like that are involved, then it takes longer. Still, I’d say it can be done in a day.”*

To manage these issues, R3 further explains that administrative personnel responsible for consolidation regularly review the consolidation area and attempt to identify related orders by locating boxes that have remained on the shelves for extended periods. This is done manually by reading order numbers on each box.

4.6 Expansion

The geopolitical situation has led to a substantial increase in production volumes and necessitated a rapid expansion of operations. R2 states this growth has led to the introduction of numerous new operational flows, which in turn has increased the number of support-related inquiries and made it more difficult for individual employees to maintain a comprehensive overview of all relevant information.

Because of this expansion, both the number of picking lines and the warehouse's operational capacity have increased substantially. As told by R3:

> *"Before, our maximum might have been around 1,000 order lines picked if we worked really hard. Now, 1,000 picked lines is almost the minimum of what you can manage here. But back then we were at most eight people in the entire warehouse, and now we're close to 30, so it's really grown a lot."*

R9 adds that current daily volumes typically range between 1,500 and 2,000 picking lines, with peaks reaching up to 3,000 lines. These peak levels exceed the warehouse's effective capacity and can result in operational delays.

Quality and workload implication

The increased volume has also affected operational quality. According to R1, the frequency of picking errors has risen across all production groups, accounting for 10-15% of all non-compliance reports each month at the company site. This indicates that the system is operating under increased strain. More broadly, the expansion has led to a significantly higher workload for warehouse personnel, further challenging the organisation's ability to maintain efficiency and accuracy.

4.7 Admin

This increased workload is particularly evident in administrative functions. R3 notes that the scope and complexity of administrative tasks have grown considerably. Whereas the administrative role was previously managed by a single individual, it is now distributed across five employees, reflecting both the increased volume and the greater coordination requirements of the operation.

R6 and R7 describes the administrative role as encompassing a wide range of responsibilities, with a primary focus on investigative tasks and the management of shortages. A substantial portion of the work also involves monitoring and responding to inquiries in the mailbox, which is notably time-consuming. In addition, the role functions as a central coordinating hub within the operation, where the administrator receives incoming tasks, allocates work, and provides ongoing support to colleagues. In practice, the administrator serves as the primary point of contact for operational questions and uncertainties.

Competence requirements and staffing constraints

R9 emphasises that the role is highly competence-intensive, and only a limited number of employees possess the required knowledge and experience. Currently, five to six individuals are capable of handling the role, while at least four are required at any given time. As a result, these individuals are, in practice, continuously assigned to administrative duties, despite the intention of maintaining a rotational schedule.

R9, R6 and R7 all agree that the onboarding of new personnel is conducted through informal, practice-based learning, where employees shadow more experienced colleagues. However, prior to assuming the role, individuals are expected to have a comprehensive understanding of the entire warehouse operation, including the ability to work across all areas, perform picking activities in all sections, and understand end-to-end processes, as inquiries may arise from any part of the workflow. R6 and R7 states that this learning process can take up to a year to complete.

Administrative workload and organisational vulnerability

The administrative function is further challenged by a high and variable workload. R6 and R7 describe that at times, there may be minimal incoming tasks, while at other times the intensity is such that additional support is required to manage the workload effectively. This is driven by a significant share of email questions, priority picking, express flow, and shortage handling that requires manual intervention.

These challenges are compounded by a high rate of staff turnover within the warehouse. As noted by the respondents, many new employees view the warehouse as a temporary position before transitioning to other roles within the organisation, making it difficult to retain personnel over longer periods. Consequently, there is a limited pool of experienced staff capable of managing the administrative role effectively.

R3, R6, and R7 emphasise the need to strengthen the overall competence level within the warehouse, with particular focus on the administrative role. R3 identifies this function as both a current bottleneck and a vulnerable part of the operation, as the high degree of manual work increases the risk of errors related to shortage handling, consolidation, and inventory processes when sufficient competence is lacking. This highlights the strategic importance of strengthening both competence and system support within this area

4.8 Information Systems

The empirical findings indicate several interrelated challenges associated with the company's information systems, which collectively impact operational efficiency, decision-making, and process quality.

System usability and stability

A recurring issue concerns the usability and reliability of the business system. As expressed by R3:

> *"Our business system is not user-friendly. You have to trick the system and find ways to accomplish what you want despite its limitations. Unfortunately, the system is not designed for our operations; instead, we have to adapt to it and make the best of it."*

This perception is reinforced by R8, who highlights that the systems are neither particularly stable nor easy to work with. Frequent updates must be continuously tested across interconnected systems to ensure compatibility, as failures during implementation may result in production stoppages. Furthermore, no formal training has been provided to employees; instead, knowledge transfer occurs informally between colleagues, despite requests for structured onboarding (R3). This lack of formal system training increases dependency on individual experience and contributes to inconsistent system usage.

Fragmented system landscape and limited integration

To compensate for limitations in the core system, R8 explains that external analytics tools such as Clicksense are used. These tools are perceived as well-functioning and enable data visualisation and analysis by extracting information from the enterprise system into external environments. However, this setup requires users to operate outside the primary system, and the data flow is unidirectional. As a result, these tools are unable to modify or reintegrate data into the core system. This creates a fragmented system landscape in which decision-support capabilities are dispersed across local functions, limiting both their long-term stability and their applicability across the broader organisation (R8).

Inadequate decision support for storage and prioritation

R1, R2, and R9 explain that the put-away process is currently only limitedly data-driven, which leads to several operational inefficiencies. There is no available master data on key attributes such as movement frequency or expected demand over time. R9 and R2 both give the same example: materials that are scheduled to be picked the following day may still be sent to an external warehouse, as this information is not visible in the system. This results in unnecessary transports that would be avoided with better system integration and data visibility.

In addition, there is a lack of data regarding picking frequency, which further limits the ability to make informed storage decisions. R8 says that, ideally, items should be classified based on demand patterns, such as identifying high-runners already during the put-away process, but such analytical support is currently absent. While large order quantities and priority signals from the planning function could serve as a proxy indicator, this is not a reliable method. For instance, when materials arrive marked as prioritised, this may be interpreted as an indication of imminent use. But in reality, prioritisation may be driven by procurement needs, such as the need to have the material registered in the system in order to process supplier invoices. Consequently, such signals do not reliably reflect actual demand or urgency in production, further complicating effective decision-making in the put-away process.

R9 and R2 explain that incoming materials do not have predefined storage locations and that no master data is linked to the materials, further complicating material handling. As a result, storage decisions are often made ad hoc and primarily based on physical size rather than operational relevance.

Ideally, R8 explains that item data from procurement should include key parameters such as dimensions, weight, and type of load carrier, enabling accurate and system-supported placement already at the point of put-away. However, when goods arrive from production or procurement, this information is lacking. As a result, staff must determine themselves whether an item is suitable for, for example, a specific bin in the shuttle system. In practice, this relies on manual estimation and availability checks rather than system support. Larger items are typically placed in pallet storage, while even larger goods may be sent to external warehouses. This size-based approach, in the absence of demand-driven data, risks creating inefficiencies by misaligning storage locations with actual picking frequency and operational needs.

R9 explains that in the absence of clear system guidance, such decisions also tend to be based on what is quickest and most practical at the moment, particularly under high workload conditions. Consequently, items are often placed in pallet storage even when this is not optimal. These practices create inefficiencies in downstream processes, as pallet picking is generally more time-consuming than shuttle picking. Finally, unit inconsistencies in the system were identified as a recurring cause of picking errors. R1, R3, R6, and R7 describe how items purchased in meters may be registered as "pieces" in the system. Similarly, a picking order may specify 15 meters of cable on two separate order lines because the cables are intended for different installation positions, even though assembly requires a continuous length of 30 meters. Such discrepancies must then be manually corrected by the planner in each individual case.

Limited traceability and material status visibility

R8 highlights another issue concerning the lack of reliable data on material status, particularly regarding when an item was last actively used. For example, in IPS (Inventory Parting Stock), the "last activity" date field may appear to indicate the most recent usage of a material. However, this metric is misleading, as it can be updated by routine events such as cycle counting or internal stock movements rather than actual consumption. As a result, it becomes difficult to determine how long materials have remained unused in inventory, increasing the risk of unnecessary stock accumulation and reducing the effectiveness of inventory control and space utilisation.

R8 further mentions that there are only two statuses a material can have during the picking process. It is either released (picklist released) or cancelled (delivered in production). Between those two stages (whether the material is still on the pallet shelf/in the shuttle, in transport, or in consolidation) there is no additional information regarding position or status of the material. R6 and R7 notes that production and planning often ask about material status.

Constraints on data-driven improvement

Finally, the lack of reliable and relevant data limits the organisation's ability to conduct structured improvement work. R2 explains that much of the responsibility for improvement initiatives falls within his role, but that these efforts are difficult to evaluate due to the absence of measurable performance indicators. Consequently, decision-making is often based on intuition rather than quantitative analysis.

For instance, R2 mentions that there is no available data on picking times linked to specific warehouse areas, which restricts the ability to identify inefficiencies. Quality is instead primarily monitored through the number of reported deviations, with approximately 200 such cases per month. While these are analysed to identify potential improvement areas, the approach remains largely reactive and lacks the support of comprehensive performance data.

4.9 Management

The empirical findings indicate several managerial and organisational challenges related to personnel management, cross-functional coordination, and continuous improvement practices. These challenges collectively affect operational efficiency, knowledge development, and the organisation's ability to systematically improve performance.

Personnel management and competence development

A recurring theme across interviews concerns challenges related to personnel, particularly staff turnover, onboarding, and competence development. R9, R6, and R7 mention that high employee turnover limits the accumulation of experience within the organisation and creates a continuous need for training new staff. As a result, knowledge levels remain uneven, and the organisation becomes dependent on a limited number of experienced individuals.

The onboarding process is largely informal, which further complicates competence development. Without structured training and clear development pathways, it becomes difficult to ensure that employees acquire the necessary skills to handle increasingly complex operational tasks. This creates long-term challenges in building a stable and competent workforce.

Organisational silos and limited cross-functional understanding

Another significant issue is the presence of functional silos within the organisation. Communication between departments is perceived as limited, and there is a lack of understanding of how different functions interact and depend on each other. This results in misaligned expectations and reduced collaboration across the organisation. As mentioned by R1:

> *"In the past, you would hear people in production say, 'What the hell, can't they even count (in the warehouse)?' But when you go out and talk to the warehouse staff and see their situation, you realise it's not that surprising that mistakes happen. A few years ago, a production operator who had been burned out was temporarily assigned to the warehouse, and he said that the warehouse is the last place you'd want to be if you've been burned out, it was extremely demanding. So, we have a misleading perception of what it's actually like, and I believe it becomes a leadership responsibility to highlight this and show that not just anyone can work in the warehouse."*

Both R3 and R8 reinforce this perspective by describing the warehouse as a "black box," where materials are added and removed without consideration, sufficient coordination or shared understanding between functions. This lack of transparency further weakens cross-functional alignment.

Lack of structure in performance measurement

The findings also indicate a lack of consensus regarding performance metrics, particularly in relation to warehouse processes. According to R1, there is uncertainty about which key performance indicators should be used, and different types of measurements are sometimes conflated. For example, picking errors may be interpreted differently depending on how error categories are defined and reported, leading to inconsistent conclusions about performance. R1:

> *"What we hear from those working with picking errors in the warehouse is that 'express flow picks have increased, and that's because there are so many errors in production.' And while that is partly true, these cases fall under error code B, which relates to construction. However, error code A: delivery and picking, is what we have examined, and those are purely picking errors originating from the warehouse."*

Limited follow-up and reactive improvement practices

A further challenge concerns the lack of structured follow-up and systematic improvement work. R1 further states that although an increasing number of measurements can be observed, they have not been translated into more effective decision-making. While data is collected, it is not consistently used to guide actions or improvements. This suggests a gap between measurement and managerial utilisation of performance data.

Both R1 and R9 notes that root cause analysis is limited, and implemented actions are rarely evaluated over time. Instead, responses to operational issues tend to be reactive, often involving the allocation of additional resources rather than addressing underlying causes. For example, an increase in deviations handled in the express flow has led to more personnel being assigned to administrative handling of deviations, rather than investigating how such errors can be reduced. This indicates a tendency to manage symptoms rather than root causes.

Impact of expansion on management priorities

According to R9, the rapid expansion of operations has significantly influenced management priorities. The primary focus has been on maintaining delivery performance and ensuring that orders are fulfilled on time. As a result, less attention has been given to developing processes and working methods adapted to increased volumes. Existing processes have instead been scaled up without sufficient adjustment, despite not being designed for the current level of operations.

5

Analysis through Lean Principles and the ETO Context

The following analysis addresses research question two: *How can the identified inefficiencies be explained through Lean principles and the Engineer-to-Order (ETO) context?* This is achieved by systematically analysing the empirical findings in relation to each of the Lean principles, while accounting for the specific characteristics and constraints of the ETO context. Subsequently, the discussion evaluates the extent to which these principles are applicable to ETO settings and considers the adaptations required for their effective use.

5.1 Value

The principle of value emphasises that value must be defined from the customer's perspective, where only activities that directly contribute to fulfilling customer needs are considered value-adding (Womack & Jones, 1997).

5.1.1 What is Value for an ETO Customer?

In an ETO context, value is created through a high degree of customisation. Alfnes et al. (2021) explain that companies operate at different levels of customisation, ranging from innovate-to-order (ITO), where each order requires new design and engineering, to redesign-to-order (RTO), where existing products are modified with changes such as configurations, components or design features. This means that companies must decide how much customisation to offer. Whether each product is largely unique, requiring full engineering for every order, or based on a standard platform with configurable features.

While increased customisation is often perceived as value-adding, it also introduces trade-offs. ETO systems tend to prioritise flexibility over flow efficiency (Alfnes et al., 2021; Strandhagen et al., 2018), which can lead to longer lead times and higher costs. Consequently, ETO companies must balance the value of customisation against efficiency, cost, and delivery time, all of which are important to the customer.

This raises the question of whether the case company operates at an appropriate level of customisation. The findings indicate that customisation is allowed late in the process. R4 and R10 note that changes to the product structure can occur even after production has started. Such changes trigger a range of internal activities, including batch changes, material reallocation, additional picking, and, in some cases, reinstallation of components. These adjustments introduce complexity and disrupt the flow of operations.

At the same time, the company is experiencing rapid growth, which places increasing pressure on warehouse operations. R3 explains that daily picking volumes have increased significantly, with previous peaks of 1,000 lines now becoming a baseline, while R9 reports peaks of up to 3,000 lines per day. This combination of high customisation and increasing volume challenges the system's ability to maintain efficient flow.

Given these conditions, this study suggests that the company should critically evaluate its level of customisation. Reducing the degree of customisation, particularly in the form of late changes, could improve flow, lower operational complexity, and reduce both costs and lead times, in line with Alfnes et al. (2021). This does not necessarily mean eliminating customisation, but rather managing where and when it occurs in the process.

It should be noted that the focus on late-stage customisation in this study is a consequence of the empirical scope, as interviews were conducted with personnel in the warehouse and final assembly. As a result, the identified challenges primarily relate to later stages of the production process, where changes to the product structure have direct operational impact. Limiting how late such changes are allowed is one potential way to improve flow. However, it is likely that similar considerations apply earlier in the process, for example at the order stage, where reducing the range of configuration options and utilising modular product structures could help establish clearer boundaries for customisation from the outset.

5.1.2 Value in the Warehouse Material Flow

In the context of the warehouse material flow, value is primarily created when materials are delivered to production in the right time, in the right quantity, and in the right condition. Activities that do not contribute to this outcome are considered waste (muda), which Womack and Jones (1997) categorise into seven types: transportation, inventory, motion, waiting, over-processing, overproduction, and defects. The interdependence of these waste types, combined with the complexity of ETO operations, makes addressing the three M:s (muda, mura, and muri) particularly important in ETO systems.

Motion

The findings indicate that the picking and associated warehouse processes are characterised by a substantial presence of non-value-adding activities, suggesting that the system is not aligned with value from the production perspective. A dominant form of waste is unnecessary motion and searching. The pallet area, for example, is consistently described as a bottleneck where limited space constrains forklift operations, resulting in inefficient movement patterns (R2). The absence of route optimisation, mentioned by R3, further exacerbates this issue, as operators are required to perform repeated retrievals of the same pallets across multiple picklists. From a Lean perspective, this reflects poor process design, where motion waste is embedded in the system rather than eliminated through structured planning and layout optimisation.

The use of mixed pallets introduces additional inefficiencies in the form of searching and increased handling complexity. When multiple items are stored on the same pallet, operators must spend time locating the correct component, which does not contribute to value creation (R3). Moreover, this practice introduces quality risks, as highlighted by R1, where sensitive components may be damaged due to inappropriate storage combinations. This illustrates how variability in storage practices (mura) can lead to waste (muda), reinforcing the interdependent nature of inefficiencies within the system (Liker, 2022; Rawabdeh, 2005).

Transportation

Transportation waste is another significant issue, particularly in relation to the use of external warehouses. Materials stored externally introduce additional handling steps and lead times before reaching production (R2, R3). Furthermore, the findings reveal instances of unnecessary back-and-forth transportation. From a value perspective, such movements do not contribute to delivering materials to production in the right time and condition, but instead extend lead time and increase operational cost, indicating a misalignment between storage decisions and actual demand.

Excess inventory

The findings also highlight issues related to excess inventory and the lack of reliable inventory data which makes it difficult to determine how long items have actually remained unused. As a result, materials may remain in storage for extended periods without being utilised in production, occupying valuable space and contributing to inefficiency. According to Rawabdeh (2005), excess inventory can lead to additional waste, including defects caused by obsolescence or scrapping. From a Lean perspective, inventory is not only a form of waste but also a mechanism that conceals underlying process problems. Ohno (1988) argues that waste hidden behind buffers and inventory cannot be effectively addressed. In this case, unreliable data and excess inventory contribute to a lack of visibility, allowing inefficiencies to persist without systematic resolution.

Defects and re-work

Defects and rework also emerge as critical sources of waste. Picking errors are reported as relatively common (R1) and can lead to significant downstream consequences, including production delays, express orders, and faulty assemblies reaching the customer. These errors are closely linked to the reliance on manual processes and limited system support, which increases the likelihood of human error. In Lean terms, defects represent one of the most critical forms of muda, as they not only consume additional resources but also undermine overall process quality and reliability (Liker, 2022).

Over-processing

The practice of position-based picking illustrates how over-processing is embedded within the system. Although intended to support production accuracy, this approach requires identical components to be picked, separated, and labelled individually according to position. Pienkowski (2014) defines over-processing as work performed beyond what is necessary, often as a result of poor process design. This definition is highly relevant in this context, as the practice creates substantial additional handling and administrative work, while also generating unnecessary packaging waste. Moreover, the intended value of this practice is not consistently realised in production, where operators may disregard positional labelling and treat the components as interchangeable. This disconnect between process design and actual usage leads to rework, unnecessary picking effort, and additional express orders when materials are perceived as missing. From a Lean perspective, this reflects a failure to align processes with customer-defined value resulting in over-processing that does not deliver corresponding benefits.

Similarly, the batch-based reservation system increases the complexity of warehouse operations and generates additional work when batch changes are required. This constitutes a form of over-processing, as the level of specificity imposed by the reservation practice exceeds what is operationally necessary for many material types, particularly standard components such as screws or cable ties. This contributes to delays and unnecessary administrative effort, further indicating that the system is not designed to support efficient value delivery to the customer.

Muri leading to muda (waiting)

The findings also highlight the presence of muri (overburden), which further drives inefficiencies. High workload and time pressure within the warehouse lead to deviations from standard procedures, such as bypassing scanning steps during consolidation. While this may provide short-term relief, it creates downstream issues, including loss of traceability, and dispersed orders, which in turn generate additional searching, waiting, and rework. Liker (2022) argues that if mura and muri are not properly managed, they inevitably give rise to further muda, as overburdened personnel are more prone to errors and process deviations. This interrelationship is clearly visible in the case company, where sustained workload peaks amplify the occurrence of waste throughout the system.

Overall, the findings demonstrate that a significant portion of warehouse activities do not contribute to the customer-defined value of delivering materials to production in the right time, right quantity, and right condition. Instead, they consist of various forms of waste that are not isolated but interconnected, often reinforcing each other and compounding their impact on lead time and operational performance, as Rawabdeh (2005) and Pienkowski (2014) suggest is typical of muda. From a Lean perspective, this indicates that the current system lacks a clear alignment with value, where processes have evolved around internal constraints and practices rather than the efficient delivery of materials to production. As a result, the system consumes resources without correspondingly increasing the value delivered to the customer, highlighting substantial potential for improvement through waste reduction and process realignment.

5.2 Value Stream

The value stream principle concerns the identification and integration of all activities required to deliver value, with the purpose of distinguishing value-adding from non-value-adding activities (Liker, 2004; Womack & Jones, 1997). A fundamental requirement for this is the alignment and integration of both material and information flows across the entire process. Womack and Jones (1997) emphasise that applying this principle requires mapping the full value stream and systematically eliminating muda across it.

Fragmented value stream

The findings indicate a lack of connection between processes, suggesting a fragmented value stream. Planning, warehouse operations, and production are not synchronised through formalised communication channels but instead rely on personnel actively seeking information and relying on informal exchanges (R2). R5 exemplifies this by noting that the most reliable way to obtain up-to-date material status is through direct, face-to-face contact with warehouse personnel. R6 and R7 add that administrative staff receive a high volume of questions about information that should be visible in the system, such as material status and delivery updates, indicating that the system fails to support transparent information flow. In Lean terms, this reflects a shortcoming in the informational flow in the value stream where, instead of information being visible where it is needed, personnel must expend effort to retrieve it. This effort constitutes a form of waste, specifically unnecessary motion and waiting (Liker, 2022). In the ETO context, where interdependencies between planning, warehousing, and production are substantial (Braglia et al., 2024), the absence of structured information flow is particularly disruptive, as errors or delays in one function are transmitted downstream without warning or visibility.

Lack of system signals

The findings also show that material requirements in the final assembly hall are assessed manually by operators, who estimate how long available materials will last and determine when to reorder (R4). This is due to the absence of time-related data regarding the duration of specific assembly activities, as well as the lack of a formalised build sequence in production. R10 notes that the system does not generate automatic signals indicating when material should be ordered. From a Lean perspective, this indicates a missing pull signal from production to the warehouse: rather than downstream demand automatically triggering upstream material release, the connection depends on individual initiative and judgement. In the ETO context, the absence of a fixed build sequence is structurally expected because each project involves unique configurations, but this increases, rather than reduces, the burden on information systems to compensate. The findings suggest that these systems are not fulfilling that role, leaving the value stream without a reliable mechanism for synchronising material flow with actual production needs.

A similar lack of data-driven signals is evident in the put-away process. R8 explains that no data on picking frequency is available, making it impossible to identify high-runners and allocate storage positions accordingly. Proxy indicators, such as materials marked as prioritised, are also unreliable as indicators of imminent use because prioritisation is sometimes driven by procurement needs. This is a clear example of local optimisation generating systemic waste. The procurement function achieves its local objective (invoice processing) at the cost of a suboptimal storage decision, which creates downstream inefficiency in the picking process. This is a pattern that Rawabdeh (2005) identifies as typical of waste interdependencies, where inefficiency in one activity amplifies waste in another. The lack of master data for incoming materials (dimensions and weight) further prevents systematic storage decisions, meaning placement is based on physical size and immediate availability rather than operational relevance. This misalignment between storage logic and picking demand is a direct source of inefficiency in the value stream.

Lack of end-to-end transparency

A third dimension of the fragmented value stream concerns the lack of end-to-end transparency. The findings reveal three visibility failures. First, material status data is unreliable making it impossible to determine how long items have genuinely remained unused. Second, there is no in-process location visibility. Personnel cannot track where a material is within the picking process (whether still at the shelf, in transport, or in consolidation), leading to manual tracking via email and administrative workarounds. Third, the consolidation process lacks system support for order completion. R3 explains that administrative personnel must physically walk the consolidation area and manually identify dispersed order components by reading labels on boxes that have remained on shelves for extended periods. These three failures are manifestations of the same underlying problem: the value stream is not transparent, and problems are therefore hidden rather than visible. This is the condition mentioned by Ohno (1988), waste that cannot be seen cannot be eliminated. Making the value stream visible is a prerequisite for systematic improvement Liker (2022), and the findings indicate that this condition is not met in several stages of the current material flow.

Taken together, the findings indicate that the value stream has not been designed as an integrated end-to-end system but has instead evolved reactively in response to operational pressures. Information and material flows are fragmented, visibility is limited at several stages, and standardisation is absent. The ETO context amplifies these problems as high product variability, complex interdependencies between functions, and unpredictable demand patterns all increase the need for a well-designed information flow and structured material management. From a Lean perspective, this means that the conditions necessary for value stream improvement (transparency, standardisation, and flow stability) are not in place. Waste accumulates across the value stream in ways that are largely invisible to those managing it. Therefore, developing a value stream map is strongly recommended to expose and address these conditions.

5.3 Flow

The study's findings provided insight into processes and material flows, highlighting both how material flow is affected by internal warehouse processes and how those internal processes, in turn, are influenced by planning practices before and during production. Flow, according to Womack and Jones (1997), involves ensuring that value-creating activities occur without interruption and emphasises a process-oriented rather than function-oriented approach. Liker (2022) further describes one-piece flow, where products move through processes one unit at a time without intermediate buffers, reducing lead times, costs, and defects. The interview study identified several practices that could be improved by adopting a more process-oriented mindset and a stronger focus on flow.

Express flow

A key example of disrupted flow is the express handling of urgent materials for production. Designed as an exception process for urgent production needs it now seems to have been normalised. Several respondents (R2, R3, R6, R7, R8, R9) explained that this "express flow" causes interruptions in the standard picking process, forcing regular work to pause until the urgent order is completed. R2 showed data of approximately 200 express cases per week for the company site. Each interruption generates waste (muda), particularly in the form of waiting when warehouse workers must reorient themselves and reset the system to a new pick list, as well as an increased risk of errors due to frequent task switching.

R9 notes that most express orders originate not from warehouse errors but from production problems such as missing or broken components, suggesting that the root cause lies outside of the warehouse. In an ETO environment, some degree of unplanned demand is inevitable given the complexity of product configurations, but the frequency and volume of express flow usage indicates that the current system has normalised exception handling as a substitute for stable flow design.

This study suggests that the case company should critically examine the necessity and design of this express flow, particularly whether it must be as disruptive as it currently appears. As illustrated in the flowchart (Figure 4.1), the same system is used for both express and regular picking, which contributes to these interruptions. Therefore, it is recommended that the company explore ways to decouple the express flow from the standard picking process, enabling a more independent and less disruptive handling of urgent materials. They should also analyse the root cause for errors contributing to the express flow, trying to reduce the need rather than only reacting to the consequences.

Consolidation area

Findings from the interviews indicate that the consolidation area constitutes a significant disruption to flow. Rather than enabling a continuous movement of materials, items are accumulated in the consolidation area and remain there until complete. As described by R3, R6, and R7, materials are placed on shelves and must later be manually located and combined, creating a batching mechanism where progress depends on the completion of all associated pick lists. This contradicts the principle of flow described by Womack and Jones (1997) and Liker (2022), where value-creating activities should proceed without interruption.

R8 explains that consolidation is performed in the warehouse due to space limitations in the final assembly hall. Moving consolidation to production could introduce additional forms of waste (muda), particularly unnecessary movement. For example, if the warehouse is unable to deliver all pick lists due to material shortages, and production requires complete orders to begin work, incomplete deliveries would occupy valuable space in production. This could result in materials needing to be transported back to the warehouse until shortages are resolved, resulting in unnecessary movement.

Although there is a need to consolidate items within the warehouse, the current process appears more disruptive to flow than necessary. A key issue is the lack of system support, as highlighted by R3, R6, and R7, which leads to unnecessary non-value-adding waiting time, which Womack and Jones (1997) distinguish from waiting that is structurally unavoidable. In many cases, consolidation is delayed while waiting for a single remaining pick list. While some delays can be explained by external factors, such as items stored in an external warehouse with limited transport frequency, respondents also describe internal inefficiencies. R3 responded that in some cases, all pick lists have been completed but not properly registered in the system. In others, the final pick list has been registered, but workers are unaware that the order is complete because orders are dispersed across multiple consolidation locations.

As a result, fully completed orders remain in storage, waiting without cause, which further disrupts flow and delays delivery to production. Each of these is an unnecessary non-value-adding delay that does not arise from any technical constraint but from the absence of real-time information and structured flow design. To mitigate this issue, R3 explains that the consolidation area is regularly checked, with workers inspecting the labels on boxes to identify any complete orders that have not yet been sent to production.

These findings indicate that flow could be improved through process redesign and enhanced system support. First, the current reliance on manual handling, particularly the placement of boxes on shelves, should be better supported to ensure that items belonging to the same order are stored together. Second, the process should be redesigned to provide clearer visibility of order status, enabling workers to easily identify when consolidation is complete and when orders are ready to be sent to production.

Uneven workload

Liker (2022) explains that variability (mura) is a common characteristic of production systems and is often driven by internal disturbances. To address such unevenness, he proposes production levelling, known as Heijunka, as a mechanism for creating a more stable and predictable workflow.

Several respondents highlight significant variability in workload within the case company. R3 reports that high workload and stress contribute to mistakes in the consolidation process. R6 and R7 further describe variability in administrative tasks, where the amount of work fluctuates considerably from day to day. In addition, R9 explains that daily picking volumes range between 1,500 and 2,000 picking lines, with peaks reaching up to 3,000, and that the final assembly hall often generates particularly large picking orders of up to 500 lines.

In line with Liker (2022) argument for production leveling, these findings suggest a need to reduce variability by moving away from large, uneven batches toward a more balanced distribution of work. This is particularly relevant for practices in planning, where large pick lists contribute to workload peaks and operational strain. Reducing variation in picklist size could help create a more even material flow and reduce operational pressure on the warehouse.

R10 notes that the company is already moving toward a more operation-driven building sequence with clearer, predefined steps, implying a more predictable planning process. Building on this development, it is recommended to further align with the principles of

Heijunka by structuring processes so that each step involves fewer materials, thereby reducing batch sizes and enabling a more even and manageable workflow.

Liker (2022) argues that production systems that fail to manage variability (mura) face an increased risk of generating waste (muda) and overburdening workers (muri). The interview findings indicate that this may be an issue in the case company. R1 notes a rise in picking errors, with 10-15% of the company's non-compliance reports linked to such errors, representing a clear form of waste (muda). In addition, R6 and R7 highlight a high level of staff turnover, which indicate employee strain and overburden (muri). Taken together, these findings suggest that underlying variability (mura) in workload and processes may be contributing to both increased errors and pressure on personnel.

To mitigate this, the company should ensure sufficient workforce capacity to handle operational demands effectively. This implies that, as the company grows, it should proactively expand and develop its warehouse capabilities ahead of demand. By staying one step ahead, the company can better absorb fluctuations in workload, reduce pressure on personnel, and support a more stable and efficient flow of operations.

Material routing

The flow is characterised by unnecessary transportation loops. R9 observes that material sometimes arrives at the company only to be sent immediately to an external warehouse, and when it is required in production shortly after, it is transported back again. R9 identifies the root cause as the system's inability to indicate when a material will be needed in production, meaning that storage decisions are made without reference to upcoming demand. In Lean terms, this constitutes transportation waste and it occurs because the information flow does not support the material flow. The ETO context amplifies this problem as long and variable engineering lead times mean that the gap between material arrival and production need is unpredictable, and in the absence of system-generated demand signals, the risk of misrouting materials to external storage increases. Material movement should be triggered by actual downstream need and the current system falls short of it.

5.4 Pull

According to Liker (2022), a pull system is based on a customer-supplier relationship in which production is driven by actual demand. The customer signals its needs, and the supplier produces and delivers only what is required, when it is required. This is often implemented through Kanban, a signalling method used to regulate demand and control the flow of materials.

The case company's reservation practices deviate from the pull principle, as they do not accurately signal either *what* is needed or *when* it is needed. In the final assembly hall, R4 explains that material reservations regularly are made months prior to production. Although pick lists are only released when materials are required, the reservation itself locks the material and acts as an early signal of demand. As a result, the signal is not triggered when the material is actually needed, but significantly in advance.

In addition, the reservations do not always reflect *what* is truly required. While some materials are project-specific and require precise specification, others, such as screws or zip ties, do not depend on a specific batch. Despite this, reservations are made at batch level, effectively narrowing the definition of what is needed beyond what is necessary. Although R3, R4, R8, and R10 emphasise that batch traceability is important after material has been installed, there seems to be no need to specify the exact batch before material is being installed into the product.

These findings indicate that the company could improve its operations by strengthening its application of pull principles. As previously discussed, current reservation practices generate early and imprecise demand signals, which limits the effectiveness of a true pull-based system (Liker, 2022). A more demand-driven approach would ensure that materials are only requested and allocated when they are actually needed, thereby improving flow and reducing unnecessary constraints in the system.

R8's suggestion to reserve materials based on volume rather than batch could further support improved flow by reducing unnecessary constraints in the system. Batch-level reservations tie materials to specific inventory units, which limits flexibility and can lead to delays when the exact batch is unavailable or requires time-consuming adjustments. By instead reserving materials based on required volume, the system allows functionally equivalent items to be used more freely, enabling a smoother and more continuous flow of materials. This reduces the need for manual intervention, minimises disruptions caused by batch mismatches, and aligns material supply more closely with actual demand, thereby supporting a more responsive and flow-oriented process.

For standard components, such as screws or cable ties, volume-based reservations could replace batch-level control. This would reduce unnecessary constraints, improve material availability, and support a more continuous flow, while still allowing batch traceability to be ensured at a later stage. Specifically, the individual material can be linked to the project when it is issued from the warehouse, rather than at the planning stage. By applying this selectively to standard components, the company can increase flexibility without compromising quality or traceability requirements.

Storage in the final assembly hall

By introducing volume-based reservations instead of batch-level allocation, additional improvement opportunities identified by the respondents become viable. In particular, R10 suggests implementing internal storage in the assembly hall for commonly used materials such as screws and cable ties. This approach aligns with pull thinking, as it reduces the need for detailed, early reservations of low-variability items and instead allows replenishment to be driven by consumption. By decoupling these standard components from project-specific reservations, the company could simplify material handling, reduce administrative complexity and improve responsiveness in the production process.

Such a solution could contribute to reducing waste (muda), particularly in the form of overprocessing and unnecessary control of materials that do not require strict specification. Furthermore, it would likely reduce the reliance on express flows. By ensuring that frequently used materials are readily available at the point of use, the need for urgent requests would decrease, thereby reducing interruptions, stabilising workflows, and improving overall flow.

The findings also suggest that the current practices may create unintended quality risks. R10 describes how strict traceability requirements, combined with the lack of on-site storage, can lead to situations where operators must order replacement for standard components, such as screws. If the original batch is no longer available, this may require a batch change, which is time-consuming. As a result, operators sometimes choose to reuse components rather than follow quality standards, in order to avoid delays. By enabling local access to commonly used materials, such situations could be mitigated, supporting both flow efficiency and adherence to quality requirements.

5.5 Perfection

The fifth Lean principle, perfection, reflects the pursuit of Kaizen (continuous improvement), emphasising that Lean is an ongoing and systematic process rather than a one-time initiative (Womack & Jones, 1997). Achieving this requires structured problem identification, standardised processes, and a shared organisational commitment to learning and improvement. In Liker (2004) four-dimensional model, this corresponds most directly to the problem-solving dimension, which emphasises scientific thinking and continuous improvement as means of moving the organisation toward a desired future state.

Lack of structured improvement work

The findings indicate several barriers that limit the organisation's ability to apply Lean principles in a continuous and systematic manner. First, there is a lack of structured improvement work. Although many of the identified inefficiencies, such as waiting times and inefficient material handling, are known within the organisation, these issues are only partially addressed in a systematic manner. While an increasing number of performance measurements are conducted, R1 notes that these are not consistently used to guide actions or improvements. Root cause analysis is limited, and R1 and R9 both observe that responses to operational issues tend to be reactive, typically involving the allocation of additional resources rather than investigating root causes. A concrete example is the increase in express flow deviations, which has led to more personnel being assigned to administrative handling rather than to reducing the errors themselves. The limited follow-up further reduces the visibility of problems, making thorough root cause analysis difficult. This suggests a reactive approach, where operational efforts are primarily focused on addressing immediate issues rather than eliminating underlying causes.

Lack of standardisation

Second, the absence of standardised processes and shared performance metrics further constrains improvement efforts. The findings reveal concrete inconsistencies in how performance is measured and interpreted. R1 describes uncertainty about which key performance indicators to use, and notes that picking errors are categorised and reported differently depending on the function, leading to conflicting conclusions about operational performance. For instance, errors classified under code B (construction-related) and code A (picking-related) are sometimes conflated, making it unclear where responsibility and improvement efforts should be directed. From a Lean perspective, standardisation is a prerequisite for Kaizen, as it enables a common understanding of performance and facilitates systematic identification of deviations (Liker, 2004). Without agreed-upon metrics and consistent measurement practices, it becomes difficult to establish a stable baseline from which deviations can be detected and addressed.

Limited organisational learning

Third, the findings reveal clear limitations in organisational learning. The information systems are described as difficult to use and poorly adapted to operational needs, and R3 notes that employees have not received formal training despite requests. Consequently, knowledge transfer largely occurs informally between colleagues rather than through structured organisational processes.

This creates a strong dependence on tacit knowledge and individual experience, which limits the organisation's ability to standardise work practices. When employees perform tasks based on personal knowledge instead of shared procedures, it becomes difficult to establish a consistent operational baseline and identify deviations. These challenges are further intensified by high employee turnover, as experienced personnel leave the organisation and take important operational knowledge with them. As a result, the warehouse becomes increasingly vulnerable and dependent on a limited number of experienced individuals capable of managing the systems and processes effectively.

Structural barriers

Structural factors further hinder improvement efforts. The rapid increase in production volumes due to a changing global context has led to a strong focus on scaling output to meet demand, while less attention has been given to adapting processes and working methods accordingly. R9 explicitly states that the primary managerial focus has been on maintaining delivery performance and fulfilling orders on time, with the consequence that existing processes have been scaled up without sufficient adjustment, despite not being designed for the current level of operations. This indicates that structured improvement work may not be prioritised. Liker (2004) emphasises that addressing the 3M's is a managerial responsibility, and that sustainable improvement requires long-term, systems-oriented thinking rather than short-term operational reaction.

ETO context

Identified challenges are further influenced by the ETO context. The high variability associated with project-based operations and frequently changing requirements Strandhagen et al. (2019) increases the need for structured processes, clear performance metrics, and systematic follow-up in order to enable continuous improvement. In Alfnes et al. (2021) uncertainty framework, the absence of structured improvement mechanisms amplifies control uncertainty (the dimension relating to planning and coordination) which is already elevated in ETO environments due to the complexity of engineering adaptations. However, the findings indicate an absence of structures required to manage this uncertainty. Instead of being managed through standardised processes, variability is handled through local adaptations and experience-based decision-making. This further reinforces the lack of consistency in how work is performed and makes it more difficult to compare performance, identify deviations, and conduct systematic root cause analysis.

Another challenge in ETO organisations are the strong interdependencies between functions which increase the need for coordination and shared understanding across the organisation (Braglia et al., 2024). The findings, however, indicate the presence of functional silos and limited cross-functional communication, which further amplifies this challenge. Insufficient coordination in ETO environments can increase uncertainty and disrupt planning, thereby reinforcing reactive behaviours and reducing the organisation's ability to work systematically with improvements (Braglia et al., 2024).

From a Lean perspective, the findings highlight a tension between the need for flexibility in ETO environments and the need for standardisation and stability to enable continuous improvement. While variation cannot be eliminated in an ETO context, it can be managed through structures that make performance visible and deviations detectable. The findings suggest that the current system lacks these structures, with standardised work processes, shared performance metrics, formal training, and systematic root cause analysis often being absent.

5.6 Summary of Analysis and Improvement Opportunities

The analysis examined warehouse material flow through the five Lean principles – Value, Value Stream, Flow, Pull, and Perfection – while accounting for the structural characteristics of the ETO context.

Figure 5.1 provides a consolidated overview of the inefficiencies identified through the analysis, structured according to the five Lean principles. The table illustrates how the challenges discussed throughout this chapter relate to each principle, ranging from the various forms of muda and the impact of late changes under Value, to the structural barriers to continuous improvement under Perfection. Together, the columns reflect the interconnected nature of the identified inefficiencies and how they collectively affect the warehouse's ability to supply materials to production efficiently.

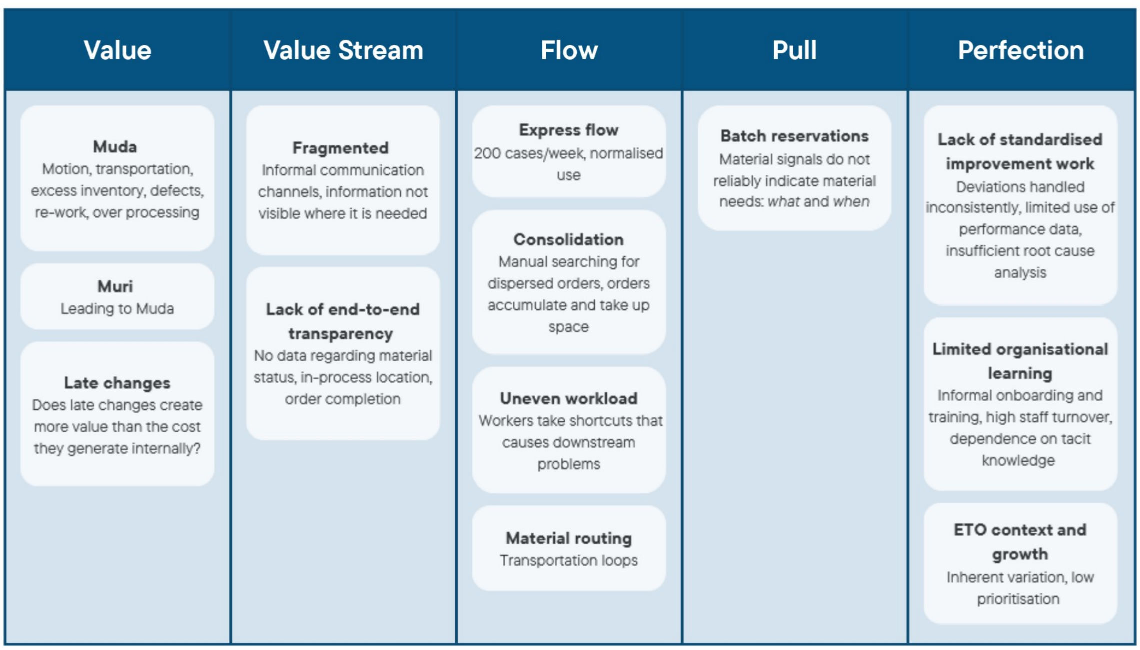

Figure 5.1: Summary of the analysis findings structured according to the five lean principles: value, value stream, flow, pull, and perfection.

Inefficiencies were identified across both core operational processes and supporting functions. At an operational level, these include unnecessary motion and searching caused by poor storage layout and the absence of route optimisation, consolidation delays driven by a lack of system support and real-time order visibility, transportation waste arising from misrouted materials and reliance on external warehouses, and fluctuating workloads that generate picking errors and place excessive pressure on personnel. At a systemic level, the findings reveal batch-based material reservations that exceed operational necessity, late product structure changes that trigger downstream disruption, a normalised reliance on the express flow as a substitute for stable flow design, fragmented information flows across planning, warehousing, and production, and the absence of structured improvement routines, shared performance metrics, and formal knowledge transfer mechanisms.

Many of these inefficiencies are not purely operational failures but are shaped by the ETO context itself. High product variability, overlapping engineering and production activities, and the absence of a fixed build sequence create conditions in which uncertainty is structurally elevated. As a result, the warehouse is expected to absorb a level of variability that the current processes and systems are not designed to handle.

Improvement opportunities

Based on the analysis, several areas for improvement could be identified. At the process level within the warehouse, several concrete changes are recommended. First, switching from batch-based to volume-based reservations for standard components such as screws and cable ties would reduce administrative rework, improve material availability, and support smoother flow. Batch traceability can still be ensured when the material is actually issued, rather than locking it to a specific batch months in advance. Second, investigating the possibility of introducing internal storage within the final assembly hall for commonly used standard components could reduce dependence on the express flow for routine items and mitigate the quality risks associated with the absence of on-site material. Third, the express flow should be decoupled from the standard picking process to reduce interruptions. Alongside this, the company should invest in root cause analysis of what drives express orders rather than just adding resources to handle them. Fourth, improving system support for consolidation, particularly real-time order status visibility, would reduce the manual labour currently required to search for dispersed orders and identify complete ones. Finally, releasing pick lists in smaller, more controlled batches would reduce workload peaks and the consolidation backlog that follows.

At the organisational level, achieving sustainable improvement requires shared, agreed-upon performance metrics across functions, and the company should use them systematically to guide decisions rather than just collecting data reactively. Structured root cause analysis should be conducted consistently in response to deviations. The company should also build formal knowledge transfer and training mechanisms to reduce dependence on tacit knowledge and individual experience, which is especially important given the high staff turnover. Finally, cross-functional communication between planning, warehouse, and production should be formalised, as the current reliance on informal face-to-face contact introduces fragility into the system.

Upstream changes that could support warehouse operations include investigating how late in the process engineering changes should be permitted, as changes introduced after the start of production create significant downstream disruption in the warehouse through material reallocations, batch changes, and additional picking activities. Improved coordination between engineering and production planning would reduce the level of uncertainty the warehouse is required to absorb. More broadly, as the company continues to grow, warehouse capabilities should be developed proactively ahead of demand rather than relying on the continued scaling of existing processes that were not designed for current operational volumes.

6
Discussion

The discussion adresses research question three: *What might the analysis suggest about the applicability of Lean principles as a diagnostic tool in non-repetitive manufacturing environments?* It builds on the findings from the first two research questions, and considers what they may suggest about the applicability of Lean principles in the case company's ETO context. Rather than treating Lean as a uniform set of tools, the discussion examines how each principle transfers, requires adaptation, or faces structural limitations given the case company's operating environment. The chapter ends with reflections on sustainability implications, theoretical contributions, limitations, and future research directions that arise from the study.

6.1 Lean applicability in ETO environments

Although Lean principles were originally developed in repetitive manufacturing environments, research indicates that they can also be applied in ETO contexts when appropriately adapted (Braglia et al., 2024; Cannas et al., 2018; Strandhagen et al., 2018). However, the structural characteristics of ETO environments, such as high product variability, project-based execution, and overlapping engineering and production activities, create specific conditions that influence how each Lean principle works in practice.

A central observation from the analysis is that many of the identified inefficiencies are not merely operational failures, but predictable structural consequences of the ETO context the case company operates in. As stated in the introduction, the case company can be characterised as an RTO company, where product novelty is concentrated in late-stage engineering adaptation rather than fundamental innovation (Alfnes et al., 2021). This means that uncertainty is particularly higher in the process and control dimensions of Alfnes et al. (2021) uncertainty framework. This can be observed in the findings. The lack of reliable demand signals and the absence of a formalised build sequence, which were identified under the Value Stream and Pull principles, are results of high control uncertainty: the planning and coordination structures that would be needed to compensate for variety in project configurations are not sufficiently developed. Similarly, the late changes to product structure that trigger batch changes, material reallocation, and additional picking operations are a direct expression of process uncertainty, where engineering activities and production overlap and interfere with each other in ways that lead to downstream waste. It is important to recognise that these inefficiencies are structurally embedded rather than purely operational. Consequently, eliminating waste in this context requires not only process improvements within the warehouse, but also a reduction in the uncertainty the warehouse is expected to absorb.

6.1.1 Value and Value Stream

The principles of value and value stream proved useful for analysing ETO operations and understanding how work flows, and they could be applied when analysing the case company without needing to change their core meaning. Defining value as the delivery of materials to production in the right time, right quantity, and right condition provides a clear and applicable standard regardless of how variable the product is. The seven waste types identified by Womack and Jones (1997) were observable in the case company's warehouse operations, and none of them required adaptation to the ETO context in order to be identified and interpreted. This suggests that Lean's waste identification framework transfers directly to ETO warehouse environments.

In ETO environments, mapping the value stream is structurally more demanding than in repetitive manufacturing due to high product variability, meaning no two value streams are the same, making it difficult to define a standard map and to identify recurrent patterns of waste (Braglia et al., 2024; Strandhagen et al., 2019). Although the initial aim for this study was to construct a value stream map, the required data, such as cycle times, takt time, and inventory levels at each process step, was not available and could not be collected within the time constraints of the study. However, the underlying idea of making material and information flows visible in order to expose non-value-adding activities remains valid. As an alternative, a flowchart was developed to map activities in the warehouse material flow, complemented by interviews to identify inefficiencies and waste. While this approach does not constitute a formal value stream mapping exercise, it serves a similar analytical purpose of connecting observed inefficiencies to specific activities and examining them through a Lean lens. The fragmented information flow, lack of system signals, and absence of end-to-end transparency identified in the Value Stream section are all problems that would be exposed through a structured value mapping. The ETO context does not prevent this, but rather it makes it more necessary.

6.1.2 Flow and Pull

The principles of flow and pull face greater structural challenges in the case company's ETO context. Liker (2022) ideal of one-piece flow assumes a degree of process repetition and standardisation that is difficult to achieve when each project involves unique configurations. At the case company, products are built in fixed positions and materials move to the product rather than the product flowing through production, which is structurally incompatible with classical continuous flow design. The findings confirm this: the consolidation process, the express flow, and the uneven workload described in the Flow section are all partly a consequence of the absence of a stable, repeatable sequence.

However, striving for smoother flow remains valuable even where pure one-piece flow is unachievable. As Liker (2022) argues, reducing buffers exposes problems. In this case, reducing the reliance on the express flow as a normalised exception mechanism, or reducing consolidation delays through better system support, would improve flow even without fundamentally changing the ETO production structure. The focus must shift to improving flow within warehouse processes and information systems, rather than trying to optimise the production sequence, which is inherently constrained by the ETO model.

Pull faces a similar adaptation challenge. Standard kanban-based pull systems assume that downstream processes can send reliable, repeatable demand signals to upstream processes (Liker, 2022, p.116). In ETO settings, the absence of a fixed build sequence means these signals are unavoidably irregular. This, together with R4's description of reservations being made months in advance, and then often repeatedly changed, illustrates the difficulty of implementing true pull logic. As argued in Section 5.4 Pull, a more realistic adaptation is to apply pull selectively: volume-based rather than batch-based reservation for standard components, while keeping reservations for project-specific materials.

6.1.3 Perfection

The principle of perfection is the one most fundamentally constrained by the company's ETO context. Continuous improvement depends on the ability to detect deviations from a standard. In repetitive manufacturing, this is possible because tasks are performed consistently enough to establish a reliable baseline. In ETO environments, however, each project introduces new configurations and requirements (Braglia et al., 2024), which means that variability cannot be absorbed through routine but must instead be actively managed. In repetitive manufacturing, workers and processes encounter the same tasks consistently enough that variation is gradually smoothed out through familiarity and habit. In ETO settings, this passive absorption does not occur, because no two projects are alike enough for stable routines to form. As a result, each new source of variability requires an explicit response: a planning decision, a coordination effort, or a deliberate workaround. Without formal processes and structured mechanisms to handle this, variability tends to be managed through individual experience and improvisation rather than through systemic solutions, creating a system that is fragile and inconsistent.

The absence of structured improvement mechanisms increases control uncertainty, which is already elevated in RTO environments (Alfnes et al., 2021). The functional silos and limited cross-functional communication identified in the findings further reinforce this, since insufficient coordination in ETO environments amplifies uncertainty and disrupts planning (Braglia et al., 2024). This creates a self-reinforcing cycle where high variability increases the need for structured processes and clear metrics, but with those absent, variability is never systematically reduced and improvement efforts remain reactive.

However, this does not mean perfection is unachievable with the company's ETO production stategy. Rather than standardising the product or the production sequence, which would be very difficult given the ETO model, a recommendation is to focus on standardising the improvement process itself: agreeing on shared performance metrics, conducting consistent root cause analysis and evaluation, and systematically communicating results to process owners. Emphasis should also be placed on building formal knowledge transfer mechanisms that do not rely on individual experience. In Liker (2004) terms, the people and problem-solving dimensions of the Lean system need to be developed before the process dimension can be stabilised.

To summarise, the findings suggest that Lean's applicability in the ETO company's warehouse environment is differentiated rather than uniform. The seven wastes transfers directly and provides a productive analytical lens regardless of product variability. The value stream principle requires methodological adaptation but the idea remains valid. Flow and pull require the most significant practical adaptation, where improvements should be focused at the level of warehouse and information system design rather than production structure. Perfection faces the deepest structural constraints, as the conditions for standardised continuous improvement are undermined by the variability that is built into ETO operations.

6.2 Sustainability Implication of Lean Improvements

This thesis is expected to generate practical implications for the case company. As a result, its findings may lead to changes in production processes. Such changes can influence the company's sustainability performance.

The Triple Bottom Line (TBL) framework is a well-established model for evaluating sustainability performance across three dimensions: social, economic, and environmental (Bhatti et al., 2025). Previous research suggests that Lean implementation can contribute positively to TBL performance, particularly within the social dimension (Jum'a et al., 2022). However, other studies indicate an inverted U-shaped relationship between investments in Lean and environmental and social performance (Wang et al., 2025). This suggests that while moderate Lean investments may improve sustainability outcomes, excessive investment could lead to diminishing or even negative effects.

Consequently, any practical recommendations derived from this thesis should be implemented with caution. The case company and other stakeholders seeking to apply the findings should be aware that overinvestment in Lean initiatives may adversely affect overall sustainability performance.

6.3 Theoretical and Practical Contribution

From a theoretical perspective, this thesis contributes to the limited body of research on how Lean can be applied as an analytical tool in ETO manufacturing environments. While previous studies have explored Lean in ETO production more broadly, few have addressed warehouse operations specifically or applied the five core Lean principles empirically in this context. By doing so in a real-world setting, the study demonstrates that Lean principles can provide an analytical lens for understanding inefficiencies in ETO warehouse material flow, even when implementation requires adaptation. The structured approach developed in this study, applying Value, Value Stream, Flow, Pull, and Perfection to the specific conditions of an ETO warehouse, offers a foundation that can be used in similar contexts in future research.

From a practical perspective, several of the identified inefficiencies correspond to challenges previously documented in ETO research by Braglia et al. (2024) and Strandhagen et al. (2018), including fragmented information flows, difficulties in synchronising material supply with production demand, and the disruptive effects of late engineering changes. The recurrence of these inefficiencies across different ETO contexts suggests that they are symptomatic of the structural characteristics inherent to ETO production rather than isolated to a particular company or industry. This strengthens the practical relevance of the findings, as it implies that the analytical approach developed in this study, and the types of inefficiencies it reveals, are likely transferable to other ETO organisations facing similar conditions.

A key practical implication concerns the differentiated applicability of Lean principles in ETO settings. Waste identification and value stream thinking can be applied with relatively little adaptation, while flow, pull, and perfection require contextual adjustment. Recognising this distinction allows organisations to direct improvement efforts more effectively, focusing on areas where Lean transfers directly while adapting its application where structural constraints apply.

Finally, the thesis highlights that the warehouse in an ETO environment should not be treated as an isolated operational unit, but as a system that absorbs uncertainty generated elsewhere in the organisation. Recognising this systemic role has practical implications for how ETO companies design their internal logistics, allocate resources, and define responsibilities across functions.

6.4 Limitations

Several limitations should be acknowledged. First, the study is based on a single case company, which limits how broadly the findings can be applied. While a case study is suitable for gaining in-depth, context-specific insights (Yin, 2018), the results cannot be directly generalised to other ETO organisations without further studies.

Second, the data collection primarily relied on interviews, which introduces a risk of bias, as responses may be influenced by individual perspectives. Furthermore, the interviews were conducted over a three-week period, which may have led to an overemphasis on current issues rather than challenges that emerge over a longer time horizon. As the study did not cover a full production cycle, there is a risk that the findings reflect problems specific to the particular phase of the production process observed during the data collection period. This also limited the ability to triangulate the data, as it was not always possible to compare interview insights with observations.

Finally, the study focuses primarily on warehouse operations. As a result, it does not fully analyse upstream processes such as engineering and production planning, even though the study showed these areas have an effect on the warehouse material flow.

6.5 Future Research

Future research could develop this study in several ways. First, conducting a comparative case study across multiple ETO companies would make it possible to identify which Lean adaptations are specific to a particular context and which can be applied more broadly. Second, further research could investigate whether the Lean-related issues connected to warehouse material flow identified in this case are common across ETO environments. Finally, the use of quantitative methods, such as simulation models or statistical analysis of picking times and lead times, could complement the qualitative insights from this study. This would enable more detailed value stream mapping (VSM), allowing for the identification of waste that most significantly impacts lead time and supporting more targeted improvement initiatives.

7 Conclusion

This thesis analyses warehouse material flow in an ETO manufacturing company to identify inefficiencies affecting material supply to production. It further examines these inefficiencies through Lean principles and the structural characteristics of the ETO context, exploring how the ETO environment shapes material flow and influences the applicability of Lean in non-repetitive manufacturing. Through a qualitative single-case study of a defence-sector manufacturer, the research has provided an in-depth understanding of how internal warehouse processes interact with planning and production, and how these interactions influence operational performance. To guide the study, the following research questions were used:

RQ 1: *What inefficiencies and sources of waste can be identified in current the warehouse material flow?*

RQ 2: *How can the identified inefficiencies be explained through Lean principles and the ETO context?*

RQ 3: *What might the analysis suggest about the applicability of Lean principles as a diagnostic tool in non-repetitive manufacturing environments?*

Inefficiencies were identified across both core operational processes and supporting functions. At an operational level, these include limited physical space, consolidation delays, variation in picking times, fluctuating workloads, limited automation, and an absence of data-driven decision-making. At a systemic level, the findings reveal batch-based material reservations, late product structure changes, normalised reliance on an express flow mechanism, siloed working practices, and ineffective improvement routines.

The identified inefficiencies can be explained as the result of disrupted flow, lack of effective pull mechanisms, and the interaction between waste (muda), unevenness (mura), and overburden (muri) within the warehouse processes. Lean principles show that issues such as waiting times, unnecessary transportation, and frequent rework stem from unstable and poorly coordinated material and information flows. These problems are further intensified by the ETO context, where high variability, project-based production, and strict traceability requirements create uncertainty in demand, planning, and execution. As a result, inefficiencies are not only caused by local process weaknesses, but by a broader system where variability and uncertainty propagate through the material flow, making it difficult to achieve stable and efficient operations.

Finally, the discussion demonstrates that Lean principles provide a productive and transferable diagnostic framework for ETO warehouse environments, though their applicability is differentiated. The seven wastes transfer directly and without adaptation. The value stream principle retains its conceptual validity but requires methodological adjustment given the high variability in ETO operations. Flow and pull require the most significant practical adaptation, improvements should initially be pursued at the level of warehouse and information system design rather than production sequencing, which is inherently constrained by the ETO structure. The principle of perfection faces the deepest structural constraints, as the conditions for standardised continuous improvement are systematically undermined by variability embedded in the ETO model itself.

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A

Interview Guide

This appendix presents the semi-structured interview guides used during the data collection process.

A.1 Picking Process (Warehouse Staff, Logistics Specialists)

- What does a typical workday look like for you?
- What is your role in the process related to pick lists?
- How do you experience the workload? Is it even or does it vary?
- Can you describe step by step what happens from when you receive a pick list until the material is delivered to production?
- When and how do you receive information about what needs to be done?
- How does the express flow differ from a normal pick list?
- Is the inflow of pick lists steady or does it come in peaks?
- Do you feel that pick lists are often similar, or do they vary significantly?
- Are there periods when you have little to do?
- What is the most time-consuming part?
- Are there steps that feel unnecessary or that do not contribute to getting the material to production?
- If you could change one thing in the process, what would it be?
- What works particularly well today?

A.2 Planning (Production / Project Planners)

- What does your role as a production/project planner involve?
- What does a typical workday look like for you?
- How do you experience the workload?
- How do you interact with production and the warehouse?
- Can you describe step by step what happens from when a material need arises until a pick list is generated?
- What triggers a material need?
- How often does the plan change after it has been set? Why?
- How are urgent needs from production handled?
- Are there buffers built into the planning? Physical/informational?
- Do you feel that the planning process affects how quickly the warehouse can deliver materials?
- If you could change one thing in the process, what would it be?
- What works particularly well today?

A.3 Assembly (Operators in Final Assembly Hall)

- How do you know when materials are needed for an operation? Are there signals indicating when it is time to order/pick materials?
- What is the process when you initiate a material need?
- Do you have a margin or buffer you usually rely on? (e.g., operations, quantity of material, time, etc.)
- Does the building process differ between projects with the same base product?
- Do materials usually arrive on time, or does it vary?
- What happens in your work when materials are late?
- What do you consider the most common reason materials are not available when needed?
- Is there anything other departments could have done differently to make your work easier?

B

Table of Interviews

Table B.1: Overview of conducted interviews

Respondent	Work role	Duration	Date	Type of interview
R1	Quality analyst	40 min	2026-03-11	Semi-Structured
R2	Maintenance technician	35 min	2026-03-10	Semi-Structured
R3	Logistics specialist	50 min	2026-03-24	Semi-Structured
R4	Production planning engineer	40 min	2026-03-18	Semi-Structured
R5	Production planning engineer	40 min	2026-03-17	Semi-Structured
R5	Production planning engineer	30 min	2026-01-28	Unstructured interview
R6	Warehouse worker	50 min	2026-03-26	Semi-Structured
R7	Warehouse worker	50 min	2026-03-26	Semi-Structured
R8	Logistics specialist	50 min	2026-03-10	Semi-Structured
R8	Logistics specialist	120 min	2026-02-02	Unstructured guiding tour in the warehouse area
R9	Acting warehouse manager	45 min	2026-03-17	Semi-Structured
R10	Senior assembler	35 min	2026-03-26	Semi-Structured
R11	Product technologist	45 min	2026-01-26	Unstructured guiding tour in the assembly hall
R12	Production planning engineer	35 min	2026-02-03	Unstructured interview

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