# IMPROVING IN-HOUSE LOGISTICS WITH LEAN FOR INCREASED MATERIAL AVAILABILITY AND CONTROL IN VARIANT HEAVY MANUFACTURING ENVIRONMENT

Lappeenranta–Lahti University of Technology LUT

Industrial Engineering and Management, Programme in Digital Service Innovation and Management, Master's thesis.

2025

Sakari Saukkonen

Examiner: Professor Janne Huiskonen

# ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Engineering Science

Industrial Engineering and Management

Sakari Saukkonen

**Improving in-house logistics with Lean for increased material availability and control in variant heavy manufacturing environment**

Master’s thesis

2025

120 pages, 23 figures, 13 pictures and 2 tables

Examiner: Professor Janne Huiskonen

Keywords: Lean, Kanban, in-house logistics, warehousing, inventory management, material availability, assembly feeding systems, FIFO logic, one-piece flow, manufacturing efficiency, standardized workflows

This master's thesis explores the application of Lean techniques for the optimization of in-house logistics to improve material availability and control within a manufacturing company transitioning to one-piece flow. The research addresses how logistics and warehousing can support a new production line aiming for a threefold increase in output, through establishing a new assembly feeding system. Key considerations driving the design of the new assembly feeding system include enhancing material availability and control, improving FIFO utilization, and standardizing internal logistics operations.

The study identifies inefficiencies such as poor material handling, lack of standardization, and information inaccuracies, exacerbated by space constraints. The proposed solutions include inventory classification, a new assembly feeding system, Kanban implementation, and standardized workflows. These changes led to improved efficiency, material availability, and job satisfaction. Reducing work-in-progress and improving material supply reliability minimized delays and boosted productivity. The thesis emphasizes training all personnel in a Lean context, alongside value and customer recognition within organizations.

Future research should explore pick-to-light systems, component standardization, and digitalization. The thesis advocates for a structured Lean culture with a continuous improvement framework to ensure ongoing optimization. The thesis provides a practical guide for companies facing similar logistical challenges in manufacturing.

# TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Teknis-luonnontieteellinen

Tuotantotalous

Sakari Saukkonen

**Sisälogistiikan tehostaminen Lean menetelmillä materiaalisaatavuuden ja -kontrollin lisäämiseksi massaräätälöintituotannossa**

Tuotantotalouden diplomityö

2025

120 sivua, 23 kaaviota, 13 kuvaa ja 2 taulukkoa

Tarkastaja: Professori Janne Huiskonen

Avainsanat: Lean, Kanban, sisälogistiikka, varastonhallinta, materiaalien saatavuus, kokoonpanonsyöttöjärjestelmät, FIFO-logiikka, massaräätälöintituotanto, tuotannon tehokkuus, standardoidut prosessit

Tämä diplomityö soveltaa Lean- menetelmien hyödyntämistä sisälogistiikan optimointiin massaräätälöintituotannossa, tavoitteena parantaa materiaalien saatavuutta ja kontrollia. Tutkimus kohdistuu yritykseen, joka siirtyy erätuotannosta yhden kappaleen virtaustekniikkaan, mikä edellyttää uuden kokoonpanonsyöttöjärjestelmän kehittämistä. Tutkimus selvittää, miten logistiikka ja varastointi tukevat uutta tuotantolinjaa, jonka tavoitteena on kolminkertaistaa tuotanto. Päätöksenteossa keskeisinä ohjureina toimivat materiaalin saatavuuden ja kontrollin parantaminen, FIFO-periaatteen hyödyntämisen tehostaminen sekä sisälogistiikan prosessien standardointi.

Työssä analysoidaan nykytila ja tunnistetaan tehottomuuksia, kuten ylimääräinen materiaalinkäsittely, standardoitujen prosessien puute ja puutteellinen tiedonkulku. Ratkaisuksi ehdotetaan uutta sisälogistiikkajärjestelmää, joka sisältää varastoluokittelun, uuden kokoonpanonsyöttöjärjestelmän, Kanbanin ja standardoidut työnkulut. Toteutetut toimenpiteet paransivat tehokkuutta, materiaalien saatavuutta ja henkilöstön työtyytyväisyyttä. Keskeneräisen varaston vähentäminen ja sisäisten toimitusketjujen luotettavuuden parantaminen minimoivat viiveitä ja lisäsivät tuottavuutta. Työ korostaa Lean-koulutuksen tärkeyttä kaikille tuotantojärjestelmän funktiolle, sekä arvon ja sisäisten asiakkaiden tunnistamista organisaatioissa.

Tulevaisuuden suositeltuja tutkimusalueita ovat pick-to-light-järjestelmät, komponenttien standardointi ja digitalisaation lisääminen. Työ tarjoaa käytännön ohjeita logistiikan optimointiin ja tuotannon tehokkuuden parantamiseen massaräätälöintituotannossa Lean- ja Kanban-menetelmillä.

## Table of contents

Abstract

# 1 Introduction

To successfully assemble products, it is essential to have the right parts available at the right time. This is the fundamental need in manufacturing companies. Globalization and heightened market competition in the markets have increased demand for more customized products and assembly to order manufacturing strategy has become more common in multiple industries. The need for increased customization has sparked interest in mixed-model assembly lines, underscoring the necessity to develop and operate flexible manufacturing systems (Chica, Bautista & de Armas 2019, 76; Coelho, Macedo, Relcas & Barbosa-Póvoa 2022, 989). These flexible manufacturing systems often impose greater demands on in-house logistics, necessitating quick, reliable, and timely performance to ensure production success. The relentless growth in customer demand for superior services, coupled with market contraction due to globalization, has resulted in narrower profit margins for businesses worldwide. In response to this challenge, logistics is increasingly recognized as a strategic tool for achieving competitive advantages in costs and services (Lai & Cheng 2016, xv). Particularly within manufacturing environments, studies have identified logistics as a crucial enabler of production processes. Consequently, in-house logistics can be metaphorically described as the lungs of manufacturing operations, with operational capacity heavily reliant on logistics performance levels (Vrat 2011). This thesis explores the requirements for a status quo-ridden in-house logistics department to adapt to the robust growth of a former startup company and outlines methods for establishing a new in-house logistics system to enhance production capacity, material availability, control, and workflow stability.

In this study, an assembly feeding system is developed for a case company transitioning from mix of one-piece and batch production to a one-piece flow manufacturing strategy. The objectives are to increase material availability and control alongside First in First out (FIFO) logic utilization while standardizing in-house logistics. This study explores how the case company can enhance its in-house logistics operations through the application of Lean and Kanban principles. In contemporary times, Lean philosophy is regarded as one of the most prevalent improvement methodologies (Kovács 2020, 2916). The core ideology of Lean focuses on the elimination of non-value-added activities (*waste)* to create value-adding processes, and to realize only value-adding activities in the production system (Belay, Welo

& Helo 2014, 131). Tortorella, Fetterman, Cauchick and Sawhney (2020, 3650) add that one of the primary aspects of Lean can be considered the pursuit of perfection, which refers to continuous improvement by repeatedly challenging the status quo. Operational excellence and continuous improvement are essential for survival in today's competitive environment; otherwise, organizations will face increased costs and longer throughput times. Typical causes for these issues include a lack of standardized tasks, leading to overproduction or underutilization of resources, insufficient productivity control resulting in missing information about the actual execution time of tasks, and undetected bottlenecks causing queues in operations or activities, leading to delays. (de los Mozos & Lopez 2020, 1697). Therefore, stabilizing the workflow and standardizing in-house logistics play a significant role in this research. Kanban, on the other hand, often refers to a scheduling method wherein operators use visual signals to determine production quantities, decide when to halt or alter the workflow. In Kanban, rules should also be applied to specify actions when problems or issues are detected and identify whom to contact for different problems. The Kanban system includes visual indicators for managers and supervisors to briefly assess the schedule status of the line (Gross & McInnis 2003, 2).

Academic literature encompasses a substantial amount of research on implementing Lean and Kanban methods to enhance in-house logistics. Nevertheless, designing effective logistics systems remains a central topic across various industries, including manufacturing (Fabri & Ramalhinho 2024, 1). The growing trend towards a greater variety of products and customization, coupled with shorter response times, underscores the critical importance of efficient logistics systems. Logistics involves the entire organization, from the management of raw materials to the delivery of finished goods. The necessity for this study is accentuated by the increasing customization in manufacturing environments, facilitated by advancing technologies that offer new solutions to address the need to balance customization with mass production. This thesis examines, through the case company, the requirements for in-house logistics in transitioning from job shop production to one-piece flow production, where logistics is responsible for supplying the production line, which has experienced an average annual production volume growth of 35 % over the last three years. Additionally, the product mix is highly variant, meaning that the most common production quantity of a specific finished good is one to two pieces. Variance in the goods presents new challenges in handling variants and material feeding for them in the desired flow production in terms of Lean, rather than singular piece production. Practically, within the case company, the relevance of the study is emphasized by current issues in in-house logistics, such as the frequent absence of materials in production, which disrupts effective production and increases work-in-process (WIP) inventory. The objective of this study is to develop an assembly feeding system for the case company based on Lean and Kanban principles, while also enhancing overall efficiency.

The primary research question of this thesis is how to establish in-house logistics and warehousing to support the new production line in achieving the target of 18 pieces of finished goods per shift. The thesis also examines how overall efficiency, and the FIFO logic of the warehouse can be enhanced in an already challenging environment. This thesis is exclusively focused on in-house logistics; therefore, purchasing, stock levels, and supply chain-related matters are beyond its scope. The structure of the thesis is as follows: first, the scope of the study, research questions, and limitations are outlined, along with a presentation of the case company. The theoretical section introduces relevant topics. Following the theoretical review, the current situation of the case company is analysed. Subsequently, new ideas and solutions are proposed for the case company, and conclusions are drawn regarding the implementation and application of theoretical principles in practice for the case company. After the conclusions, the key findings from the thesis are reviewed, and the thesis's position in relation to other academic literature on the topic is assessed.

## 1.1 Research questions and methods

Efficient logistics systems have been receiving increasing attention in the business sector, particularly in manufacturing companies (Fabri & Ramalhinho 2023, 1144). This interest arises from heightened competition, and it has been recognized that effective logistics systems can provide competitive advantages through cost reduction while simultaneously enhancing customer service levels (Muñuzuri, Larrañeta, Onieva, & Cortés 2005, 15–28; Fabri & Ramalhinho 2024, 1). Logistics pertains to material flows both between and within organizations. In-house logistics, on the other hand, refers specifically to operations related to material flows within a single business or plant (Fabri & Ramalhinho 2023, 1144). According to Fabri and Ramalhinho (2023, 1145), improving in-house logistics flow can lead to reduced delays, minimized production disruptions, and decreased logistics costs. In-house logistics are typically cost-intensive due to the high demands of material handling, such as manual picking operations. Achieving effective planning and control in in-house logistics operations requires decision-makers to be aware of the current state of systems and identify bottlenecks within existing operations. (Coelho et al. 2022, 990).

This study aims to propose methods for enhancing in-house logistics and material availability within a manufacturing facility whose production strategy is make-to-order from predetermined features (hereafter referred to as variants), but also frequently incorporates custom modifications and engineer-to-order processes. Consequently, the manufacturing strategy can be characterized as a mix of make-to-order and engineer-to-order. The current production follows a job shop model; however, due to increased demand, the case company has decided to establish a new production line based on the flow principle. This study is part of the new production line implementation project within the case company, focusing on the logistics and warehousing aspects required for in-house logistics to adapt to the new operational approach and achieve the targets set for material feeding to meet the planned capacity of the new production line.

The study is structured around three distinct research questions, with the primary question being:

- How can in-house logistics and warehousing be set up to effectively support the new production line in achieving the target of 18 pieces of finished goods per shift?

The primary research question is integral to the case company's initiative to alter its manufacturing strategy for its high-demand product family, aiming to increase internal capacity to meet rising demand. The thesis will assess the current in-house logistics and redesign the existing assembly feeding system to fulfil the new production line's requirements. The main drivers for decision-making in the new assembly feeding system are enhancing capacity, material availability, and control. Additionally, the thesis introduces tools and practices to improve overall in-house logistics efficiency and work quality. The thesis aims to enhance in-house logistics efficiency by implementing Lean and Kanban principles. The supportive research questions are:

- How can logistics personnel's focus be simplified and directed towards the core value activity of material feeding for production?
- How can material availability, product control, and FIFO logic in the warehouse be improved?

Due to increased production volumes, the case company has faced challenges with material availability, resulting in elevated WIP levels as material shortages are frequently identified during assembly operations. Consequently, material availability and product control are emphasized as sub-research questions, exploring how they can be enhanced in the material feeding process. The functionality of FIFO logic is deemed crucial for the case company, as heavy customization and research and development activities can easily lead to obsolete stock if changes and developments in assembly parts are implemented carelessly without prioritizing the consumption of older stock. This situation is currently escalating warehousing and scrapping costs for the case company, arising from inadequate control and information flow within in-house logistics.

## 1.2 Goals and scope

This thesis aims to propose methods for enhancing material feeding efficiency in an assembly-to-order manufacturing strategy, particularly when finished goods exhibit a high number of variants. This variability can lead to significant differences between products due to an R&D-driven approach where products are tailored to customer needs, and customer-specific adjustments are common, necessitating a wide array of parts for assembly. This thesis develops a new material feeding system for a case company transitioning from single-piece production to serialized one-piece flow production in a variant-heavy environment. The study's objective is to reduce waste in the case company, improve the visual control of the assembly flow, and create a material feeding system with increased capacity. Additionally, the workload for in-house logistics operators is stabilized.

This paper concentrates on in-house logistics and warehousing solutions, excluding supply chain and purchasing from its scope. The traditional logistics grouping is illustrated in Figure 1 below. Conventional classification distinguishes incoming and outgoing logistics from in-house logistics; however, This thesis also addresses elements of inbound and outbound logistics that are directly relevant to the responsibilities and workload of in-house logistics personnel. This decision is supported by the necessity of considering the flowchart of the finished good, which would be incomplete without addressing the beginning and end of the product flow. The finished good requires external operations during the flow, where logistics is responsible for packing, shipping, and receiving goods from supplier processes.

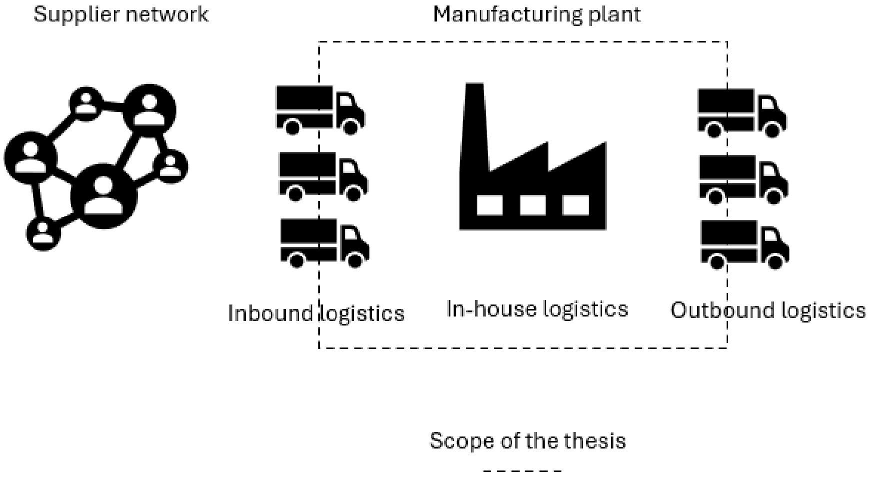


*Figure 1. The traditional classification of logistic types. Adapted from Ritvanen, Inkiläinen, von Bell and Santala (2011, 21).*

The research exclusively focuses on one production line selected by the case company due to the significant impact of the product line on revenue and business. The aim of this paper is to bridge theoretical frameworks and practical applications of in-house logistics and warehousing within the demanding environment of a highly variant assembly-to-order manufacturing system. This is particularly relevant for an organization experiencing rapid growth, where the fundamental operational foundation is challenged by the increasing variant and demand load, leading to issues in manufacturing operations and on-time deliveries.

The research paper seeks to identify the requirements for material handling and process changes necessary on the logistics side to transition from a job shop culture to a batch and ultimately serial production strategy, driven by increased demand. It aims to establish a connection to a broader framework for practitioners facing challenges with material feeding capacity and extensive customization. The goal of the research is to discover practical solutions to enhance material availability for the assembly line, addressing the prevalent issue of missing parts during the assembly phase, which causes confusion and excess WIP goods. Reliable and flexible part feeding to the assembly line is deemed crucial by Faccio, Gamberi, Persona, Regattieri, and Sgarbossa (2013b, 188), as missing parts lead to assembly line stoppages and inefficiencies on the assembly side.

In a broader scope, this study aims to offer guidance and insights for any warehouse environment facing challenges with non-standardized workloads and unclear priorities, as well as dealing with significant variance and exceptions. As according to Bozer (2012, 9, 12), the principles of Lean warehousing do not differ across various types of warehouses. Furthermore, this paper seeks to present easy-to-implement, low-cost solutions for control and material availability in any production environment.

The use of Lean tools and principles in this thesis was selected due to their widespread recognition in academic literature as among the most effective strategies for developing competitive and continuously improving organizations, while also enhancing operator-level well-being through involvement. Furthermore, de los Mozos and Lopez (2020, 1697) assert that eliminating non-value-adding activities is often the greatest potential source of improvement in productivity and customer service. Additionally, it was anticipated that the case company would eventually undergo a Lean transformation project at the group level, making it prudent to begin shifting the operating model in this direction.

## 1.3 Presentation of the case company

The case company in this thesis was established in 2009 as a startup. It manufactures electrical solutions and has a strong collaborative foundation with LUT University in research and development. The company has steadily gained market share, and in 2017, it was acquired by an international family group. Today, the case company is part of the global group and one of its divisions. The company operates factories in four countries: Denmark, China, Finland, and the United States. In 2022, the company's sales totalled 55.7 million euros, and it employed 374 people. The company focuses on two business units: off-highway and on-highway, concentrating on equipment and machinery within these respective units. The product portfolio of the case company includes electric machines, power electronics, and electric converters. Electric motors are further categorized into small and large electric motors. Small motors are high-volume and highly customized, yet suitable for serial production. Large motors, on the other hand, are always project-based and designed from scratch to meet customer needs. This thesis focuses on the high-demand product family of small motors.

The company can be categorized as an electronic manufacturing service (EMS) provider. According to Raghavan, Yoon and Srihari (2014, 343), EMS providers often construct electronic assemblies and solutions based on the specific requirements of their typical customers, who are usually original equipment manufacturers (OEMs). Consequently, EMS providers face the challenge of developing new products, enhancing existing ones, and adapting to changing customer requirements, which can easily result in excess stock or manufacturing with outdated revision components, leading to rework and customer complaints. To manage high-mix volume and ever-changing requirements, EMS providers require an up-to-date production and production control system with a high level of visual control. (Raghavan et al. 2014, 343). This observation has been recognized by the case company during increased demand and shifting requirements, leading to various issues in the small motors segment, which is the high-demand product family with significant customization, unlike the power electronics segment. This situation has prompted the business decision to reform the small motors production line to accommodate increased demand and changes. This thesis is part of the internally referred "flowline-project" focusing on developing the logistics aspect for the new production line to meet predefined output and visual control requirements.

The research is of significant interest at the group level of the case company, as the project is unique from the group's perspective, and successful outcomes are highly desirable for potential implementation in other divisions with similar manufacturing strategies. The project is substantial at the group level, with its budget comprising 10.8% of the 2023 total sales of the existing production line. It is considered unique within the group due to its nature, which involves implementing a serial-production-like line in an R&D-driven production environment and is designated as a pilot project for identifying best practices.

# 2 Warehousing and inventory classification

## 2.1 Warehousing

Warehousing is a crucial activity for all manufacturing companies. According to Freitas, Silva, Ferreira, Sá, Pereira and Pereira (2019, 1075) a warehouse can be defined as a facility or department responsible for receiving, storing, and preserving raw materials, semi-finished goods, or finished products, while also preparing materials for picking and shipment. Warehousing should not be viewed merely as a necessary expense; rather, optimal warehouse formation and operation play a vital role in creating and maintaining competitive advantage in manufacturing companies (Jármai & Voith 2020, 194). de los Mozos and Lopez (2020, 1697) also assert that effective logistics management, including warehousing, can significantly enhance an organization's competitiveness through improved productivity. According to Vrat (2014, 244), warehousing is a cost-intensive logistical process typically aimed at reducing operational costs and improving efficiency. Martins, Pereira, Ferreira, Sá and Silva (2020, 1723) characterize similarly the primary goal of warehousing as the efficient storage and movement management of goods, alongside the provision of flexibility in resource allocation.

Vrat (2014, 244) states that if materials cannot be stored and retrieved effectively, it can easily negate effective measures related to warehousing, such as order processing, in-house logistics, and stock level control. Furthermore, an ideology can be established for warehousing: if stored materials cannot be used effectively, they should not be stored. Ineffective warehousing requires items to be plausibly searched for when needed, leading to unproductive work, increased expenses, and, in the worst case, the inability to locate needed materials. This situation results in warehousing costs, labour expenses, and production stoppages as items must be reordered despite stock quantities indicating otherwise. In such cases, warehousing the item has only incurred various costs without fulfilling its purpose of ensuring material availability.

In addition to understanding what to store, maintaining the tidiness of the warehouse is a fundamental principle for efficient operations. An organized warehouse includes specific locations for all materials, ensuring they are stored only in designated areas. Furthermore, floor guidelines can be employed to visually indicate locations for certain materials, and warehouse shelves should be clearly marked with sufficiently large fonts to facilitate easy reading at a glance. (Karhunen, Pouri & Santala 2004, 321; Sheldon 2008, 126).

Generally, the role of component and sub-assembly inventories in a production plant is to ensure the efficient functioning of production and assembly operations. Therefore, decisions regarding inventory levels, supply methods, and warehouse locations can significantly affect production costs (Battini, Faccio, Persona & Sgarbossa 2010). Mancini, Gamberi, Regattieri and Persona (2004) and later Mancini, Persona and Regattieri (2006) have emphasized the importance of component management policies in creating flexible and efficient assembly systems, a point also noted by Battini et al. (2010, 775). A common strategic decision in the goods-producing industry is whether to maintain a centralized warehouse or multiple decentralized warehouses. Typically, the advantages of a centralized warehouse include reduced component stock and increased available space for production needs, albeit at the cost of longer procurement times, more frequent replenishment actions, and increased transportation frequency. (Battini et al. 2010, 775–776).

In assembly-to-order production, the centralization versus decentralization dilemma is even more complex. It is influenced not only by load unit inventory and transportation costs, and the positioning of warehouses and assembly stations, but also by unit space availability for warehouses and supermarkets, as well as the ability to share components across products amid high structural diversity and product variance. (Battini et al. 2010, 775–776). In assembly-to-order systems, the location, dimensions, and supply feed of subassembly warehouses are critical variables that require careful consideration. Persona, Battini, Manzini and Pareschi (2007) assert the impact of structural diversity among assembly parts on stocking policies. Conversely, multiple sources in the academic literature, such as Hsu, Lee and So (2007) alongside with Zhang, Ou and Gilbert (2008), confirm that the complexity of determining the correct physical locations for common assembly parts is increasing.

## 2.2 Material handling

Material handling can be broadly defined as encompassing all movements of materials within a manufacturing environment. Stephens (2019, 209) defines material handling as the function of moving the right materials to the right place, at the right time, in the right quantity, in sequence, and in the right condition, with the objective of minimizing production costs. Conversely, Garcia-Diaz and MacGregor Smith (2024, 230) define material handling as any activity associated with the movement, packaging, and storage of substances in any form. In contemporary manufacturing, material control systems are an integral component of modern material handling systems. These systems typically comprise multiple interconnected systems, such as part numbering, location tracking, and inventory control systems. Alongside these, standardization, lot size definition, order quantity determination, and safety stock management represent basic requirements for material handling and movement in industrial plants. (Stephens 2019, 209).

In material handling, as an operational activity, movement efficiency and safety are paramount concerns. When reviewing and planning material handling processes within a plant, the following factors warrant careful attention: The type and quantity of materials being moved dictate the type and nature of material handling equipment that should be employed, as well as the cost per unit of transportation. Consideration should also be given to the amount of work-in-process, excess inventory levels, and instances of repeated handling of the same material. The spatial aspect is also crucial, including the amount of floor space required for efficiently storing and handling materials. (Stephens 2019, 209–210). If warehouse operations are not carefully considered, the warehouse can evolve into a bottleneck. Metaphorically, the warehouse can be described as the heart of operations, and the capability of operations is directly related to the heart's ability to pump blood to the body, with the manufacturing operations acting as limbs representing different manufacturing lines or processes.

Stephens (2019, 212) identifies the reduction of unit costs as the primary objective of material handling, given that Garcia-Diaz and MacGregor Smith (2024, 230) have emphasized that material handling can account for 30–75 % of production costs. This overarching goal can be further deconstructed into a checklist format, providing a more readily approachable framework for achieving it:

1. Maintain and improve product quality, reduce damage, and provide adequate protection for materials.
2. Promote safety and improve working conditions for personnel.
3. Enhance productivity and efficiency of operations.

4. Optimize the utilization of existing facilities.
5. Minimize dead weight and unnecessary material movement.
6. Maintain effective inventory control. (Stephens 2019, 212; Garcia-Diaz & MacGregor Smith 2024, 230).

The two first points are rather self-explanatory, whereas the third point of the checklist encompasses fundamental principles, such as ensuring materials flow in a straight line while minimizing travel distances, leveraging gravity where feasible, moving larger quantities of material at once, mechanizing and automating material handling processes whenever possible, and maintaining and improving material handling efficiency ratios. The fourth point suggests acquiring versatile equipment, utilizing vertical building space to mitigate the scarcity of floor space, and integrating all material handling equipment into a cohesive system. (Stephens 2019, 212). Furthermore, the College Industry Council on Material Handling Education (CICMHE) of the Material Handling Institute Inc. has developed a set of ten principles of material handling:

1. The Planning Principle forms the foundation of effective material handling, stemming from the premise that all material handling activities should be the result of a thoroughly considered plan. This plan should comprehensively define the needs, performance objectives, and functional specifications of the proposed methods from the outset. The plan should consider both the strategic objectives of the organization and its immediate needs. Documentation within the plan should include existing methods and associated issues, physical and economic constraints, and future requirements and goals. The overarching aim of the plan is to promote coherence between engineering, process design, process layout, and material handling methods, rather than treating them as independent or sequential practices.

2. The Standardization Principle dictates that material handling, as an overall function, should be standardized to the extent possible while still achieving overall performance objectives without compromising required flexibility or modularity. This principle emphasizes that standardization, flexibility, and modularity are not inherently incompatible.

3. The Work Principle emphasizes that the amount of work involved in material handling should be minimized without sacrificing productivity or the service level required for manufacturing operations. To reduce work, fundamental concepts to consider include

simplifying processes by reducing, combining, shortening, or eliminating unnecessary movements. It is also important to remember that the shortest distance between two locations is a straight line.

4. The Ergonomic Principle emphasizes that human capabilities and limitations must be identified and respected when designing material handling tasks and equipment to ensure safe and effective performance. A key consideration for this principle is that material handling equipment should be selected based on its ability to eliminate repetitive and strenuous manual handling, as well as its ease of use for operators.

5. The Unit Load Principle emphasizes that unit loads should be appropriately defined and configured to achieve material flow and inventory objectives at each stage of the supply chain. While both large and small unit loads are common, smaller unit loads are often more consistent with manufacturing strategies that emphasize operational objectives such as flexibility, continuous flow, and JIT strategies.

6. The Space Utilization Principle dictates that all available space should be utilized effectively. This includes considering the use of overhead space for load transportation within the facility, an option that is often overlooked. Additionally, on the floor level, work areas should be organized, and unblocked aisles should be maintained to eliminate congestion and improve flow.

7. The System Principle dictates that material movement and storage activities should be fully integrated to create a coordinated, operational system encompassing receiving, inspection, storing, production, assembly, packaging, order selection, shipping, transportation, and the handling of returns. A key aspect of this principle is the integration of information flow and physical material flow, treating them as concurrent activities. This integration enables the development of methods for easy identification of materials and products, as well as the determination of their location and status within the plant.

8. The Automation Principle, as its name implies, promotes the mechanization and automation of material handling operations where feasible to improve operational efficiency, responsiveness, consistency, and predictability.

9. The Environmental Principle emphasizes that material handling operations should consider energy consumption and environmental impacts. This principle includes the use of reusable packaging materials and other sustainable practices.

10. The Life Cycle Cost Principle insists that a thorough economic analysis should account for the entire life cycle costs of all material handling equipment and systems.

According to Stephens (2019, 217) and Garcia-Diaz and MacGregor Smith (2024, 230–231), the above CICMHE's principles provide valuable guidelines for creating or reviewing material handling operations. However, it is important to recognize that some principles may conflict with others, underscoring the fact that logistical procedures are always case-sensitive, requiring careful consideration to determine the best approaches and trade-offs for each specific situation (Stephens 2019, 217).

In recent years, there has been a growing interest in incorporating advanced material handling systems, driven by increased competition within the manufacturing industry, where reduced response times are a critical success factor for production systems (Ahmadi-Javid & Ardestani-Jaafari 2021, 2353). Plant layout plays an integral role in material handling, and material handling and material flow are key areas to consider during layout planning. Typically, when addressing facility layout problems, material flows are treated as deterministic factors. Material handling and flows should be carefully considered during layout planning, as maximizing production capacity is unattainable if compromises are made on the logistics side, leading to bottlenecks in the material flow to the production area. A further challenge to material flow arises with the introduction of new products, as potential changes in the flow can only be fully understood shortly before the product's release to production. (Ahmadi-Javid & Ardestani-Jaafari 2021, 2353).

Benjaafar, Heragu, and Irani (2002, 58) have highlighted that factories regularly introducing new products often cannot afford frequent disruptions. They promote that a conscious decision is often made to tolerate the inefficiencies of the existing layout rather than continuously redesigning and developing layouts that may quickly become obsolete if the product lifecycle is short. However, Raghuram and Arjunan (2022, 2413) suggest that layout changes are desirable if a high level of benefits can be achieved. Therefore, the potential benefits should be evaluated on a case-by-case basis, as a high degree of flexibility to adapt the layout is desirable in modern warehouses (Raghuram & Arjunan 2022, 2413). Ahmadi-Javid and Ardestani-Jaafari (2021, 2353) have also emphasized the importance of investing in the design of facility layouts to ensure they can perform effectively despite unpredictable changes in material flows. Furthermore, Freitas et al. (2019, 1075) emphasize the crucial role of layout decisions in the warehouse, positioning it as a key enabler for minimizing movement and transportation waste in the context of Lean principles.

## 2.3 Inventory classification and analysis

Inventory analysis and classification, while closely related, are not synonymous. Classification entails the categorization of inventory items into distinct groups based on predefined criteria, such as value or demand patterns. Conversely, inventory analysis involves a more in-depth investigation of the classification data to identify trends and patterns, ultimately aiming to optimize inventory management practices. Indeed, inventory classification is a prerequisite for effective inventory analysis (Hänggi, Fimpel & Siegenthaler 2022, 84–86). In essence, classification provides the foundational structure upon which inventory analysis builds, enabling the extraction of meaningful insights and facilitating improved decision-making within an organization. Consequently, these concepts can be characterized as distinct yet complementary elements within the broader domain of inventory management.

Over time, various classification criteria have been developed for inventory analysis. The classification of items is crucial for manufacturing logistics in industrial enterprises, as it supports effective stock management and facilitates the realization of optimization opportunities (Scholz-Reiter, Heger, Meinecke & Bergmann 2012, 445). Praveen, Simha, and Venkataram (2016) emphasize that inventory classification enables the identification of critical items, thereby ensuring the maintenance of necessary service levels. Furthermore, they highlight its importance in enabling companies to operate more efficiently. Given that inventory classification is not the primary focus of this research, only a select few methods will be introduced.

Inventory classification is often categorized into single-criterion and multi-criterion approaches. Single-criterion methods are characterized by their unidimensionality and reliance on a single characteristic for categorization (Wang, Ng & Ng 2018, 1441). These methods are widely adopted due to their simplicity and ease of comprehension at all organizational levels, owing to their rule-of-thumb nature. Among the single-criterion classification models, Wang et al. (2018, 1441) identify the ABC, FNS, XYZ, SDE, and HML frameworks as traditional classification methods. These methods are summarized in

Table 1. Of these traditional methods, the ABC and XYZ classifications will be reviewed in greater detail.

*Table 1. Traditional inventory classification methods adapted from Wang et al. (2018, 1442).*

| **Method** | **Characteristic** | **Category** |
|---|---|---|
| ABC | Annual value € | A (High €€€)<br>B (Medium €€)<br>C (Low €) |
| FNS | Demand volume | F (Fast)<br>S (Normal)<br>N (Slow) |
| XYZ | Demand frequency | X (Regular / High)<br>Y (Fluctuating /Medium)<br>Z (Irregular / Low) |
| SDE | Lead time | S (Scarce)<br>D (Difficult)<br>E (Easy) |
| HML | Unit value € | H (High €€€)<br>M (Medium €€)<br>L (Low €) |

The ABC model is arguably one of the most widely recognized inventory classification methods. It is based on the well-established Pareto principle, which posits that a small percentage of any group typically accounts for a large proportion of the total value. In the ABC approach, items are categorized based on their monetary value, with each category assigned a specific threshold value determined by the user. (Wang et al. 2018, 1442). A key advantage of ABC analysis is its focus on cost-intensive items, facilitating strategies such as minimizing obsolete stock and maximizing inventory turnover ratios for these high-value components. However, a notable disadvantage is that the method prioritizes monetary value and does not account for the criticality of components in the production process. (Kumar, Rajan & Balan 2014, 29).

The XYZ analysis, while also a single-criterion classification method, follows the basic principles of ABC analysis but differentiates items based on fluctuations in their consumption patterns rather than monetary value. The classes can be summarized as follows: X-class items exhibit relatively constant consumption with fluctuations occurring at regular intervals; Y-class items demonstrate more pronounced fluctuations in consumption, often driven by trends, moderate seasonality, or other predictable factors; and Z-class items display highly irregular consumption patterns. (Scholz-Reiter et al. 2012, 466).

Wang et al. (2018, 1442) highlight the limitation of relying solely on single-criterion models, as they only address one influential factor. In practice, a multitude of factors often necessitate consideration. For instance, the ABC method, if implemented without regard to demand, can lead to suboptimal inventory management by treating high-demand and low-demand items identically. Furthermore, the qualitative nature of the categories within these models, combined with their dependence on arbitrary threshold values, renders them unsuitable for mathematically driven inventory planning methodologies. (Wang et al. 2018, 1442).

To address the limitations inherent in single-criterion analysis models, academics have developed multidimensional analysis models that often integrate multiple single-criterion methods. The ABC/XYZ analysis is a typical example of such an integrated model. According to Scholz-Reiter et al. (2012, 446), the ABC/XYZ model is commonly employed, with the ABC analysis serving as the primary classification framework and the XYZ analysis providing supplementary insights. In the ABC/XYZ analysis, classification is performed based on criteria derived from both individual models, as summarized in Table 2.

*Table 2. Classifications of ABC/XYZ model according to Pandya and Thakkar (2016, 84).*

| | **A** | **B** | **C** |
|---|---|---|---|
| **X** | high value<br>continuous demand<br>high predictability | average value<br>continuous demand<br>high predictability | low value<br>continuous demand<br>high predictability |
| **Y** | high value<br>fluctuating demand<br>average predictability | average value<br>fluctuating demand<br>average predictability | low value<br>fluctuating demand<br>average predictability |
| **Z** | high value<br>irregular demand<br>low predictability | average value<br>irregular demand<br>low predictability | low value<br>irregular demand<br>low predictability |

Stojanović and Regodić (2017, 36–37) has described the classes of Table 2 as follows:

- **AX:** Characterized by high value, consistent consumption patterns, and accurate demand forecasts. These items necessitate precise planning and ordering strategies, enabling the maintenance of minimal safety stock levels.
- **AY:** While also significantly impacting overall value, these items exhibit fluctuating consumption patterns and moderate forecasting accuracy, necessitating more flexible planning and inventory management approaches.
- **AZ:** These high-value items present the greatest inventory management challenge due to their irregular demand and unpredictable nature, rendering accurate forecasting difficult.
- **BX:** With moderate value, consistent consumption, and accurate forecasts, the primary focus for these items is on achieving efficient stock minimization.
- **BY:** These items also possess moderate value but exhibit sporadic consumption patterns and moderate forecasting accuracy, requiring a balanced approach between ensuring availability and minimizing inventory costs.
- **BZ:** Having a minimal influence on operations, these items are characterized by average value, irregular demand, and low predictability. Purchasing can be infrequent, and planning efforts may be less intensive or even outsourced.
- **CX:** These items have a minor impact on total value but benefit from continuous demand and accurate forecasts. Procurement should align with immediate needs.
- **CY & CZ:** Similar to BZ items, these categories exhibit low value and minimal operational impact, warranting minimized resource allocation and effort. (Stojanović & Regodić 2017, 36–37)

Berhan, Kitaw, Gobachew and Haasis (2021, 63) have demonstrated that the ABC/XYZ classification method can improve inventory management systems that lack proper inventory control mechanisms. Furthermore, their study indicated that the implementation of a Kanban system alongside of the method reduced inventory-related costs by approximately 75 %. It is important to note, however, that this study was conducted in pharmaceutical supply agencies, which generally maintain more expensive inventories compared to manufacturing companies. Conversely, the medical sector is known for its high-quality service level, a standard that is increasingly expected (and will continue to increase) in manufacturing companies. This trend highlights the potential of Kanban systems as a means for achieving cost savings and underscores the value of inventory classification as customization needs increase.

# 3 Lean principles in production and material handling

Lean principles and practices are widely recognized globally as a proven approach for efficiently building organizations focused on continuous improvement (Sayer & Williams 2007, 1). Lean can be described as a long-term philosophical approach centered on eliminating waste, thereby streamlining organizational processes to deliver greater value to customers (Hänggi et al. 2022, vii). Hänggi et al. (2022, vii) summarize Lean as production without waste or unnecessary detours, while ensuring quality, punctuality, and productivity. Lean has generally proven to be a suitable approach for continuous development in businesses, regardless of their field of operation or size (Sayer & Williams 2007, 1). While Lean has established itself as a successful approach in organizing and operating organizations, Lean warehousing remains a relatively new concept in academic literature compared to its application in manufacturing environments (Sharma & Shah 2016, 572).

Lean is founded on the principle of prioritizing the customer (both internal and external). In an ideal process, the customer is the central focus, receiving the right product, at the right place, at the right time, in the right quantity, and with the right quality. Over time, this concept has been referred to by various names, such as the 5 Rights (5R) and the just-in-time (JIT) principle, and it forms the central idea behind the origin of Lean production. (Hänggi et al. 2022, vii). In logistics, the 5Rs have been extended to the 7Rs, incorporating right price and right information (Lai & Cheng 2016). Furthermore, at the core of Lean lies the adoption of a culture of continuous improvement (Hänggi et al. 2022, vii). Martins et al. (2020, 1729) emphasizes the importance of maintaining discipline within an organizational culture of continuous improvement. They further state that to achieve the desired results, the organization must adapt continuous improvement methods to its resources and targets. Additionally, Manos and Vincent (2012, 21) have highlighted the crucial role of training in Lean implementation, noting that a common reason for failing to create a Lean organization is a lack of providing a clear understanding of the purpose of Lean, which is essential for driving acceptance of change.

## 3.1 Waste recognition and elimination

Lean is founded on the principle of identifying and eliminating nonproductive activities, referred to as waste. In Lean methodology, waste is categorized to facilitate the identification, quantification, and elimination of inefficiencies within a process. (Hänggi et al. 2022, 1). While the specific categorization may vary slightly depending on the academic source, the core categories remain consistent. For example, Manos and Vincent (2012, 54), alongside Hänggi et al. (2022, 2), have identified seven types of waste:

1. Overproduction
2. Inventory
3. Transportation
4. Motion
5. Waiting
6. Over processing
7. Defects.

However, Myerson (2012, 19), Bozer (2012, 20), and Wright (2017, 70) have extended the categorization to eight classes, adding behavioural waste as a distinct form of waste. In practice, this can manifest as personnel's resistance to changing current work methods and habits. Another form of behavioural waste is the underutilization of personnel's potential, which can result from insufficient training for assigned tasks or failing to assign individuals to tasks that best suit their abilities. (Myerson 2012, 25; Wright 2017, 72). According to Myerson (2012, 25), personnel's willingness to embrace change and actively develop work processes is a critical factor for the success of Lean projects.

Overproduction waste encompasses any form of manufacturing, ordering, or processing that occurs before it is necessary. Manos and Vincent (2012, 54) highlight overproduction as a particularly significant form of waste, as it can contribute to all other types of waste. Bozer (2012, 24) points out that the waste associated with producing sooner than required or in excessive quantities is often overlooked in manufacturing companies. Overproduction waste frequently leads to excess inventory, which is another distinct form of waste. Inventory waste can be categorized into four different forms: raw materials, semi-finished goods, finished goods, and materials for rework, as well as WIP. Inventory waste is generated when items are warehoused for longer than necessary. It is considered waste because it ties up excess capital that could be used for value-creating activities and occupies valuable space within the manufacturing plant. (Myerson 2012, 20; Manos & Vincent 2012, 55; Hänggi et al. 2022, 2–4).

Transportation waste, also referred to as movement waste, encompasses all activities related to transporting, temporarily locating, filing, stocking, stacking, or moving materials, people, tools, or information. In an ideal scenario, materials should only be handled twice upon receipt: once when placing them in their designated storage location and a second time when retrieving them for use. (Myerson 2012, 22; Manos & Vincent 2012, 55). In practice, it is common for companies to move the same item multiple times from one location to another. Vrat (2014, 11) asserts that the excessive material handling and movement incur invisible and hidden costs within warehousing operations. Consequently, Tuohy (2009, 29) and Myerson (2012, 22) emphasize the importance of minimizing the number of times a particular material is handled. Vrat (2014, 11) further points out that companies often fail to attribute these hidden costs specifically to warehousing, instead writing them off as general costs. This practice makes these costs far more difficult to identify, consider, and ultimately reduce (Vrat 2014, 11). Myerson (2012, 22) also elaborates that the two touch ideal rarely occurs, even though all excess movement is wasteful as Tuohy (2009, 29) and Vrart (2014) also have noted. To eliminate excess movement, a carefully considered layout and a visually organized warehouse are essential for achieving high efficiency (Myerson 2012, 22).

Motion waste is sometimes conflated with transportation waste in common usage. Motion waste specifically refers to movements that do not add value to the product or service. Pouri (1983, 10) suggests that a rule of thumb for an effective warehouse is to locate frequently used items closest to their point of use and ensure they are readily accessible. Myerson (2012, 22) supports this by providing a practical example of storing frequently used materials at waist level on shelves, rather than on higher levels. Typical forms of motion waste include searching for tools and storing materials too far from their point of use (Myerson 2012, 22; Bozer 2012, 23; Manos & Vincent 2012, 56). Ohno (1988) identified material handling waste as one of the most significant forms of waste. Material handling waste encompasses transportation, motion, and inventory waste. Minimizing material handling waste has been claimed to yield cost reductions of between 10 % and 30 % for companies. (Kilic, Durmusoglu & Baskak 2012, 1135).

Probably the most well-known form of waste is waiting waste. In essence, it can be defined as time spent waiting for materials, supplies, information, or personnel needed to complete an operation or task (Manos & Vincent 2012, 55; Wright 2017, 72). In a warehouse environment, waiting waste often occurs while waiting for replenishment during picking or waiting for equipment to become available for use (Bozer 2012, 23). Over-processing waste occurs when excessive time and effort are expended handling materials or information without adding value for the customer. Typical forms of over-processing waste in practice include copying information, using expensive and complicated equipment for simple tasks, and excessive checking. (Myerson 2012, 24; Bozer 2012, 24; Manos & Vincent 2012, 55). To review over-processing waste, one should question why a task is performed in a certain way and seek opportunities to simplify operations (Myerson 2012, 24).

Defect and error waste in a production environment regularly relates to repairs, rework, or the scrapping of materials (Myerson 2012, 24). According to Bozer (2012, 24), typical defects in warehousing include damaging items during transportation, picking the wrong item, or picking the incorrect quantity. Common reasons for such waste occurring are insufficient training, inaccurate or uncalibrated tools and equipment, poor layouts, and excessive processing, along with excess inventory (Myerson 2012, 24–25). Wright (2017, 71) has highlighted that fixing the root causes of defect and error waste costs time and money for companies, which can lead to the neglect of root cause analysis.

When waste does occur, it should be viewed as an opportunity to learn and improve overall performance. Wright (2017, 70) emphasizes the importance of the concept of "failing early" as a learning opportunity to change and improve, ultimately leading to the avoidance of larger mistakes. Therefore, the ability to efficiently identify waste is paramount. According to Imai (2012, 205), one of the biggest mistakes corporate managements can make is to isolate themselves physically from their company and lead from their office. Gemba walks have been developed as a tool to counter this issue (Dysko 2012, 4). "Gemba" is a Japanese word meaning the place where "the real work" is done (Wright 2017, 76). Hänggi et al. (2022, xxiv) have defined "Gemba" as the place where value creation happens in a Lean context. A "Gemba walk" is a tour of the shop floor where one attempts to understand the perspective of the operators working there. The idea of the walk is to gain a deeper understanding of what is happening in practice and to see if the process descriptions and standard operating procedures (SOPs) align with the actual reality. (Wright 2017, 76–77).

The Gemba process is illustrated in Figure 2. Gemba has gained recognition as an important tool for understanding processes and empowering show-and-tell sessions when viewed from the shop floor perspective (Wright 2017, 76–77).

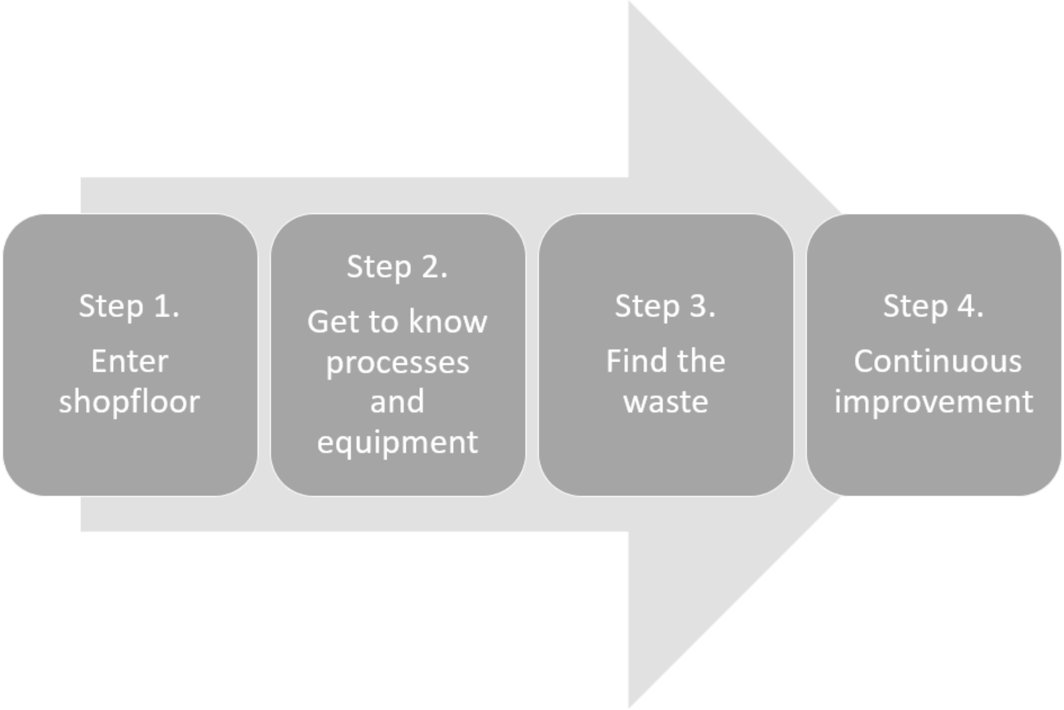


*Figure 2. Gemba process, adapted from Dysko (2012, 4).*

Another effective technique for identifying waste is the spaghetti diagram. Niemann, Reich, and Stöhr (2024) define the spaghetti diagram as a process analysis tool used to visualize process flows and work procedures. According to Hänggi et al. (2022, 79) and Niemann et al. (2024, 119), this technique primarily focuses on movement and transportation waste. The diagram is used to visualize and quantify the waste generated by paths in the manufacturing process of a finished good. The core idea is to present the amount of travel and movement an operator must perform from their workstation within the production cycle. (Hänggi et al. 2022, 79–80). Niemann et al. (2024, 122) highlight the strengths of the diagram, noting that no prior knowledge of the process is required, and the process can be initiated quickly with minimal resources. Furthermore, it presents a simple and visual representation of where waste occurs while visualizing the process and its execution for the user (Pyzdek 2021, 25). Mourato et al. (2021, 1933) posit that the spaghetti diagram constitutes an efficacious methodology for waste identification within warehouse and production settings, owing to its depiction of the static state, thereby excluding the dynamic variables that typically impinge upon logistical systems. Conversely, a potential disadvantage of the technique is a lack of clarity and increased complexity if the definition step of the process is not carefully executed. (Niemann et al. 2024, 122).

The starting point for using the spaghetti diagram for process analysis is a clearly defined layout of the area being analysed (Pyzdek 2021, 26; Niemann et al. 2024, 119). According to Niemann et al. (2024, 119), a Gemba walk can be combined with the creation of a spaghetti diagram to observe and record movements for the diagram. Furthermore, they emphasize that the observed objects do not always have to be employees; they can also be the paths of materials or the flow of required documentation. Therefore, the diagram creates a high level of transparency within the current process, revealing efficiency losses due to distances and suboptimal layout (Niemann et al. 2024, 119). The application of the spaghetti diagram can be divided into five steps, as presented in Figure 3.

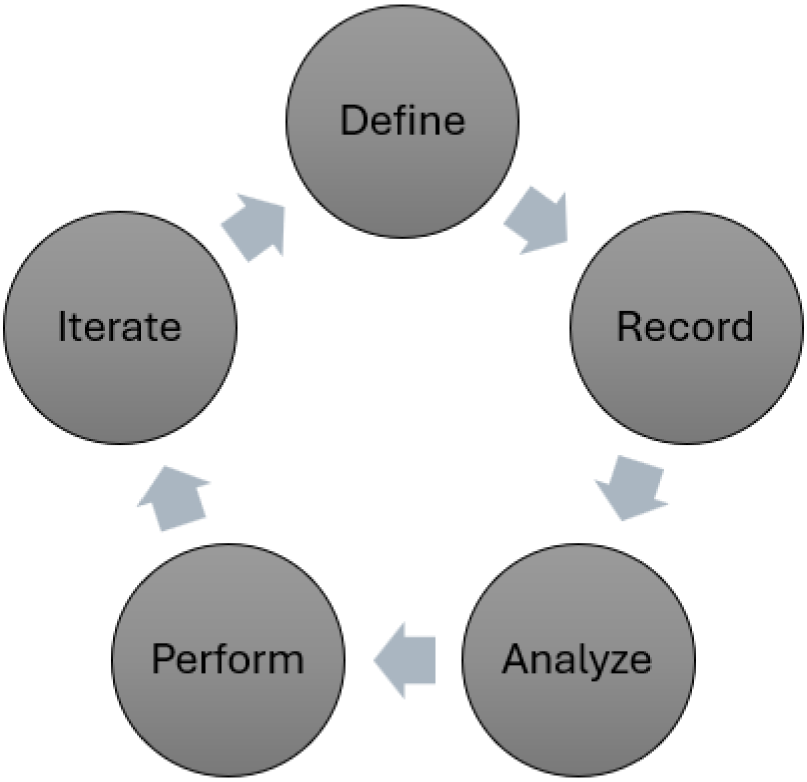


*Figure 3. Application steps of spaghetti diagram, adapted from Niemann et al. (2024, 121).*

The first phase, definition, consists of three dimensions that need to be defined before recording the current situation. Firstly, the work area to be analysed must be defined, as previously mentioned. Emphasis should be placed on clearly defining where the process begins and ends. Following this, the layout can be recorded, ideally to scale, using existing factory layouts whenever possible. Secondly, the temporal dimension should be defined. It is crucial to choose an observation period that allows for a clear statement about the process to be made during the analysis. For example, if multiple shifts are used, all of them should be analysed. If too short a time span is used for observation, the information may not be reliable enough for analysis. The third and final definition to be made is the determination of the observation object. This step refers to defining whether the operator's movement, material flow, or documentation flow will be the focus of the analysis. (Niemann et al. 2024, 121).

Following the three-phased definition step, the recording step begins, which involves drawing the process flow. Niemann et al. (2024, 121) emphasize that every single movement, including redundant movements, should be recorded during this step. Therefore, if the spaghetti diagram is created internally, it is crucial to maintain objectivity and avoid embellishing the truth. When the diagram is drawn accurately to scale on the layout, it enables both a qualitative and quantitative assessment of the current situation. Quantitative analysis can be performed by measuring the distance travelled, which is a key indicator of waste in the current process. Qualitative evaluation involves analysing the drawn lines in the diagram. High frequency, long path lines, and crossing lines are indicators of waste. As the name of the diagram suggests, a tangled, spaghetti-like appearance often signifies a high degree of waste. (Niemann et al. 2024, 121).

The final two steps of the process are defining measures and repetition. After analysing the current issues, measures must be defined to eliminate waste and design a process that is as efficient as possible (Niemann et al. 2024, 122). Niemann et al. (2024, 122) advise that, for implementation, actions should be ranked based on the advantage gained and the effort required to implement them. They further suggest prioritizing "low-hanging fruit" – actions that offer significant benefits with relatively little effort. The final step stems from the Lean ideology of continuous improvement. Therefore, after implementing corrective actions, the process should be restarted to review whether the corrective actions eliminated the waste as intended and to identify any remaining inefficiencies that can be addressed. (Niemann et al. 2024, 122).

Time and motion study has been defined by Barnes (1968) as the systematic study of a work system with the purpose of developing a preferred system and method, standardizing them, and determining the normal time required for a typical worker to complete a specific task or operation. van Zelst, van Donselaar, van Woensel, Broekmeulen and Fransoo (2009, 624) divides this definition into two phases: first, the definition and identification of a preferred method for performing work; and second, the determination of a standard time for the task. According to Che and Abdul (2014, 971), time study is an observation process for determining the amount of time required to perform a unit of work, which can involve different time elements such as external, internal, and machine time. Through time study analysis, unnecessary activities or actions, which constitute waste in Lean terms, can be identified. Time study is often used as a tool to increase productivity and as a root cause analysis technique for identifying the origin of waste. (Che & Abdul 2014, 971).

Hänggi et al. (2022, 16) has identified nine principles for eliminating waste from production. The first principle is the pull principle, which means aligning production with current customer demand (internal or external). The pull principle is a straightforward method for setting fixed limits to prevent overproduction, operating on the idea that a defined maximum quantity should not be exceeded. (Hänggi et al. 2022, 16). The most common driver of the pull principle is Kanban, which is explained later in chapter 3.4

The second principle is flow, which aims for effective product flow where the product moves through different operations in a sequential manner, rather than performing multiple different operations on the product at a single location. The ultimate expression of the flow principle is one-piece flow, where the product moves through production from one operation to the next without interruption. (Hänggi et al. 2022, 16–25).

The third principle is the takt principle, which refers to process balancing. Takt time represents the throughput time of a product through each step and indicates the frequency with which the customer requires the product. In the takt principle, bottleneck operations are addressed either by reducing the activities performed in the process step or by multiplying the process stations to meet the takt time (Manos & Vincent 2012, 62; Hänggi et al. 2022, 27–28). According to Manos and Vincent (2012, 62), takt time is a prerequisite for building an efficient continuous flow and a standardized working environment.

The zero-defect principle is the fourth principle, which aims to eliminate error and defect waste. In practice, this involves defining the root causes of defects. However, according to Wright (2017, 71) and Hänggi et al. (2022, 28), minor defects are often overlooked and compensated for, for example, by ordering extra pieces to cover the problem. The rationale behind this approach is to save time for other tasks rather than spending it analyzing the issue. They argue that this type of cover-up is very harmful for sustainable troubleshooting, as it downplays the magnitude of the issue and obscures the underlying problem. This leads to an accumulation of unresolved issues, leaving production personnel to find quick fixes and exception rules to avoid the issue in the future. (Wright 2017, 71; Hänggi et al. 2022, 28). Hänggi et al. (2022, 28) highlight that the zero-defect principle is one of the most challenging principles to adopt because it requires a thorough cultural change to embrace the mentality of fixing issues at their source.

The fifth principle is the separation of waste and value creation. This principle involves distinguishing between activities that generate waste and activities that create value. By separating these activities, it becomes easier to eliminate waste because it is not dispersed across multiple process steps. A practical example is consolidating material transport into a single, combined route. (Hänggi et al. 2022, 28–29).

The sixth principle is the FIFO principle, which is commonly applied in warehousing and production environments. By adhering to FIFO logic, obsolescence in warehousing can be minimized, and the wasteful work of sorting and checking stock for validity can be eliminated. (Hänggi et al. 2022, 29–33). The seventh principle suggested is minimum distance. This principle aims to address motion waste, which, according to Hänggi et al. (2022, 34), is one of the largest sources of time waste in many processes. They further state that motion waste is often the sum of multiple small instances of motion waste, which accumulate into a significant time loss over the entire production process.

The eighth principle, value stream orientation, places the optimization of individual operations within a broader context. As illustrated in Figure 4, optimizing a single operation can generate significantly more waste in the overall process compared to value stream optimization, as shown in Figure 5. When optimizing the value stream, the associated information flow must be considered alongside the physical material flow. (Hänggi et al. 2022, 35–36).

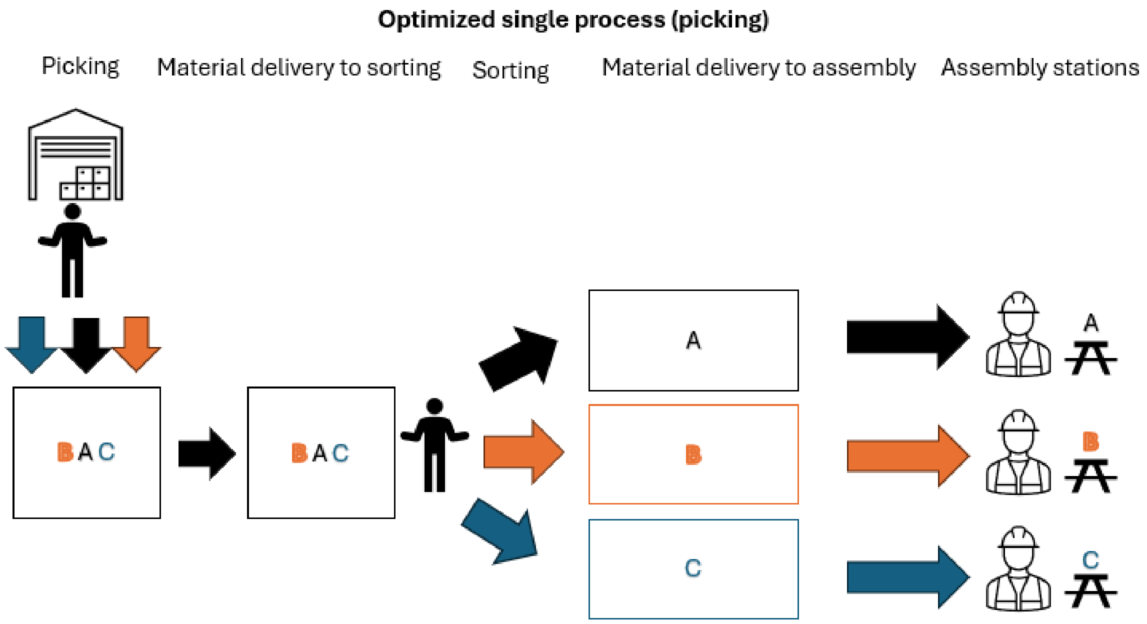


*Figure 4. Optimized single process. Adapted from Hänggi et al. (2022, 35).*

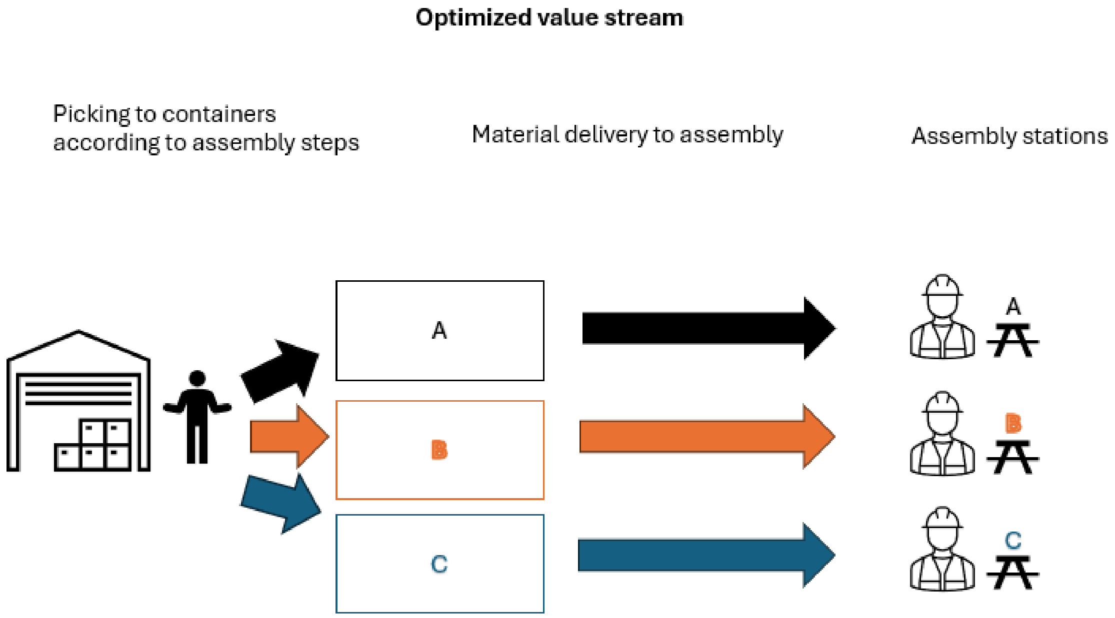


*Figure 5. Optimized value stream. Adapted from Hänggi et al. (2022, 35).*

For value stream optimization, value stream mapping (VSM) can be utilized as a tool to identify value-creating steps (Wright 2017, 56). Value stream mapping is a systematic approach for studying existing business processes. The basic VSM process begins with creating a current state VSM. After that, the VSM is analyzed to identify value-adding, critical, and bottleneck processes. The third step is to draw a future state VSM, where problematic processes are eliminated, optimized, or replaced to reduce waste. The last step is to create an implementation plan for the future state VSM. (Raghuram & Arjunan 2022, 2418). An example of the value stream mapping process is illustrated in Figure 6.

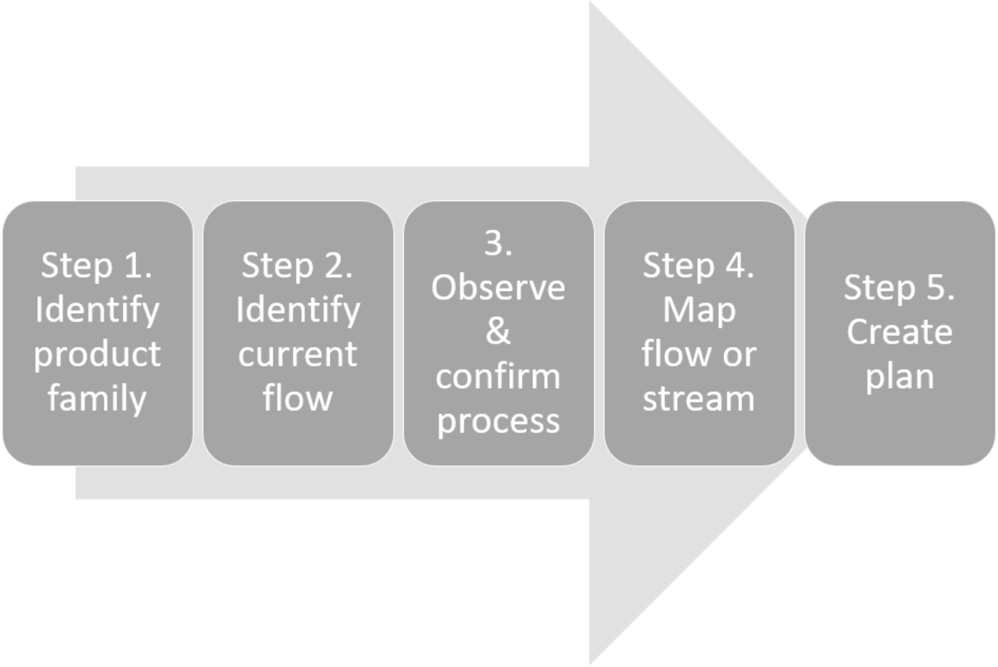


*Figure 6. Value stream mapping process, adapted from Wright (2017, 54).*

The ninth and final principle for waste elimination is standardization. Since Lean thrives on the ideology of continuous improvement, standardization is a key element in ensuring that implemented solutions remain in use in practice. New ideas and ways of working are often forgotten if they are not anchored in daily work through standardization. Standards can take various forms, such as training programs, process descriptions, or even technical tools. (Hänggi et al. 2022, 37). Hänggi et al. (2022, 37–38) highlight that developing and adhering to standards is a core element in building a Lean organization. They also emphasize that when creating standards, it is important to design them in a way that they serve to prevent errors and make the work easier.

## 3.2 Lean in warehousing

Academic literature typically identifies waste in manufacturing environments as overproduction, over-processing, waiting time, transportation, defects, inventory and storage, along with the underutilization of employees (Vinodh & Balaji 2011, 4027; Sharma & Shah 2016, 571). Therefore, in a warehousing environment, the Lean concept, in its core, creates a contradiction, since a strict implementation would imply that nothing should be stored, and everything should arrive JIT based on a pull system (Pereira, Anholon, Rampasso, Quelhas, Leal Filho & Santa-Eulalia 2021, 3). Multiple academic sources have resolved this contradiction by stating that, even though storing is an activity that does not add value, it is a necessity to ensure that customer needs are met at the correct time (Frazelle 2002; Myerson 2012, 77; Swart 2016). Sharma and Shah (2016, 572) have elaborated that, in this context, the focus should be on operations involving significant time and cost, eliminating waste in these operations as much as possible while optimizing processes that add value to the customer. While a common definition of a Lean warehouse is lacking in academic literature, Sharma and Shah (2016, 572) have defined it as a collective approach of factors that are applied to improve warehouse functions. According to Martins et al. (2020, 1725), academics have established a common consensus that Lean contributes to improved operational performance, especially in terms of cost reduction and effective improvement of productivity and lead time. In warehouse operations, this competitive edge manifests as ensuring better stock control, improved picking accuracy, and lower stock levels (Martins et al. 2020, 1725).

According to Freitas et al. (2019, 1075), JIT aims to reduce waste and is therefore commonly introduced alongside Lean principles. Hänggi et al. (2022, vii) have similarly stated that anything that interferes with the implementation of JIT principles constitutes waste in the context of Lean production. JIT is also beneficial in terms of in-house logistics as it is an approach to minimize inventory and WIP. In a JIT system, only a specific set of materials is available for production during a defined time period, such as a shift or working day, and no excess materials should be staged in the production area during this timeframe. (Raghavan et al. 2014, 344). According to Emde and Boysen (2012b, 394), JIT strategies are often utilized in Lean logistics to ensure a reliable supply for final assembly while minimizing WIP. They also emphasize the importance of effective in-house logistics in production environments characterized by high product variety and consequent part diversification to secure competitiveness, as storage space near assembly stations is often the scarcest and most expensive. Vrat (2014, 23) states that JIT is an ideal inventory management concept where any material demand can be fulfilled wherever and whenever, just in time, without supply shortages and without keeping any inventory on hand. Also, Myerson (2012, 78) highlights JIT logistics as being suitable in environments where logistics requires flexibility and agility to meet rapidly changing short-term customer demand. Agility gained through Lean operations improves a warehouse's effectiveness and an organization's competitive capabilities (Ahmed 2022, 1811).

According to de Koster, Le-Duc, and Roodbergen (2007, 481), warehousing and order picking are among the highest priority areas for productivity improvements due to their labour and cost intensity. Sharma and Shah (2016, 572) further state that, because warehousing operations contribute significantly to total waste and costs in a manufacturing firm, it is a highly suitable function for implementing Lean philosophy. Also, Myerson (2012 77) emphasizes that there is still an enormous amount of untapped potential to be realized in warehousing and logistics through the application of Lean principles.

Practitioners often fail to recognize the differences between efficiency and Lean thinking. In academic literature, these two concepts have a central distinction. Efficiency thinking focuses on the best ways to utilize available resources, assets, and technologies to increase profits with the least number of resources, even though this might not be a long-term profitable strategy. (Ohno 1988; Sharma & Shah 2016, 572). According to Sharma and Shah (2016, 572), current academic literature regarding warehousing has adopted efficiency thinking, which leads to unbalanced warehousing systems by optimizing one or more performance measures while neglecting others. The objective of a Lean warehouse, in essence, is to serve the customer faster, with less storage space, less inventory, and with increased accuracy. The key difference between warehouse optimization and a Lean warehouse is the engagement of all functional and cross-functional personnel with technological and decision-making issues at every level of continuous improvement. (Sharma & Shah 2016, 572). Hines, Holweg, and Rich (2004, 995) have identified creating and maximizing value for people as the most challenging task in warehousing because of the required cultural and environmental changes, which take extended periods of time to establish.

To establish a Lean warehouse, the key is to engage personnel in developing self-awareness and understanding each person's responsibility in warehousing operations. It is important to maintain an uninterrupted value flow within the warehouse. (Raghuram & Arjunan 2022, 2411). Building on the waste recognition, analysis, and elimination techniques presented previously, the following seven key areas should be the focus of Lean implementation in the warehouse, according to Dharmapriya and Kulatunga (2011, 513–518) and Raghuram and Arjunan (2022, 2411–2412):

- **Material handling and storage system:** Layout is a significant contributor to warehouse efficiency and should be carefully designed to optimize the use of available storage space as previously presented by multiple sources. Poorly designed layouts can easily lead to disorganized, inefficient operations and increased costs. In addition, ineffective space utilization increases storage costs per unit. A key metric in a warehouse environment is the time it takes to receive, put away, locate, and pick materials for use. In material handling, an effective process needs to be defined with regard to material, manpower, and money (the 3Ms). (Dharmapriya & Kulatunga 2011, 513– 518; Raghuram & Arjunan 2022, 2411–2412)

- **In-house logistics:** Material movement within the warehouse is often seen as a necessary and negligible activity. Therefore, it is frequently not optimized, leading to increased costs in labour and extending to include storage space, equipment maintenance, rent, utilities, and so on. Ineffective processes result in longer process times, which accumulate to increased storage needs, resource consumption, and reduced throughput. (Curcio & Longo 2009). Raghuram and Arjunan (2022, 2411) point out that a carefully designed layout can utilize the fast-medium-slow (FMS) technique for goods movement. According to them, in the FMS technique, materials are categorized by their throughput times, with fast-moving items being made most easily accessible and slow-moving items least accessible.

- **Inventory management:** Inventory management is a widely researched topic in academic contexts, and practitioners have also recognized the value of inventory optimization. Li and Kuo (2008, 1144) have stated that parts availability is a key measure for inventory management, along with tracking and optimizing current inventory levels.

- **People movement:** The movement requirements of personnel are directly correlated with the efficiency of the layout. An inefficient layout and a randomized storage system increase unnecessary movements for warehouse staff. (Raghuram & Arjunan 2022, 2411–2412).

- **Delays:** Schrotenboer, Wruck, Roodbergen, Veenstra and Dijkstra (2017, 6405) identify people as a typical source of delay in warehouses. Raghuram and Arjunan (2022, 2412) have extended the typical sources of delays to also include systems and materials. Delays often arise through bottleneck operations, which can be effectively addressed through Lean practices (Schrotenboer et al. 2017, 6405; Raghuram & Arjunan 2022, 2412).
- **Excess production or processing:** As mentioned earlier, excessive processing is a form of waste that is also common in warehousing environments. It is not uncommon for the same material to be moved around the warehouse multiple times, contrary to the principle of placing it in storage and then directly taking it to its point of use (Raghuram & Arjunan 2022, 2412).
- **Defects:** In warehouse environments, a "first-time right" approach is highly desirable. Common defects in warehouses include inventory mismatches, handling damages, and lost items due to misplacement (Baudin 2004). Raghuram and Arjunan (2022, 2412) suggest that root causes should be analysed using techniques such as the five-why analysis or brainstorming and then eliminated accordingly. They further suggest that Poka-Yoke is an effective tool for addressing manual errors and defects.

The definition of process flow is of paramount importance in a Lean warehouse environment. To effectively optimize a warehouse, an initial investigation of existing processes is necessary to facilitate the implementation of Lean practices. (Pereira et al. 2021, 3–4). This perspective is corroborated by Salhieh, Altarazi, and Abushaikha (2019, 95), who assert that the implementation of Lean principles in a warehouse should commence with a thorough assessment of current waste streams. Prior to conducting an "as-is" analysis, Bozer (2012, 10) emphasizes the necessity of identifying the warehouse's customers and the value proposition offered, aligning with core Lean ideologies, as understanding customer needs is fundamental to the establishment of a Lean warehousing system. Limère, Landeghem, Goetschalckx, Aghezzaf and McGinnis (2012, 4047–4048), in conjunction with Raghuram and Arjunan (2022, 2415), highlight the presence of specialized, non-mandatory processes that vary across warehouses. While not essential, these processes exert a considerable influence on warehouse operations and inventory flow (Limère et al. 2012, 4048; Raghuram & Arjunan 2022, 2415). The process-centric nature of warehousing is further underscored by Raghuram and Arjunan (2022, 2417), who posit that the optimization of warehouse processes through the application of Lean principles will, in turn, engender a Lean warehouse. Myerson (2012, 89) and Salhieh et al. (2018, 94–95) have identified that Lean warehousing focuses on the efficient assembly of orders, minimizing non-value-added activities within receiving, stocking, picking, packing, and shipping operations. The fundamental principles of Lean implementation, as defined by the Lean Enterprise Institute (LEI), are presented in Figure 7.

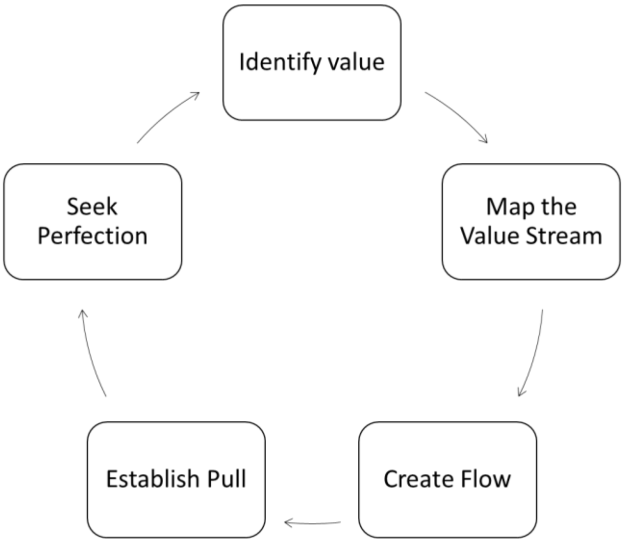


*Figure 7. The five principles guiding the implementation of Lean methodologies, adapted from the Lean Enterprise Institute (LEI, 2024).*

Bozer (2012, 12–13) adapted the following steps in his study and further elaborated on them within the context of warehousing:

1. Define value from the customer's perspective for each product family.
2. Identify all steps within the value stream and eliminate those that do not add value.
3. Establish a tightly sequenced series of value-creating steps to ensure a seamless product flow to the customer.
4. Implement the pull principle within the flow.
5. Iterate the process continuously, striving for perfection.

Bozer (2012, 13–15) critiqued the conflation of these principles with implementation strategies, noting the absence of a dedicated quality principle (zero defects). He argued that the "seek perfection" step primarily represents the continuous improvement aspect of Lean philosophy. Consequently, Bozer (2012, 16) developed a "House of Lean" model specifically for warehousing (Figure 8), integrating elements from the manufacturing "House of Lean" and the implementation steps outlined by the LEI (Bozer 2012, 10–18). Due to the defined scope of this study, supplier involvement, as represented in Bozer's "House of Lean," has been excluded from consideration.

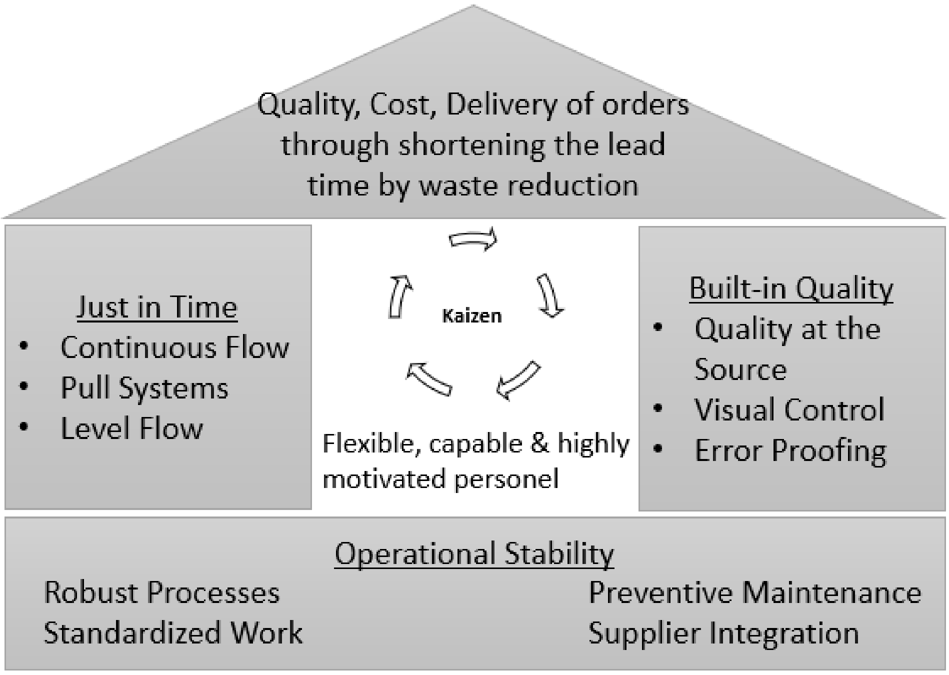


*Figure 8. "The House of Lean" model for warehousing, adapted from Bozer (2012, 16).*

Within the foundational layer of the "House of Lean," standardized work is frequently misinterpreted as mere standardization, which is inaccurate. Standardized work, rather, pertains to the standardization of how individuals perform their tasks, establishing the most effective methodologies as standard practices. This involves the creation of standard methods, processes, and timeframes for typical warehouse operations, such as unloading, put-away, picking, and packing. (Bozer 2012, 16). Standardized work has been shown to increase worker satisfaction and can yield substantial cost savings in warehousing and material feeding contexts (Mourato, Pinto Ferreira, Sá, Silva, Dieguez & Tjahjono 2021, 1932). Processes are intrinsically linked to standardized work, generally referring to the consistent and repeatable execution of required activities. Furthermore, it implies the existence of processes capable of adapting to a diverse range of operating conditions and accommodating variations. A common example of a non-robust system in a warehouse environment is a manual picking system that necessitates excessive movement throughout the facility. Preventive maintenance is directly transferred from the original "House of Lean," signifying that a warehouse cannot achieve a Lean state with low equipment uptime. (Bozer 2012, 16–17).

The pillars supporting the "House of Lean" are flow and quality. In Lean methodologies, optimal flow is characterized by one-piece flow, which aims to minimize batch quantities. Within a warehousing context, the material handling batch size is reduced by decreasing material handling distances through one-piece flow to manufacturing cells and through the implementation of internal milk runs to supply those cells. Furthermore, picking in batches is antithetical to the flow principle, as the goal is one-piece order processing. Common systems in warehouses include walk-and-pick systems, where pickers traverse the storage area, selecting items according to a picklist. One approach to mitigate the waste associated with walking is to implement a part-to-picker system, where containers are retrieved to the picker one by one in small batches and subsequently returned to the warehouse. However, this approach often transforms the walking waste into set-up time associated with the picker's interaction with the material handling system. Consequently, batch picking is often more feasible than single order picking in warehouse environments. Therefore, the focus in warehouse environments is frequently directed towards reducing set-up times and optimizing picking operations. The second pillar of the "House of Lean" represents quality, which should originate upstream in the process, directly at the source. (Bozer 2012, 18–20). Ideally, no defective items or products are passed forward in the flow stream. According to Bozer (2012, 20), typical defects in warehousing include storing items in incorrect locations and picking the wrong item or an incorrect quantity. He suggests that RFID tags and barcode solutions are suitable for minimizing these human-based defects.

## 3.3 Supermarkets

The growing adoption and application of JIT principles have spurred the increased implementation of supermarket systems within warehousing operations (Faccio, Gamberi & Persona 2013a, 2997; Faccio et al. 2013b, 187). Coelho et al. (2022, 989) suggest that supermarkets offer a viable approach to optimizing parts supply to assembly lines operating under JIT and just-in-sequence (JIS) methodologies. A supermarket, in this context, constitutes a decentralized storage area strategically located throughout the shop floor. It functions as an intermediate buffer for components required by adjacent assembly lines. Typically, logistics personnel transport parts from the supermarket to assembly stations, where demand is signalled via a Kanban system. During replenishment cycles, empty containers are collected and returned to the supermarket for restocking. (Faccio et al. 2013a, 2997; Faccio et al. 2013b, 187).

Traditionally, high-volume production has been organized as flow lines to capitalize on economies of scale and achieve higher productivity rates. In today's global market, characterized by increased competition, companies are compelled to offer a wider range of diverse products. A common approach to meeting this demand is configuring the production system as a multiple mixed-model assembly-line system, where each production line is capable of producing numerous variants from a common base product, with the base product differing by each production line (Emde & Boysen 2012b, 393; Faccio et al. 2013a, 2997). According to Emde and Boysen (2012a), a significant challenge within this production model is the feeding of parts to the assembly lines. Stable and flexible part feeding is crucial, as issues in delivering parts can lead to assembly line stoppages. Increasing safety stocks around the assembly lines can reduce production efficiency by occupying limited space at assembly stations and escalating inventory costs. (Emde & Boysen 2012a; Faccio et al. 2013a, 2997).

Due to increased variant demand in JIT-based production, supermarkets have gained attention as a solution to the issues highlighted by Emde and Boysen (2012b). Supermarkets are typically equipped with flow shelves that utilize a Kanban two-bin system. Logistics operators deliver full boxes or containers from the supermarket to assembly stations, while collecting empty ones for refilling. Each shelf contains two boxes of each material; when an operator finishes the first box, it is removed, allowing the full box to fall into its place. The removed box is placed on a shelf that flows in the opposite direction, serving as an indicator for logistics personnel to collect empty boxes for refilling. Material refilling deliveries are often scheduled according to fixed routes and times, commonly referred to as a "milk run". (Faccio et al. 2013a, 2997).

## 3.4 Kanban

In manufacturing processes, JIT manufacturing is a desirable objective (Niemann et al. 2024, 137). According to Freitas et al. (2019, 1075), JIT principles are also beneficial and effective in warehousing operations, complementing their application in manufacturing. JIT necessitates that the correct parts within a flow process are available at the appropriate time, in the required quantity, and at the designated location. Niemann et al. (2024, 137) suggest that the Kanban system is highly effective in ensuring these requirements are met. Kanban, a Japanese term popularized by the Toyota Production System, translates as "signboard" and has evolved into a synonym for demand scheduling (Toyota Motor Corporation 1998; Gross & McInnis 2003, 1). Kanban was initially introduced in the late 1940s by Taiichi Ohno as a tool to control production between different processes and to facilitate the implementation of JIT manufacturing. More specifically, Kanban was developed to minimize WIP between manufacturing processes while simultaneously reducing the costs associated with holding inventory. (Ohno 1988; Gross & McInnis 2003, 1–2; Sendil Kumar & Panneerselvam 2007, 393). In contemporary practice, Kanban has evolved into a globally utilized control method, its popularity arising from its reduction of complexity, low susceptibility to interference, decentralization, and the associated reduction in control effort. Kanban has been identified as a means of ensuring smooth production according to Lean management principles, enabling minimal throughput times alongside high production flexibility. (Niemann et al. 2024, 137).

Initially, Kanban was employed by Toyota to reduce costs and manage machine utilization. Since its inception, Kanban has evolved into a more versatile tool, and Toyota has continued to utilize it, not only for its original purpose but also to identify impediments to flow and to recognize opportunities for continuous improvement. (Gross & McInnis 2003, 2). Niemann et al. (2024, 137) note that Kanban is frequently described in academic literature as embodying the "supermarket principle". This description originates from the pull principle, wherein the removal of an item from a shelf triggers the replenishment of that slot with the corresponding item (Hänggi et al. 2022, 126, 134). According to Hänggi et al. (2022, 126–130), Kanban provides an efficient means of establishing a rapid, decentralized restocking system. They further assert that, with proper utilization, Kanban can reduce inventory levels, shorten lead times, and enhance control over supply security to the assembly line.

Gross and McInnis (2003) define Kanban scheduling as a form of demand scheduling. They posit that in processes controlled by Kanban systems, operators produce goods based on actual usage rather than forecasted demand. To meet the criteria of a true Kanban-scheduled process, production controls must ensure that product is only produced to replace product consumed by its customers and that production is solely based on signals transmitted by those customers. Consequently, a Kanban schedule replaces traditional production schedules with visual signals and predetermined decision-making processes. (Gross & McInnis 2003, 2–3). Hänggi et al. (2022, 130) add that the visual nature of Kanban enhances transparency and control over material availability within the manufacturing area. Niemann et al. (2024, 137–138) concur with Gross and McInnis (2003, 2–3), defining the basic Kanban model as an operational line where a customer order triggers a request for materials from the first process step. The material then moves along the line until the required product is completed. Upon completion of the order, the resulting material shortfall triggers an upstream production order to address the shortage. (Niemann et al. 2024, 137–138).

A key understanding of Kanban scheduling is that it functions primarily as an execution tool rather than a planning tool. Kanban, in its various forms, directs process operations on a day-to-day basis. To clarify, Kanban scheduling does not replace material planning; instead, it leverages material planning information to create the Kanban system. Kanban typically replaces daily scheduling activities for processes and the need for continuous monitoring of schedule status to determine the next items to produce or to manage changeovers between manufacturing items. This approach empowers operators with greater involvement and increased interest in controlling the line, while simultaneously reducing the workload of material planners, production planners, and supervisors, freeing up their time to address exceptions and implement overall improvements. (Gross & McInnis 2003, 3). Mourato et al. (2021, 1947) emphasize the well-established principle that every process requires a degree of constant monitoring and improvement to achieve success. According to Gross and McInnis (2003, 3–5) with Kanban, the controlling responsibility is transferred from managers to operators.

In general, the implementation of Kanban systems leads to improved productivity and reduced capital costs. The specific benefits of Kanban, as identified by Gross and McInnis (2003, 4), include:

1. Reduced inventory levels.
2. Improved process flow.
3. Prevention of overproduction.
4. Placement of control at the operational level.
5. Creation of visual scheduling and management of the process.
6. Improved responsiveness to changes in demand.
7. Minimisation of inventory obsolescence risk.
8. Increased supply chain management capabilities.

According to George (2002, 38), arguments against the benefits of Kanban, which often advocate for the economic order quantity model, typically fail to recognize the hidden costs associated with inventory, such as overhead, rework, scrap, and material handling. Gross and McInnis (2003, 4) alongside Lage Junior and Godinho Filho (2010, 14) further emphasize that inventory reductions, combined with the factors mentioned by George (2002), make Kanban a necessity for companies to maintain a competitive edge. They also suggest that the additional benefits derived from Kanban implementation can foster a cultural shift within the company, promoting a culture of continuous process development. (Gross & McInnis 2003, 5; Lage Junior & Godinho Filho 2010, 14).

Gross and McInnis (2003, 5) suggest that if Kanban quantities are calculated based on current conditions of downtime, scrap rates, and changeover times, a decrease in inventory levels ranging from 25 % to 75 % can be expected. Initially, it is crucial to collect the necessary data to identify and understand the production process. This data gathering allows the organization to base its decisions on factual information rather than assumptions and unrealistic perceptions of the actual production process. The collection of accurate and precise data is essential for calculating sufficient Kanban sizes. The importance of this data accuracy is vital for the successful implementation of Kanban. Therefore, organizations should maintain a brutally honest assessment of their processes' true capabilities to achieve realistic Kanban quantities that effectively meet actual demand. Concurrently with the data collection process, it may also be beneficial for the company to conduct a value-stream-mapping exercise for the plant. (Gross & McInnis 2003, 9).

When calculating initial Kanban container sizes, it is crucial to base these calculations on current operating conditions rather than future plans or idealized operational scenarios. The calculation should consider production requirements, system scrap rates, process productivity rates, planned downtime, and changeover times to establish a replenishment interval for the containers. These replenishment intervals then inform the determination of ideal order quantities. Furthermore, the final Kanban container should include a buffer for safety stock to account for potential disruptions in delivery times. (Gross & McInnis 2003, 9–10). Bonvik, Couch, and Gershwin (1997), and later Faccio (2014, 546), observed that in many Kanban implementations, Kanban calculation parameters are often determined using rules of thumb or simplified formulas. An example of such a formula is Toyota's own Kanban calculation formula, presented below in Equation 1. These initial steps lay the foundation for the entire Kanban process. Therefore, a truthful and accurate assessment of the process's current state is paramount (Gross & McInnis 2003, 9–10; Sendil Kumar & Panneerselvam 2007, 397).

*Equation 1. The Toyota's formula adapted from Sugimori, Kusunoki, Cho and Uchikawa (1977).*

$$\boldsymbol{n \geq D * L * (1 + \partial)/a}$$

$$n\text{=}number\ of\ Kanban$$

$$D = consumption\ rate$$

$$L = replesnihment\ lead\ time$$

$$\partial = stock\ keeping\ unit\ (SKU) capacity$$

$$a = positive\ safety\ factor$$

The process of calculating quantities for Kanban systems necessitates an objective assessment of the actual situation and mitigates potential biases that participating stakeholders might hold. This method also prompts a review and challenge of informal rules and comfort levels, which are often the underlying cause of increasing inventory levels over time. By utilizing realistic information, a level of confidence is established that the calculated quantities will enable successful supply to customers. In terms of advantages, in addition to the inventory reduction, the associated cost savings and the physical space previously occupied by inventory are also freed up. This newly available space can be utilized for new business opportunities or can eliminate the need for plant expansions or additional leased offsite warehouse services. (Gross & McInnis 2003, 5). A properly executed Kanban system improves the overall flow of operations. This improved flow is achieved not only through reduced inventory space but also through the order created by the designed Kanban material flow. Traditional Kanban flows incorporate elements such as control points and visual hanging signs, which provide clear instructions for material movement. These enhanced controls contribute to maintaining and controlling inventory levels effectively. (Gross & McInnis 2003, 5).

Designing the Kanban process in a visually intuitive manner, thereby empowering operators to control production lines, fosters involvement and provides opportunities to influence their own workflow, ultimately improving motivation and efficiency. Another positive outcome is that it frees up supervisors and managers to focus on other value-added tasks instead of closely monitoring daily production. To realize the full benefits of operators controlling the line, it is essential that they receive appropriate training and mentorship to succeed in their new roles and environment. (Gross & McInnis 2003, 6).

A Kanban system reduces the effort required for control and planning while simultaneously increasing the responsiveness of production. In addition, Kanban offers a high degree of supply security for materials while minimizing inventory levels. Furthermore, its simplicity, ease of understanding, and high level of involvement at lower organizational levels facilitate its implementation. A key limitation of the system, however, is its low tolerance for disruptions in the flow, which can lead to production stoppages. Moreover, strong fluctuations in demand cannot be effectively compensated for via the Kanban system. (Niemann et al. 2024, 143).

Kanban systems are frequently classified based on their nature in academic literature (Hänggi et al. 2022, 134; Niemann et al. 2024, 139). Hänggi et al. (2022, 134) categorize Kanban systems into production, transport, and supplier Kanban. Niemann et al. (2024, 139), on the other hand, expands this classification into a multilevel system (presented in Figure 9.) identifying production and transport Kanban as the basic types.

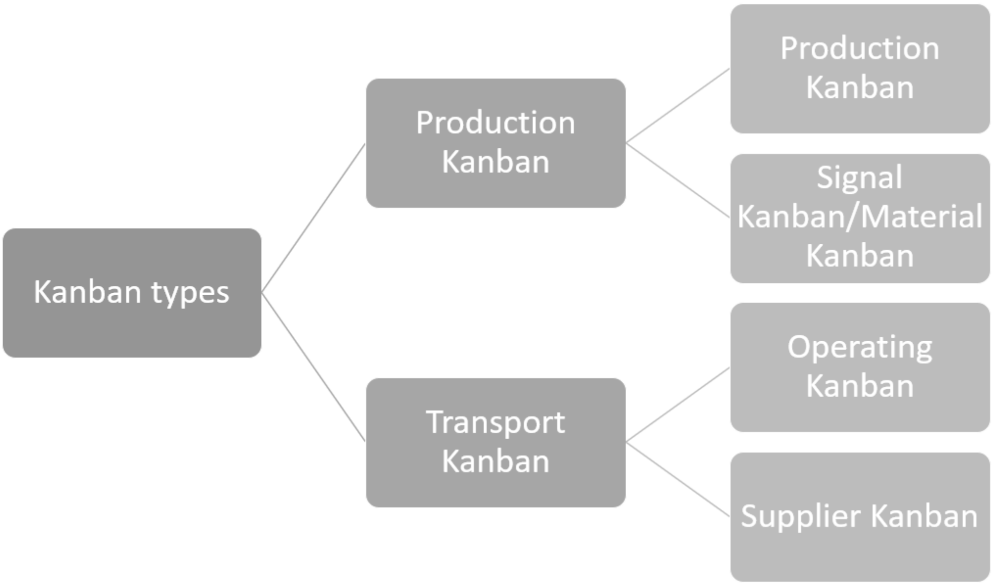
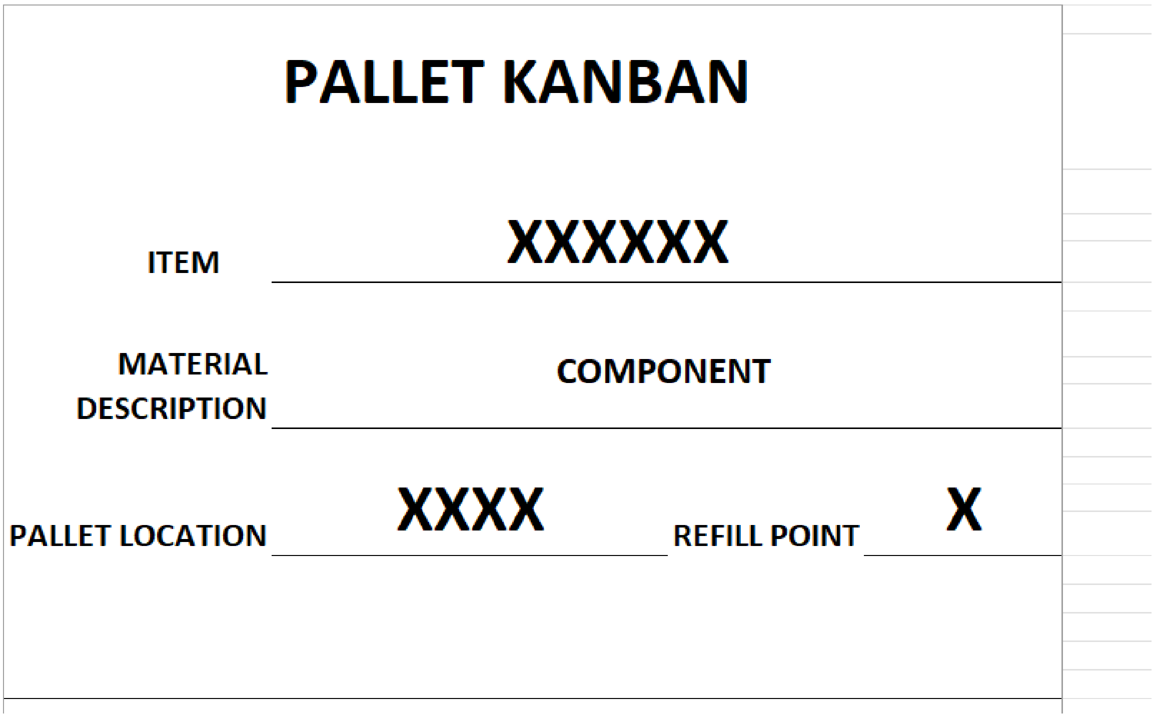


*Figure 9. A classification of Kanban types, adapted from Niemann et al. (2024, 139).*

Production Kanban represents the fundamental model, where the signal initiates a production order for replenishment. Transport Kanban signals trigger a transportation process for replenishment. Supplier Kanban signals initiate a process for replenishment from an external supplier. (Hänggi et al. 2022, 134). While Niemann et al. (2024, 134) classify Kanban systems somewhat differently, the underlying definitions remain consistent. The primary distinction lies in the categorization of Production Kanban, which is further divided into Production Kanban, referring to continuous production, and Signal/Material Kanban, referring to batch production.

Kanban is often used interchangeably with the term "Kanban signals" or "Kanban cards" (Lage Junior & Godinho Filho 2010, 13). These signals, which can be either digital or traditional paper cards (an example of the latter is illustrated in Figure 10). accompany the physical containers in which the material is stored. A digital Kanban signal might involve a scale measuring the weight of a container; when the weight falls below a predefined level, the scale sends a signal for replenishment. Both types of signals share a common characteristic: they have predefined trigger points such that when a certain stock level falls below a predetermined threshold, a signal for replenishment is sent. (Hänggi et al. 2022, 134; Niemann et al. 2024, 140).



**PALLET KANBAN**

ITEM XXXXXX

MATERIAL DESCRIPTION COMPONENT

PALLET LOCATION XXXX

REFILL POINT X

*Figure 10. Example of traditional physical paper version of Kanban card or signal for pallet materials.*

Hänggi et al. (2022, 134) observe that the traditional physical Kanban card remains a common practice. As illustrated in Figure 10. the card contains all the necessary information for replenishment. This card is physically transported from the sink (place of consumption) to the source (place of production or refill) (Hänggi et al. 2022, 134; Niemann et al. 2024, 140). Hänggi et al. (2022, 134) emphasize that in complex and highly variable production environments, the card has the advantage of containing all the necessary information about the item to be re-procured or refilled. They further state that these cards can be used to control the replenishment of even thousands of parts without encountering problems, due to their inherent simplicity. Practitioners often grapple with the question of whether the card should be fixed to the container or not. Academic literature suggests that there is no definitive right or wrong answer; the decision depends solely on the specific situation. The key is to thoroughly consider the organization of the cards and containers and to design the overall process according to the needs of the process. (Hänggi et al. 2022, 134–135).

Hänggi et al. (2022, 135) recommend initiating the Kanban process with traditional cards to launch the system as quickly as possible and realize immediate benefits. Following the initial implementation of the basic card-based Kanban system, the cards can be digitized with barcodes and scanners to integrate Kanban functionality into the Enterprise Resource Planning (ERP) system (Hänggi et al. 2022, 135). Also, Niemann et al. (2024, 141) advise digitizing the Kanban system, when feasible, to eliminate manual bookings in the ERP system and to obviate the need for methods of controlling the circulation quantity of the Kanban cards due to disturbances.

While Hänggi et al. (2022) present Kanban as a plug-in solution suitable for all types of production, Lage Junior and Godinho Filho (2010, 13–14) alongside with Niemann et al. (2024, 140–141) have defined specific conditions for the effective implementation of a Kanban system:

- The material flow must adhere to the flow principle**.** This mitigates the impact of strong demand fluctuations. Failure to meet this requirement can lead to high demand peaks that cannot be accommodated by the Kanban containers, resulting in a disruption of the material flow.
- In production environments with a high degree of product variation, short setup times are essential for economic production.
- Variants or similar products that share similar processing sequences should be produced on a single production line to minimize setup effort.
- To prevent material shortages, a high level of quality control is necessary to detect faulty parts before they enter the process**.** The detection of faulty parts within the process can create supply gaps, leading to line stoppages. (Lage Junior & Godinho Filho 2010, 13–14; Niemann et al. 2024, 140–141).

Although Hänggi et al. (2022) do not explicitly define conditions for a Kanban system to function effectively, they do outline the circumstances under which Kanban is more appropriate for calling parts compared to traditional, push-driven material planning. The decision of when to use Kanban can be informed by inventory analysis, such as the ABC-XYZ classification presented in Chapter 2.3 In general, items with high to medium consumption rates are suitable for Kanban implementation. Conversely, items with low consumption rates and high value (A-Z items) should be provisioned using a demand-driven approach, as Kanban implementation would result in a high stock value remaining unused (Figure 11). (Hänggi et al. 2022, 135–136). Similarly, Mourato et al. (2021, 1935) highlight that a Kanban supermarket supply model is an efficient C-part feeding system for assembly lines, particularly for components with high consumption rates. They advocate for storing items in standard-sized boxes within the supermarket, arranged on shelves according to the assembly operator's needs. When a box is emptied, the assembly operator moves it to a predetermined shelf location for logistics personnel to refill the empty boxes periodically via milk runs.

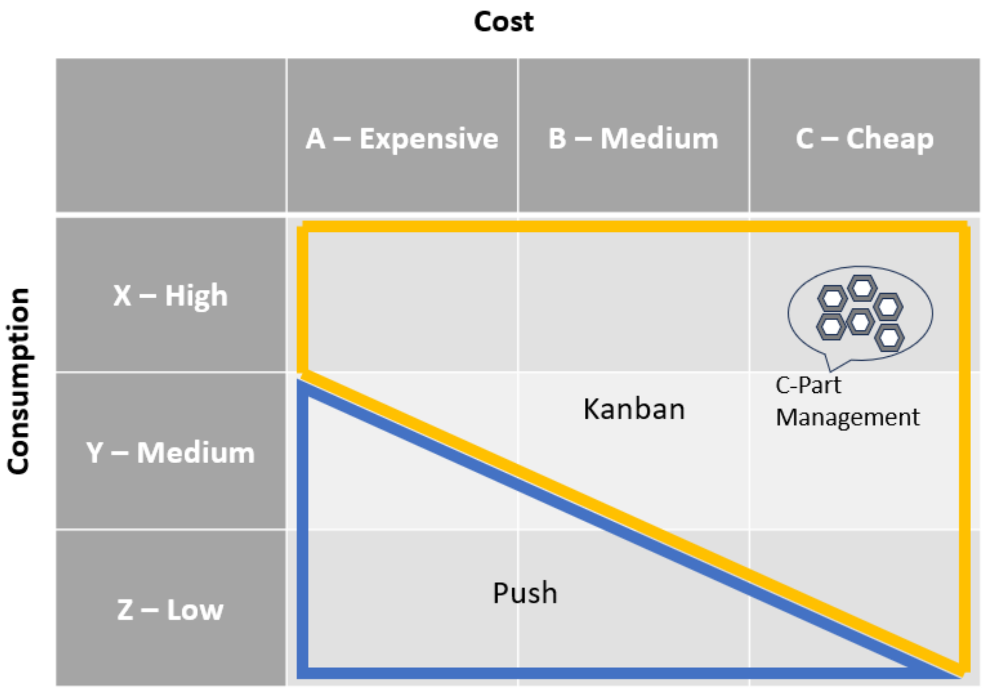


*Figure 11. When to push and when to pull. Adapted from Hänggi et al. (2022, 135).*

Most manufacturing companies utilize common parts, which are classified as C-parts in Chapter 2.3  As previously explained, C-parts are low-cost, high-volume items such as bolts, screws, and nuts. Despite their low purchase price, the high variance in demand can generate significant administrative and logistical effort and expenses. Often, to maintain reasonable stock levels of C-parts, they are purchased in smaller quantities, leading to frequent orders and administrative costs that exceed the order values. An alternative approach involves purchasing in larger quantities, but this increases physical stock levels, consuming scarce storage space. To address this dilemma, the Supplier Kanban system has been developed. (Hänggi et al. 2022, 136–137). There are multiple possible ways to set up a Supplier Kanban, but according to Hänggi et al. (2022, 136–137), one of the most common methods is the two-box replenishment system. In this system, when a refill box is taken into use from the warehouse, an automated order (e.g., triggered by a scanner) is sent to the supplier, who is responsible for replenishing the shelf after the order has been placed. This method benefits both parties. The purchasing party receives on-demand replenishment in optimal quantities with minimal effort, while maintaining FIFO logic. Conversely, the supplier can bundle orders from different customers and/or parts in larger, more economical quantities and plan efficient delivery routes between different customers. (Hänggi et al. 2022, 136–137).

# 4 Assembly feeding systems

## 4.1 Products and the production process

The Product-Process framework (Figure 12) presented by Hayes and Wheelwright in 1979, has evolved into a classic model for illustrating product-process classification. The framework concept was later validated by Spencer and Cox (1995) (Kumar, Tsolakis, Agarwal & Srai 2020, 5). It was designed to assist managers in strategic decision-making by aligning process type with product characteristics, including volume, mix, and demand variability (Kemppainen, Vepsläinen & Tinnilä 2008, 716; Stravrulaki & Davis 2010, 129; Helkiö & Tenhiälä 2013, 217). Hayes and Wheelwright's model emphasizes trade-offs, suggesting that achieving low production costs necessitates reducing product variety and production flexibility while adhering to a dedicated manufacturing process (McDermott, Greis & Fischer 1997, 66; Helkiö & Tenhiälä 2013, 217).

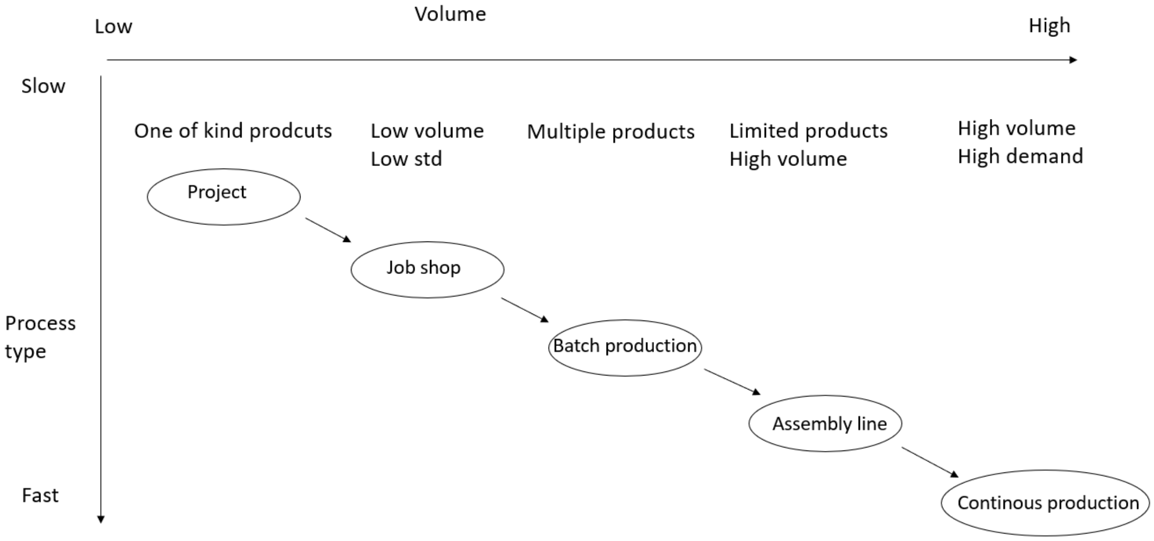


*Figure 12. Product-process matrix, adapted from Hayes-Wheelwright (1979).*

The framework posits that high-volume, low-variance products are optimally suited for continuous processes, while medium-volume, medium-variance items are best suited for assembly line or batch production. Conversely, low-volume, high-variance products should be produced using a job-shop or project-type production process (Kemppainen et al. 2008, 716; Stavrulaki & Davis 2010, 129; Helkiö & Tenhiälä 2013, 217). McDermott et al. (1997, 66) have emphasized that, according to the model, several trade-offs occur when transitioning from a job-shop environment to a flow-shop environment, particularly concerning product variety, volume, market responsiveness, quality, and costs.

Aligning production processes with products in this manner clearly reveals potential issues that arise when products are produced using unsuitable processes. Stavrulaki and Davis (2010, 129) highlighted a common example: firms experiencing growing product volumes without necessary capital investments to reduce variable costs will incur high opportunity costs, as customers may shift their business to competitors offering similar products at lower prices and/or shorter lead times. Despite the widespread acceptance of the framework's normative proposition, empirical evidence regarding the performance implications of the recommended production-process combinations remains mixed (Klassen & Menor 2007, 1025–1032; Kemppainen et al. 2008, 717; Helkiö & Tenhiälä 2013, 217). Additionally, several studies have noted that manufacturers can perform well with product-process combinations that contradict the model's propositions (Kemppainen et al. 2008, 717–718; Helkiö & Tenhiälä 2013, 217). For instance, McDermott et al. (1997, 82) argued that newer manufacturing technologies enable companies to employ a less restrictive set of manufacturing options than those presented in Hayes and Wheelwright's production-process matrix. Jimenez-Partearroyo, Medina-López, and Juárex-Varón (2024, 1496) emphasize the necessity for updating the matrix, given that the adoption of flexible manufacturing systems prioritizing mass customization has become increasingly important for industrial companies in recent times.

## 4.2 Components of part feeding systems

The efficiency of manufacturing operations is a composite of multiple factors. Arguably, one of the most important aspects of manufacturing operations is the structure of parts feeding into the manufacturing process. In general, parts feeding systems can be considered within the scope of in-house logistics. These systems encompass a wide range of processes, from the initial storage of parts to their delivery to the required stations or points of use within the manufacturing area. (Kilic & Durmusoglu 2015, 57). Choi and Lee (2002, 124) emphasize that the actual delivery of parts from the storage areas to the assembly stations or points is controlled by the parts feeding system.

The functionality of parts feeding systems and their main components are illustrated in Figure 13. These systems can be divided into three main components: storage of parts, transport of parts, and feeding policy. Kilic and Durmusoglu (2015, 57) emphasize that these components should not be considered or handled as independent functions or sections due to their close interrelationship and mutual influence. They present that for example, the effectiveness of part storage is dependent on the feeding policy and the available material handling equipment. Kilic and Durmusoglu (2015, 57) have also observed that parts feeding policies are a relatively under-researched area of logistics compared to the other two main characteristics of parts feeding systems.

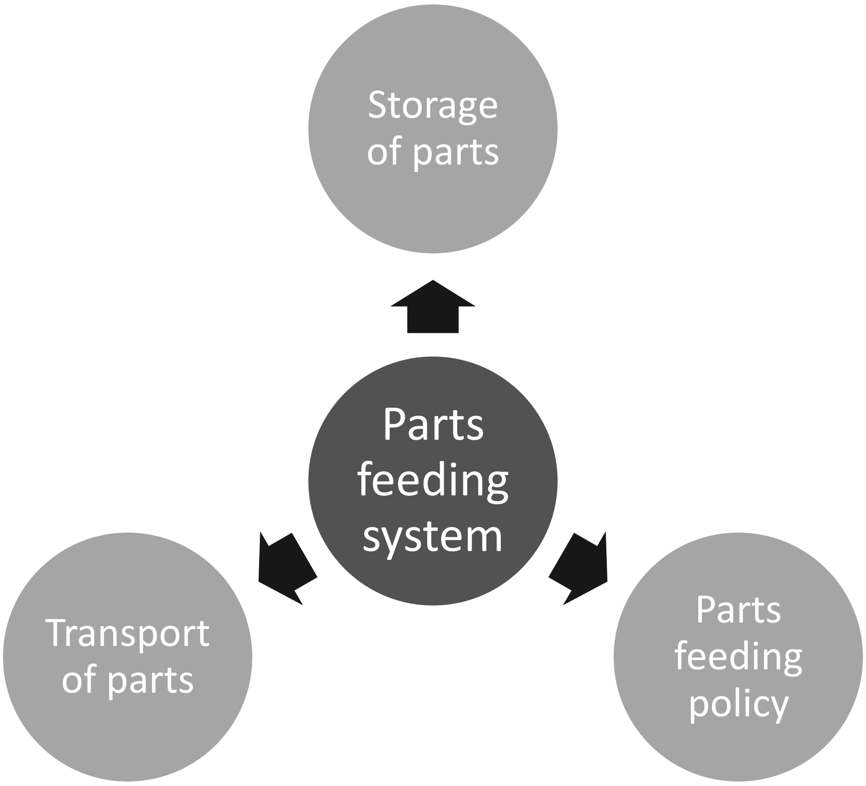


*Figure 13. Structure of parts feeding system. Adapted from Kilic and Durmusoglu (2015, 58).*

The storage of parts, transport of parts, and parts feeding policy can be further divided into subsections, as presented in Figure 14. According to Kilic and Durmusoglu (2015, 57), the storage of parts can be divided into four main subsections: storage type, policies, accessories, and picking methods and policies. Storage types can be characterized as either centralized or decentralized. The decision between centralized and decentralized storage affects various criteria, such as material handling, labour costs, inventory control, and lead time. (Satoglu, Durmusoglu & Dogan 2006). Heragu (2022) has categorized storing policies into five main types: class-based storage policy, cube-per-index policy, dedicated policy, random storage policy, and share-based storage policy. Storage accessories, as the third component, refer to physical storage equipment such as racks, shelves, and storage bins (Kilic & Durmusoglu 2015, 58). The fourth subcomponent is picking methods and policies. Berg and Zijm (1999) have further divided picking methods into two main groups: automatic picking and manual picking. According to them, manual picking can be further divided into batch picking and single order picking.

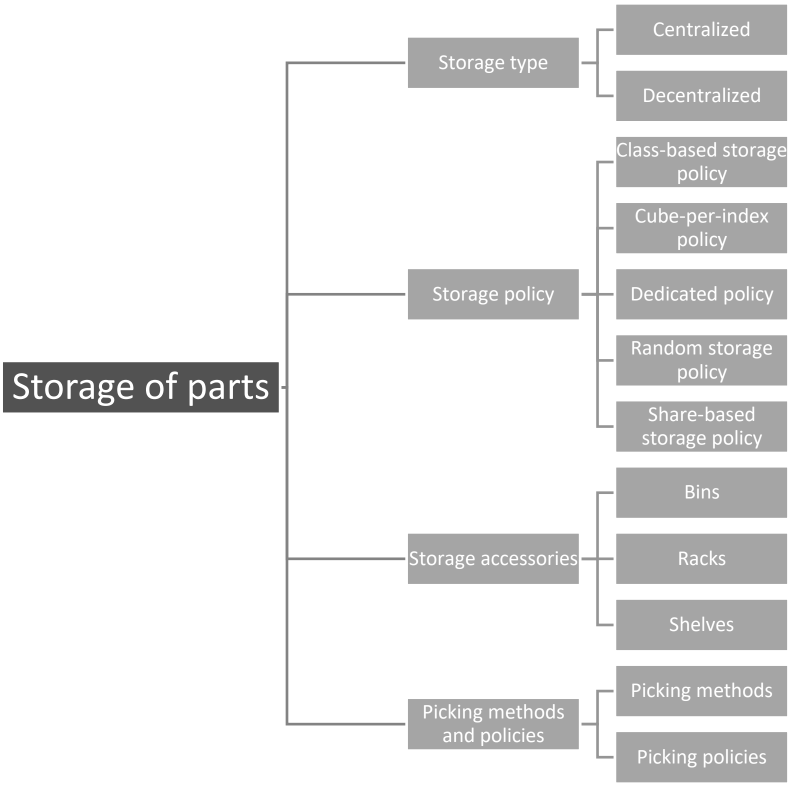


*Figure 14. Subcomponents of storage of parts in the parts feeding system. Adapted from Kilic and Durmusoglu (2015, 58).*

The transport of parts can be considered within the domain of material handling systems, which are a critical factor in reducing production costs (Kilic & Durmusoglu 2015, 58). Drira, Pierreval, and Hajri-Gabouj (2007, 257) have found that costs can be decreased by 10–30 % when an efficient material handling system is implemented. Therefore, material handling equipment plays a vital role in the transportation of parts to the production area. The operational chain of using the optimal vehicle in the right place, at the right time, with the right method for the right part is required for an efficient and effective material feeding system and should be thoroughly considered. (Kilic & Durmusoglu 2015, 58). Regarding material handling, Baudin (2004) has identified forklifts, pallet jacks, pushcarts, tuggers and trains of tow carts, networks of conveyors, and automated guided vehicles as the main material handling devices. In addition to material handling equipment, the movement and routing of materials are also essential aspects of the parts feeding process (Kilic & Durmusoglu 2015, 58).

The third component of a parts feeding system is the feeding policy, which, as its name suggests, is the method of delivering parts to the assembly stations. Different policies offer different advantages and disadvantages, and therefore, the selection of a policy should be considered on a case-by-case basis. In principle, feeding policies can be divided into line-side stocking, kitting, Kanban-based feeding, and hybrid feeding. (Kilic & Durmusoglu 2015, 59).

## 4.3 Line-side stocking-feeding policy

Line-side stocking is used synonymously with terms such as continuous supply, continuous replenishment, or point-of-use storage systems, and multiple sources have identified it as the oldest parts feeding policy (Hua & Johnson 2010; Faccio 2014; Kilic & Durmusoglu 2015, 60). In a line-side stocking policy, materials are stored in individual containers near the assembly lines or at the assembly stations themselves. Materials are distributed to the stations from a central warehouse, such as a supermarket. During distribution, empty containers are collected from the stations, serving as a replenishment indicator. Container quantities are determined by the stored materials and their demand, based on product variance. (Kilic & Durmusoglu 2015, 60). An example flow of this policy is illustrated in Figure 15 below.

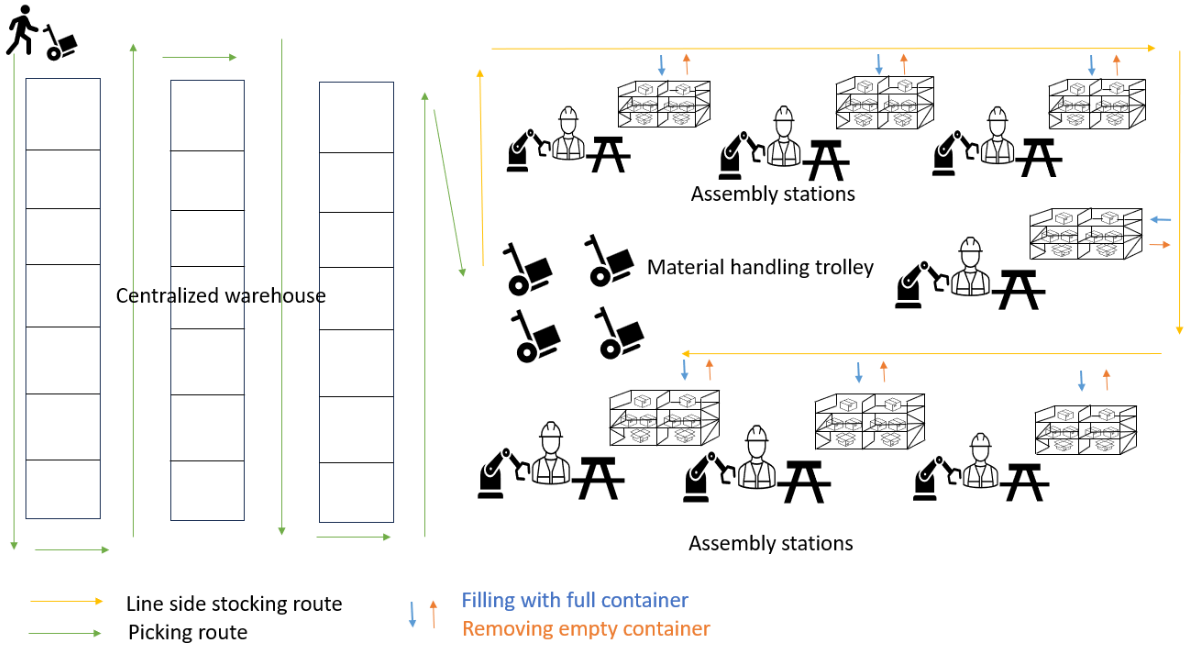


*Figure 15. Line-side stocking policy in practice.*

Kilic and Durmusoglu (2015, 60) emphasize the continuous material availability as the main advantage of line-side stocking. This means that in case of problems with the material, it can be directly replaced from the container. However, Corakci (2009) and Faccio (2014) have pointed out that a high variety of parts used in assembly necessitates a high number of containers, causing the stock to occupy a significant portion of the production area. This, in turn, reduces assembly efficiency due to wasted time searching for the right components. In the line-side stocking feeding policy, the packaging type is a determining factor for the material handling equipment and replenishment type. If the packaging type is a unit load, forklifts are used for material handling within the plant, and a reorder-point inventory system is used for replenishment. If the packaging type is a small box, periodically moving tugger trains on predefined paths are used as in-house material handling equipment, and replenishment is handled with a two-bin inventory system. (Limère et al. 2012, 4048).

## 4.4 Kitting-feeding policy

Kitting is recognized as a common approach in manufacturing environments (Hua & Johnson 2010, 779; Faccio 2014, 546). In general, kitting requires that all components of a finished good are collected before being sent to the assembly line. Kitting activities commonly include warehouse actions such as sorting, picking, counting, and so forth. These activities are commonly performed manually due to the limited mobility and vision capabilities of robots. (Hua & Johnson 2010, 779). Caputo and Pelagagge (2011, 86), along with Faccio (2014, 546), have elaborated that kits are usually prepared in a stock area using a pick list generated from the bill of materials for a specific order and then delivered to the assembly line according to the production plan.

The kitting material supply system has been defined in academic literature as follows: Kitting delivers specific sets of components and subassemblies to the production location, such as an assembly line, in predetermined quantities. Each kit is collected, transported, and stored in specific containers. A kit is a specific set of components and subassemblies that together provide the necessities for one or more assembly operations for a single finished good. Kits can be divided into two different types: stationary kits and traveling kits. Stationary kits are delivered and consumed at a single workstation, whereas traveling kits move along with the finished good and feed multiple workstations before being consumed. (Bozer & McGinnis 1992; Corakci 2008, 19; Limère et al. 2012, 4048; Kilic & Durmusoglu 2015, 61) According to Kilic and Durmusoglu (2012, 229), the main factors in designing kitting systems are the number of kits, the number of kitting workers, and the kitting area.

Kilic and Durmusoglu (2015, 61) state that kitting provides more control and tidiness of the assembly area due to the reduced number of containers for each component compared to the line-side stocking policy. In addition, according to them, depending on the decrease in WIP quantities, less space is required in the assembly area, making kitting an advantageous policy for situations where the number of product variants is high. Caputo and Pelagagge (2011, 103) have noted that if there are not many product variants and components are restricted to fewer types, line-side stocking should be applied. Caputo and Pelagagge (2011, 86–87), Limère et al. (2012, 4050), and Faccio (2014, 546) have identified the following advantages of kitting in their comparison of line-side stocking and kitting:

- Decreased stock levels.
- Less wasted productive work time (searching and movement).
- Easier replenishment timetable planning compared to bulk replenishments.
- Improved working economics.

In addition, multiple sources have noted that kitting leads to increased parts availability while reducing part shortages in the assembly area (Battini, Faccio, Persona & Sgarbossa 2009; Caputo & Pelagagge 2011; Faccio 2014, 546). However, Carlson with Hensvold (2008, 70) and Faccio (2014, 546) emphasize that mistakes in the kit preparation phase or the occurrence of nonconforming parts in the kits can cause interruptions to production or insufficient quality. Kilic and Durmusoglu (2015, 61) have also pointed out that a disadvantage of kitting is the costs generated by additional part handling during kit preparation, and Bozer (2012, 29) states that academics generally agree that kitting is one of the costliest activities in a warehouse. Caputo and Pelagagge (2011, 86) conclude that kitting is well-suited for production with large product variety, such as in mass customization contexts.

The design and optimization of kit picking should consider layout optimization, picking management optimization, kit optimization, and kitting scheduling optimization (Faccio 2014, 546–547). de Koster et al. (2007, 487–496) have determined that, regarding picking area layout optimization, the general aim should be to minimize total management and logistic costs, paying attention to the relationships and physical flows between different areas in in-house facilities. This includes optimizing the number of storage blocks, depot locations, the number and dimensions of shelf aisles, and considering the utilization of cross-aisles (de Koster et al. 2007, 487–496). In picking management optimization, the primary focus of research is to minimize the total travel distance, or the total time used for picking. This is typically achieved through the definition of appropriate picking policies, the appropriate storage assignment, and the optimization of the picking sequence. (Faccio 2014, 547).

According to Corakci (2008, 25), the amount of time spent in unproductive movement while searching for components can be reduced through kitting. Hanson and Medbo (2012, 1123) have identified that, in terms of kit optimization, presenting parts in a logical order according to the assembly sequence can further reduce searching and sorting time. Furthermore, their study demonstrated that kitting could increase productivity and material availability compared to a Kanban feeding system, in which parts are stored and provided in containers. In addition, the training process is simplified, which reduces the training costs for assembly workers. Ergonomic aspects should also be emphasized when determining the composition of kitted parts. (Faccio 2014, 547). Battini, Faccio, Persona and Sgarbossa (2011) found in their study related to ergonomics that large and heavy parts require kitting to reduce space occupation and ergonomic impact at the assembly station.

The sequencing of production at assembly lines is influenced by the scheduling of kitting preparation. In a mixed-model assembly line production environment, the production sequence has a significant impact on the workload at the assembly station. Several studies have demonstrated that the kit preparation scheduling issue can be addressed by optimizing assembly line sequencing to reduce the variability of station workloads, thereby increasing assembly line production and reducing WIP stock levels. (Battini et al. 2009, 357–358; Azzi, Battini, Faccio & Persona 2012, 6096; Faccio 2014, 457).

## 4.5 Kanban-based feeding policy

Kilic and Durmusoglu (2015, 62) have defined the Kanban-based feeding policy as consisting of supermarkets, which are decentralized storage areas serving as intermediate points between the central warehouse and the assembly lines or areas. These supermarkets are intended to replenish the assembly stations through the constant replenishment of consumed parts, which are pulled by the Kanban system. In this policy, the supermarket containers should only contain materials required for the assembly of the final product, and a Kanban card containing all the relevant information regarding the related part should be attached to each container in the supermarket. (Faccio 2014, 545–546). Chaouiya, Liberopoulos, and Dallery (2000) have verified that the delivery of components based on a Kanban system is an effective control mechanism for assembly feeding systems, a finding that has been corroborated by Caputo and Pelagagge (2011, 89). The main points of focus in designing a Kanban-based feeding system are the definition of the required Kanban and the supermarket layout and design (Faccio 2014, 546; Kilic & Durmusoglu 2015, 62;). The most common metrics used in Kanban quantity optimization are the average cumulative throughput rate, the minimization of average production lead time, and the average WIP (Sendil Kumar & Panneerselvam 2007, 399–400; Kilic & Durmusoglu 2015, 62).

Kanban-based feeding optimization can be divided into long-term and short-term considerations. First, location planning, i.e., determining the number of supermarkets to use and their optimal placement, should be carefully considered. In addition, the contents of the supermarkets should be determined according to the needs of the assembly lines. Second, handling resources should be defined, such as deciding the number of handling operators assigned to each supermarket and the assembly stations to be fed per operator, along with the route from beginning to end in the supermarket. Third, operator scheduling and routing should be optimized by determining the optimal point for each stopover on every route. Lastly, loading should be optimized, meaning that the number of parts managed by each assembly station should be decided, aiming to optimize the number of parts at each station while minimizing inventory without running into part stockouts. (Emde & Boysen 2012b, 394–395; Faccio 2014, 547–548; Kilic & Durmusoglu 2015, 62). As studies have focused on Kanban number optimization, these studies have mostly been conducted in JIT systems (Sendil Kumar & Panneerselvam 2007, 405).

## 4.6 Hybrid feeding policy

Different kinds of production models and environments have different demands; therefore, there is no single feeding policy that suits every production environment. As a result, academic discussions present differing statements regarding the superior policy (Hua & Johnson 2010, 782). Kitting has been promoted by Ding (1992, 42–43) and later by Carlson and Hensvold (2008, 70), but conversely, studies by Henderson and Kiran (1993, 48), along with Field (1997, 42–44), have found line-side stocking to be a superior feeding policy. Given the existence of contradicting studies regarding feeding policies, multiple studies have been conducted comparing the existing policies in different manufacturing environments (Bozer & McGinnis 1992; Hua & Johnson 2010; Caputo & Pelagagge 2011; Faccio 2014; Kilic & Durmusoglu 2015). Throughout the academic discussion, a few key factors have been identified as effective measures in selecting a feeding policy, which are: product and component volume, variety, and size; component storage and material handling; production control methods; and the system of operational performance (Hua & Johnson 2010, 785–797; Kilic & Durmusoglu 2015, 63). Similarly, Mourato et al. (2021, 1935) have pointed out that supply models are often decided according to the characteristics of each type of material supplied. According to them, typical factors affecting the decision are weight, size, and consumption rate.

As a result of the multiple factors affecting the choice of a feeding policy system, some studies have developed hybrid feeding policies, which involve the simultaneous application of multiple feeding policies. Hybrid feeding policies are based on classifying parts and choosing the best feeding policy for each individually classified group. Part classification can utilize methods such as ABC classification and the economic value of the components, which is also known as the Pareto principle. Hybrid delivery policy identification is carried out using the sequence X/X/X, where X indicates the chosen feeding policy for the related component class. (Caputo & Pelagagge 2011, 94–96; Kilic & Durmusoglu 2015, 63). Hybrid feeding policy can be considered a relatively new policy compared to others, according to Kilic and Durmusoglu (2015, 63), since the first research on hybrid feeding was conducted by Caputo and Pelagagge in 2008, titled "Analysis and optimization of assembly lines feeding policies," presented at the MITIP conference in Prague.

# 5 Current state of the case company

This chapter presents an analysis of the organization's current situation, and the challenges associated with its existing operating model. The assessment of the current state is informed by the author's observations and experiences within the company over a period of two and a half years, supplemented by discussions with key stakeholders across the organization. The analysis employs the theoretical frameworks and methodologies outlined in Chapters 2 and 3 Initially, a general overview of the plant layout and the small motor production area is provided, alongside a discussion of the underlying principles guiding the development of the new production area. This section serves to contextualize the thesis, providing a foundational understanding for subsequent decision-making processes. Following this introductory overview, a detailed analysis of the current state of warehousing and in-house logistics is presented.

## 5.1 Overview of the operations and the plant

The case company's facility currently encompasses two distinct manufacturing areas: one dedicated to the production of small electric motors (SM), and another focused-on power electronics (PE) and inverters. Figure 16 provides a schematic illustration of the plant's existing layout. The two production lines are physically separated by an automated warehousing system, a service provided by an external supplier.

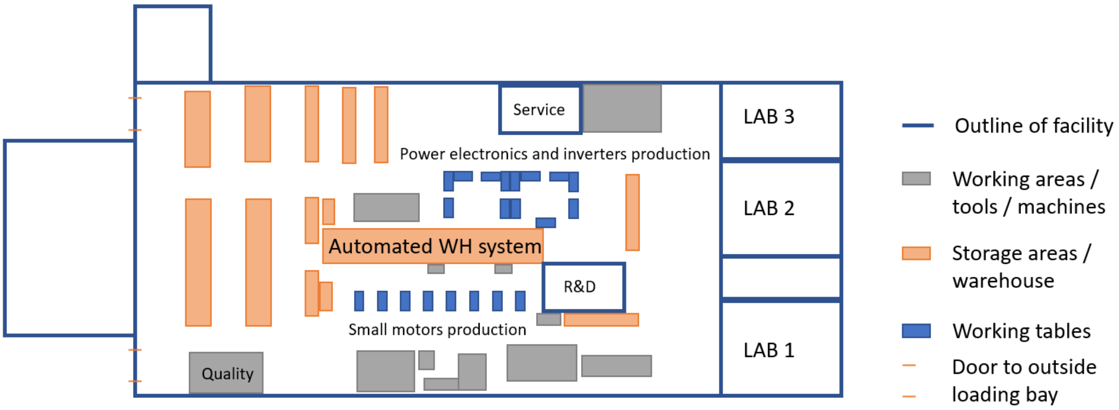


*Figure 16. The current plant layout of the case company is illustrated schematically.*

The current SM manufacturing area comprises individual workbenches where operators assemble the final product from its constituent components (refer to Picture 1). In reference to the Figure 12. Product-process matrix, adapted from Hayes-Wheelwright (1979), as depicted in Figure 12 the current production model aligns with characteristics of both job shop and batch production. The production mix is characterized by a high degree of variation, with frequent introductions of novel variant combinations, indicative of a job shop environment. Conversely, batch production also occurs, driven by increased volumes of specific variants produced in batches. In the current operating model, smaller components are kitted prior to assembly, while larger components are delivered to the assembly table in a kit according to JIT principles.

*Picture 1. Current SM production area before the project.*

To illustrate existing inefficiencies within the production process, a spaghetti diagram was developed to visualize bottlenecks and unnecessary operator movements during assembly. Figure 17 presents a simplified representation of the on-scale layout version of this diagram. As noted by Mourato et al. (2021, 1933) in academic section, the spaghetti diagrams are an effective tool for minimizing waste in production systems or warehouses by illustrating the static situation, albeit without capturing the dynamic elements that typically influence logistics systems. Consequently, they are considered essential for tracking operator and product movements, facilitating the identification of non-value-adding activities that warrant minimization.

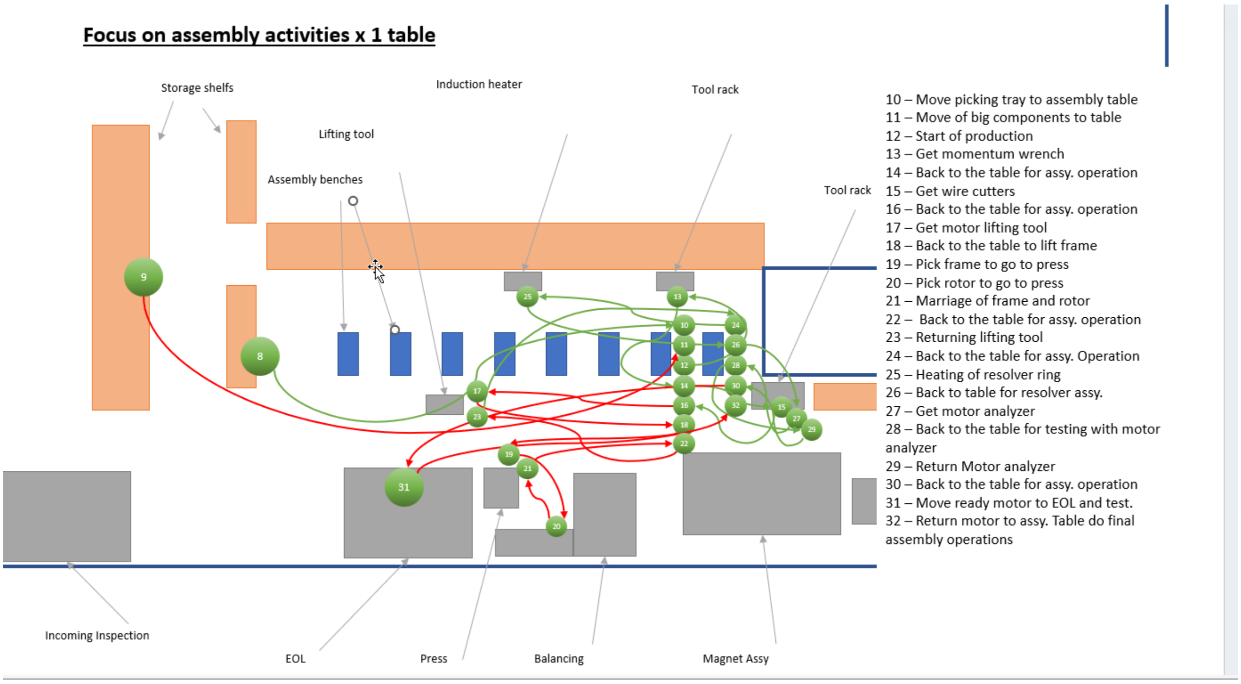


*Figure 17. Spaghetti diagram of assembly process in the current state.*

The diagram reveals significant back-and-forth movement, coupled with a lack of a clearly defined process flow. The primary causes of these movements were frequently observed to be either the retrieval and return of tools or travel to and from assembly equipment. Furthermore, it was noted that operators often experienced delays while waiting for tools or equipment, resulting in considerable waiting waste.

The analysis led to the conclusion that the existing mixed production system would not achieve the established targets, necessitating a transition to serial production. Consequently, a new conceptual layout for the production line was designed, following multiple rounds of layout design and iteration, and is presented in Figure 18. The new layout demonstrates a complete transformation of the production area into a serial production environment with one-piece flow. In this revised production model, assembly workers will remain stationary at their designated assembly stations, and in-house logistics will be responsible for the movement of goods between stations.

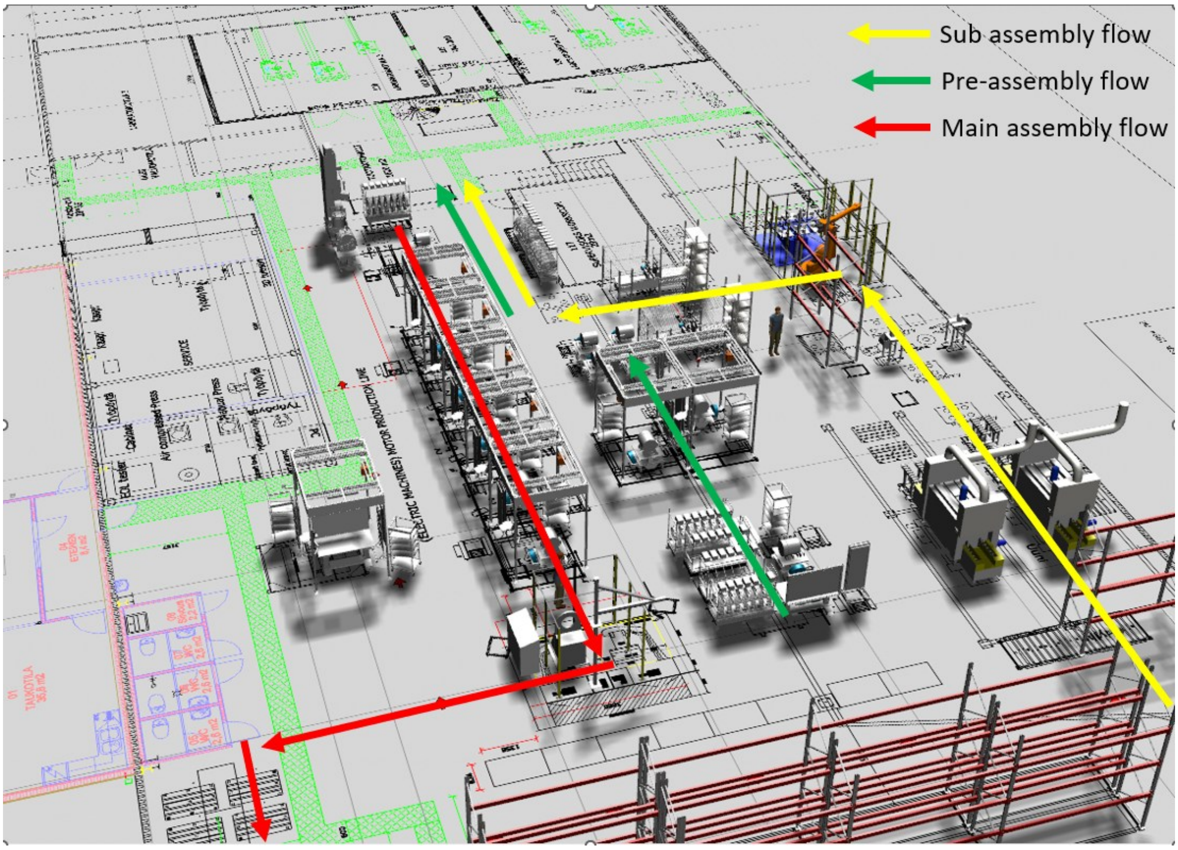


*Figure 18. The new SM production layout.*

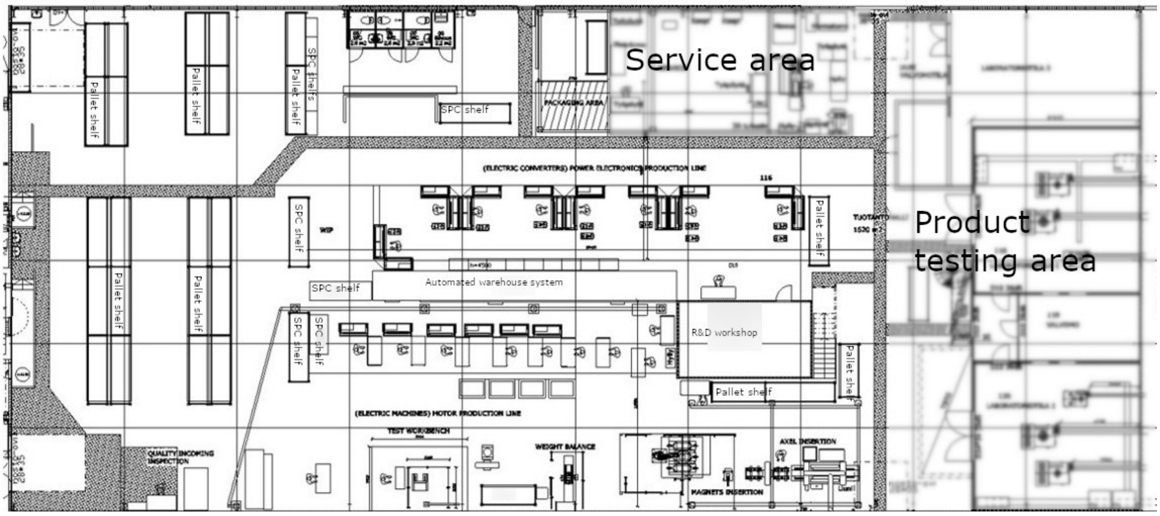
As a result of the new layout implementation, the power electronics and inverter assembly area will be relocated to another company facility, where sufficient space is available for conversion into a production area. This new layout and operating model establish revised operational parameters and requirements for logistics, reflecting the shift from batch production to a serial production environment. The target for the new production line is to maintain the capability to introduce new product variants while simultaneously increasing efficiency and output. The proposed in-house logistics model and associated improvements are detailed in Chapter 6 following a description and analysis of the current state of in-house logistics.

## 5.2 Warehousing and in-house logistics

In academic literature, warehouses have been classified and categorized in various ways. For instance, Bozer (2012, 9–10) categorizes warehouses as raw-material and component, WIP, finished goods, distribution, fulfilment, local, and value-added service warehouses. However, warehouses often encompass some or all these different warehousing types, as well as other activities that fall outside the typical warehousing scope, particularly in manufacturing environments. For example, in the case company, the same warehouse contains components, semi-finished goods, finished goods, and WIP materials.

Warehousing operations at the case company are distributed across multiple locations. The primary warehouse, which supplies the production lines, is currently located within the same premises as the SM, PE, and inverter production areas. The company maintains a secondary location nearby for storing infrequently accessed items and materials received in quantities too large for storage solely within the primary production area warehouse. This secondary warehouse is also responsible for shipping finished goods to customers. Finished goods are packed at the primary production area warehouse and then transported to the long-term storage location to await shipment. In addition to these two locations, warehousing activities are also conducted on a smaller scale at a third company site. This third location houses the production area for large electric motors, where components specific to those motors are stored and received. Smaller components that are also used in other production areas are distributed from the primary warehouse to this location based on demand.

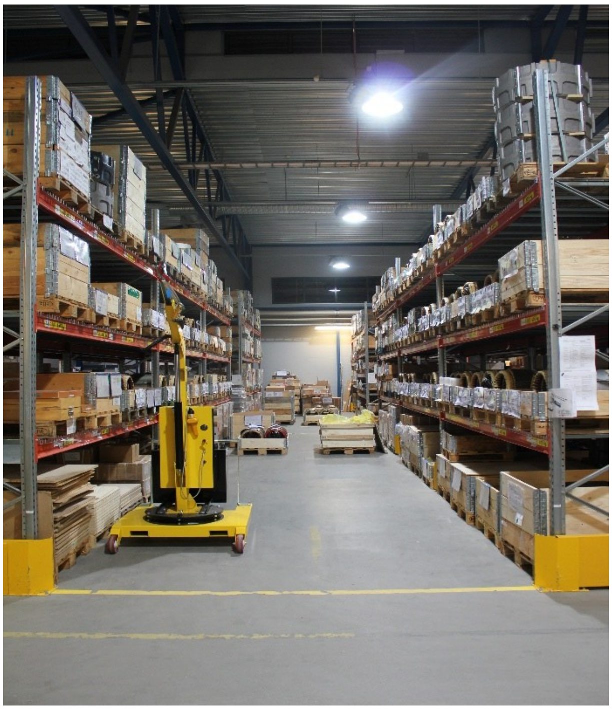
The primary warehouse contains pallet racking, a limited number of smaller shelves for storing smaller, heavy components, and an automated warehousing system. The layout of the primary warehouse is depicted in Picture 2. While the FIFO principle is intended to govern warehousing operations, it is not consistently implemented due to a lack of traceability regarding the relationship between specific batches and purchase orders, as well as the arrival sequence of batches and orders. Pallet rack locations are identified with unique slot names; however, the materials handled do not have designated storage locations. Incoming goods are stored in available spaces within the pallet racks, and pallets are frequently stored on the floor in front of the shelf racks due to insufficient available storage space.



*Picture 2. Current state layout of the case company main warehouse, SM, PE and inverter production area.*

In the case company, the warehouse is responsible for all fundamental warehousing processes, as outlined in the academic literature, including receiving, put-away, picking, packing, and loading. Currently, receiving and put-away represent a significant time constraint for the case company's warehouse personnel. Identified issues include inconsistent, unclear, and variable material marking, naming, and identification practices by suppliers. This necessitates extensive investigation to match received materials with internal material codes and to determine appropriate storage locations within the warehouse. Due to the high product variety, the warehouse contains a large number of similar components that are visually difficult to differentiate. This frequently leads to errors in misplacing items with incorrect counterparts, resulting in the need to re-sort materials when the mistake is discovered.

Secondly, the pallet racks lack fixed locations for materials stored on pallets, and incoming materials are placed in any available slot. This consistently leads to searches throughout the warehouse for the correct materials, as there are no fixed locations or information flows to indicate where materials can be found. The warehouse is also struggling with a significant amount of slow-moving or obsolete materials, leading to a shortage of shelf space and forcing the storage of some goods in the shelf aisles, generating multiple unnecessary movements of the same material (Picture 3). This lack of information flow is also a primary contributor to excess WIP from production, which is returned to the warehouse and occupies valuable space.



*Picture 3. Materials stored on the floor between pallet shelfs.*

Once material is placed in the warehouse, its usage is tracked solely by a pallet card (Picture 4), which indicates the quantity remaining on the pallet. There is no corresponding transaction in the ERP system to reflect the withdrawal of material from the pallet into the production area. This leads to production plans that consistently include items for which all necessary components are not available, as the stock has already been physically allocated to other finished goods, WIP, or has been consumed without being recorded in the system. This lack of recording is often due to errors in the case company's bills of materials. A fundamental issue in the case company is the lack of transparency regarding actual stock levels, arising from discrepancies between the ERP system and the physical material flow. This commonly manifests as production plan failures due to missing parts, which are only identified during the assembly phase by assembly operators.

Material Code [redacted]

Description:
SHIELD N-END
[redacted]

Product family [redacted]/PAINTED

8 ~~10~~ ~~11~~ ~~13~~ PCS

Classified as Business

*Picture 4. Pallet card for information flow.*

In addition to regular receiving and put-away activities, workload and excess material handling are generated by the weekly packing and shipping of materials to an external supplier. Two large components, the stator and frame, are packed for this supplier. These components arrive at the warehouse from different suppliers and are stored separately. Packing for the supplier requires first locating the desired materials for shipment, which is conducted according to the production plan rather than following a FIFO logic. After locating the materials, they must be removed from the pallet shelves and packed for the supplier, with the remaining materials returned to the shelves. The packed materials are then placed in available floor space to await transportation. Upon their return from the supplier, the materials must be re-identified, labelled, and put-away in the warehouse. This process is illustrated in greater detail in Figure 19, where the overall material process flow is reviewed more closely.

Furthermore, the warehouse is tasked with performing several activities that fall outside the conventional scope of warehousing. The warehouse and its personnel are often viewed as a "do-it-all" function in the case company's other functions, to which other departments outsource minor and inconvenient tasks. For example, the warehouse assists the R&D department in gathering project parts without adequate knowledge or coordination and manages the shipping and receiving of project items without the necessary information or contact persons. Additionally, the warehouse performs electrical quality checks on a key component of the electric motor, a task that should be performed by the quality control department, leading to confusion regarding responsibilities in the event of a test failure.

The primary function of the warehouse within the company was originally defined as supplying and servicing the production lines. The warehouse has also been understaffed relative to the required activities. Ideally, it should be supplying the production lines by picking and preparing materials, but the warehouse has been excessively occupied with handling incoming and outgoing materials, as well as other tasks outside of traditional warehousing. Consequently, material preparation and picking have effectively been removed from the scope of warehouse activities. The responsibility for material preparation and picking has shifted to the assembly workers. Utilizing assembly operators for material preparation introduces several issues in material tracking and handling. Furthermore, it represents a form of waste in Lean terms, as the operators are not engaged in their core activities and are not directly producing value.

## 5.3 Material flow and feeding system in the case company

The current assembly feeding system employed by the case company is kitting, wherein two kits are assembled to form a complete stationary kit for a finished good. The kitting process is divided into two distinct phases. In the first phase, smaller components are picked using an automated part-to-picker system and collected into an assembly kit. The second phase involves picking larger components that cannot be stored in the automated system. Some of these components require lifting equipment to be moved into the assembly area.

The initial stage involves small material picking. A material picking list is generated through the ERP system and shared with the automated warehousing system, which operates as a part-to-picker system. An operator initiates the picking process by selecting the appropriate finished good from a touchscreen user interface. The system then presents packages to the operator one at a time, displaying on the interface screen the quantity of items to be picked from each package. The operator places the picked items on a tray (Picture 5), which is labelled with the finished good's material number on its side.

*Picture 5. Two full picking trays.*

The second stage of picking involves the selection and gathering of larger and heavier items, which are stored on pallets. These items are combined as a pallet kit from the pallet racking and transferred to the end of the assembly bench. Subsequently, the frame is lifted with a crane onto the assembly table to initiate the assembly process. The material flow is presented in a spaghetti diagram in Figure 19, which has been simplified from the actual diagram created using the precise plant layout, as suggested by Niemann et al. (2024, 121). Prior to creating the diagram, it was decided to focus solely on the material flow within the primary warehouse, excluding other sites from the scope. The diagram was specifically created to address the material flow, as it had been identified as problematic within the case company through Gemba walks.

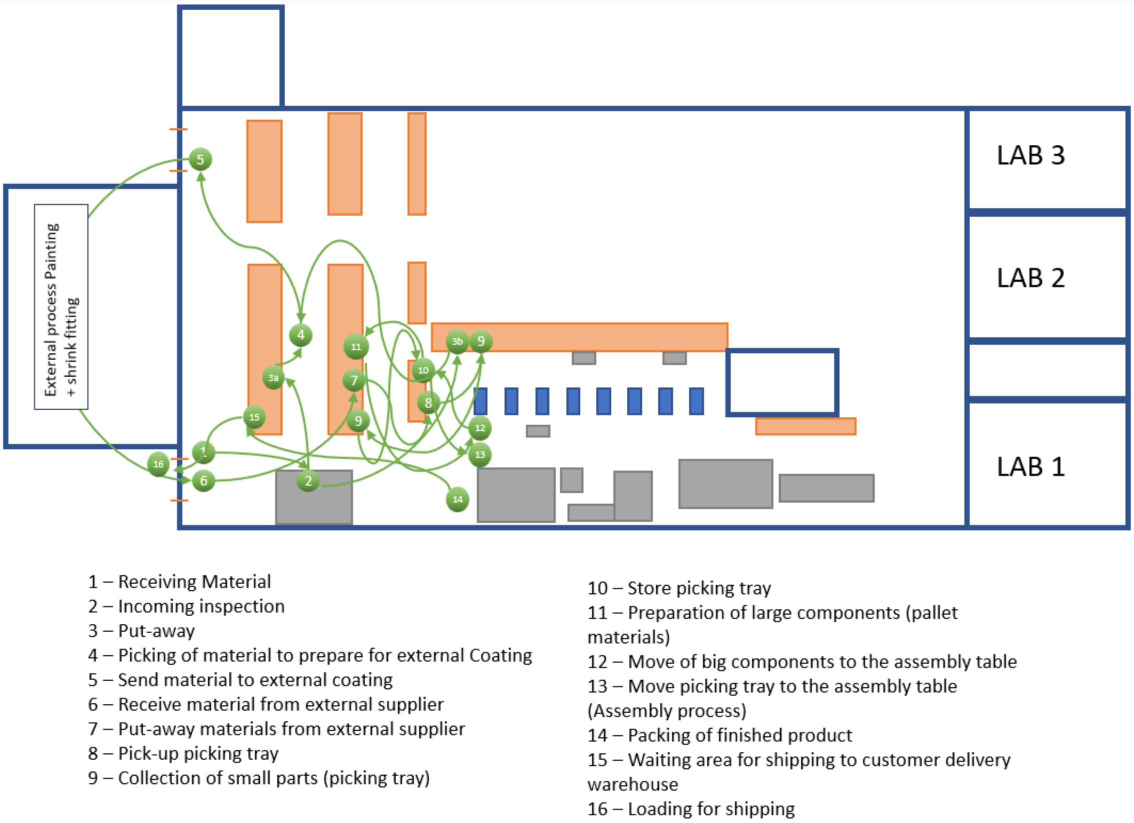


*Figure 19. Spaghetti diagram of the material flow in the current state.*

The spaghetti diagram reveals multiple overlapping movements in the material gathering process prior to delivery to the production area. The diagram exhibits high-frequency, long-path lines and crossing lines, which, according to Niemann et al. (2024, 121), indicate a high degree of waste. This high degree of waste highlights the development potential for the case company to improve its in-house logistics in order to achieve predetermined targets.

## 5.4 Waste analysis and key problems

While spaghetti diagrams provided clear indicators of common wastes such as transportation, motion, and waiting, in conjunction with insights from Gemba walks, more detailed data was required to quantify these wastes. To identify and quantify the magnitude of these current issues within the case company, a time study was conducted on the warehouse operators to obtain reliable data on wasteful activities and to address any internal team biases regarding these issues. To ensure the quality and objectivity of the time study, the data collection was performed by an external certified service provider. The time distribution of the operator's workday is presented in Figure 20.

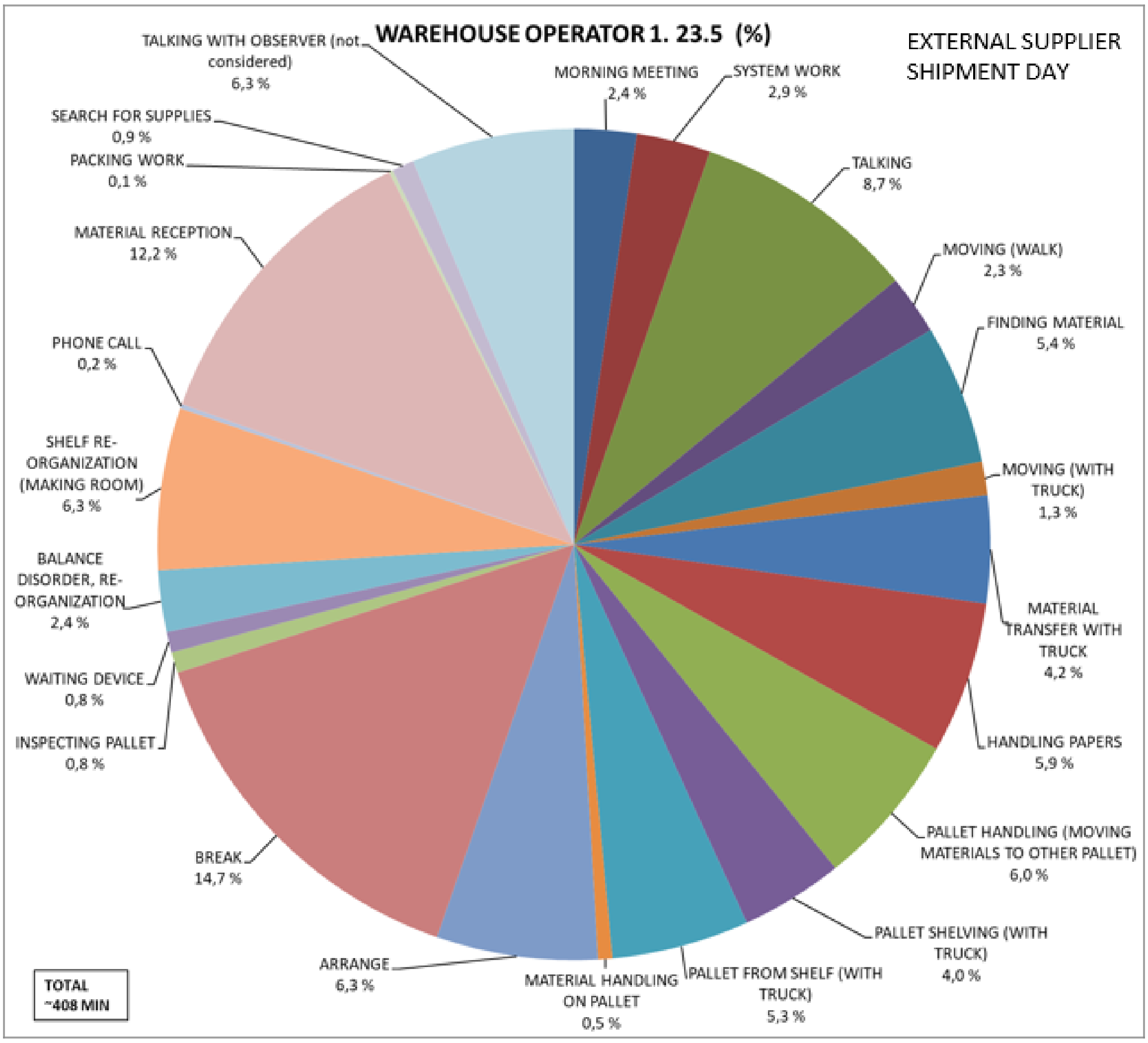
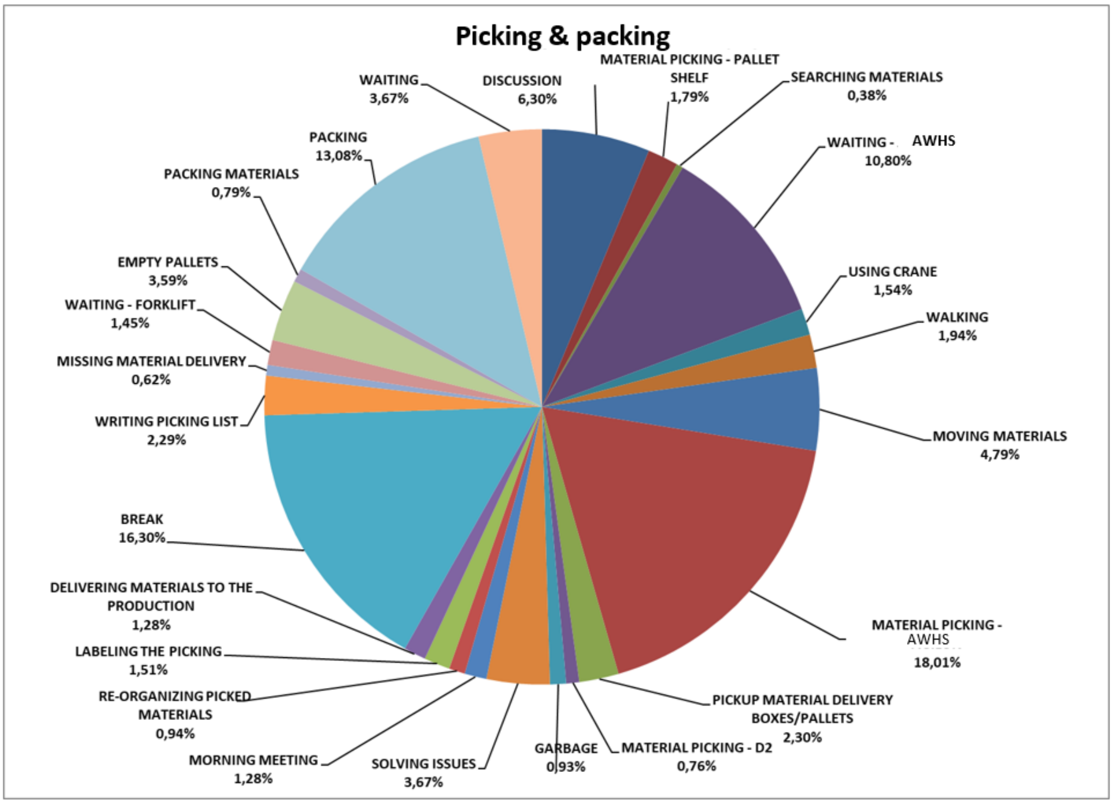


*Figure 20. Time distribution of a warehouse operator.*

The analysis of the time study identified the root causes of waste in the operations. Time studies are a useful tool for capturing the current state of operations, collecting actual times taken for activities, and especially for identifying unproductive activities. Figure 20 reveals the presence of most of the different forms of waste presented in Chapter 3.1 At first glance, waiting, transportation, and motion waste are significant contributors. The current limited space is insufficient to meet production demand, resulting in constant shelf reorganization, movement, and material handling. Lack of space and inadequate information flow also force operators to spend time searching for materials and supplies, as well as handling excessive paperwork. These factors, combined with constant rearrangement and excessive material handling, disrupt the warehouse operator's workflow, hindering their ability to follow standardized working instructions and a daily activity plan. During the analysis, it was also discovered that the lack of information flow prevents the implementation of FIFO logic, leads to missing materials, creates challenges with inventory balance, and causes inefficiency in picking, as optimized picking routes cannot be created without fixed stock locations for materials.

Picking was time-studied separately from the warehouse operators, as it is currently performed by temporary resources including dedicated material pickers and packers, as well as by assembly workers due to a lack of resources on the warehouse side. In addition to picking, the packing of finished goods was also considered, as it is a warehouse process. The results of the picking and packing time study are presented in Figure 21.



**AWHS = Automated warehouse system**

*Figure 21. Picking and packing time study.*

The picking and packing time study shares several similarities with the results presented in Figure 20. In particular, waiting waste is a significant factor. Additionally, excess handling, a lack of information flow, and issues with available space are also observed in both analyses. The study also examined the picking process for three units of finished goods, measuring the entire picking duration. The average picking time for one finished good was 68.42 minutes. Based on the time study, it was concluded that the current picking process is not an efficient method to sustain the desired output of 18 finished goods per shift, as it would require approximately 20 man-hours to complete the picking for a single shift.

Although the sample group was small, it clearly highlighted the inefficiency of the method. The materials picked were relatively common variants with a low number of features. The picking system had been a useful method previously when assembly operators were also performing the picking from the AWHS instead of warehouse personnel. This allowed them to work on assembly operations while waiting for the system to retrieve new material for picking, effectively performing finished good assembly and picking for the next item for assembly in parallel.

Currently, the AWHS is causing significant delays in both the picking and refilling processes. Warehouse operators must wait for each material box to arrive individually and manually input the put-away quantity into the interface. This same information must also be manually entered into the ERP system, as the AWHS and ERP system only have a one-way information connection for withdrawals from the AWHS system. In addition to the system's slowness, it is prone to errors, which further reduces its capacity and can even lead to shutdowns when material extraction is not possible. The system also contributes to excess handling, as packages are stored and retrieved separately, requiring manual removal of empty boxes and manual combination of some packages. The system's poor information flow and the need for constant manual adjustments also cause discrepancies between physical and system stock balances, generating more work for managers to identify root causes and resolve the issues, often leading to material unavailability when needed.

Currently, because material preparation is the responsibility of a larger number of individuals, more time is spent searching for materials in the warehouse. This is due to the lack of fixed locations for items and the fact that assembly workers and material pickers are not aware of where items are placed upon arrival at the warehouse. As more people have access to the warehouse, issue and reverse tracking of actions becomes more difficult, leading to increased costs and man-hours for supervisors and managers due to poor information flow and control over material withdrawals. During the in-house current state analysis, relevant parties and observations from Gemba walks highlighted that missing parts situations from either the warehouse or the assembly area is significant performance constraint, contributing to excess WIP in the already limited warehouse and operational space. In addition, the absence of necessary parts leads to inefficiencies, such as the need to transport WIP items back and forth, as well as store them. In the worst-case scenario, this results in delays and waiting waste, requiring the preparation of additional kits to resume assembly work.

The most common cause of WIP was material shortages, where assembly had commenced but missing materials were discovered during the process, or were not even in stock. To determine the root cause of these missing materials, a master data analysis was conducted on the bills of materials (BOM) for the finished goods. The analysis revealed that only approximately 35% of all used bills of materials were 100% accurate, while 65% contained incorrect quantities, mismatches between items, or missing items. This BOM issue generates WIP, as the systems indicated that all materials should be available, but the systems either did not include all the materials used or indicated that incorrect materials should be used.

# 6 New in-house logistics system

When developing new operational methods, it is crucial to identify the necessary changes and their underlying rationale. The identified root causes should serve as key guiding principles during the planning and implementation of changes. For the case company, the core improvement topics are material availability in production to reduce WIP and improve production plan performance. Material availability is closely linked to control points within the process and the integrity of information flow alongside the materials, which are currently insufficient in the case company.

The second key point is efficiency, with the goal of increasing the production capacity of the production line from 4.5 units to 18 units per shift while maintaining the same man-hours as in the current state. This also necessitates increased efficiency and output from the warehouse to effectively supply the production line. Achieving efficiency requires clear indicators of what needs to be done, when, and by whom. Therefore, the third key point is standardizing warehouse processes and work, enabling clear responsibilities and priorities for warehouse personnel to focus on and prioritize the most crucial activity of the warehouse: feeding the production line and ensuring timely material availability.

## 6.1 Inventory classification and material storing system improvements

For the case company, the time study clearly demonstrated that the current picking method utilizing the AWHS was an inefficient way to handle picking with increased volumes. The decision to discontinue the use of the AWHS raises a logistical question: where to store the parts (approximately 1600 unique material numbers), and how to manage the put-away and feeding processes for assembly. To define an effective approach for storing the smaller parts, an inventory classification was conducted, as this had not been previously practiced in the case company. The ABC/XYZ method was selected for the classification because the current state analysis revealed that only unreliable and inconsistent data was available. Therefore, a simple material classification would be the most effective way to ensure effective component management in the short term.

The material classification for the new operating model was customized from the presented ABC/XYZ model. Given the lack of reliable data for material consumption presented in previous chapter, the classification could not be strictly mathematically calculated. Therefore, the classification was based on a rough rule of thumb, considering unit price and yearly consumption while accounting for inventory adjustments. In addition, the criticality of components to production was considered, along with their lead time and the severity of the impact a material shortage would have, whether it would affect only a few variants or most of them. This criterion was added to the review because it was identified as crucial in terms of material availability.

Based on the descriptions of the classification groups defined by Stojanović and Regodić (2017, 36–37) in page 28, several key points from the material classification were noteworthy (Figure 22). Firstly, only a small number of materials fell into the AX category. The expensive components were mostly classified as AZ materials, as they were typically customer order-based and often unique to the finished product. Conversely, a notable number of materials were classified as BX, indicating common consumption without significant fluctuation, as these were often components used across product families. Some variant components were classified as BY, causing balancing issues with availability and inventory, which were highlighted for review outside the scope of this study. The majority of materials (55%) were classified as CY and CZ, indicating low monetary value. However, contrary to the implied minimal operational impact suggested by Stojanović and Regodić (2017, 37), these materials were frequently subject to shortages and interfered with operations due to overly strict material planning, bill of material (BOM) issues, and a lack of sufficient coverage profile.

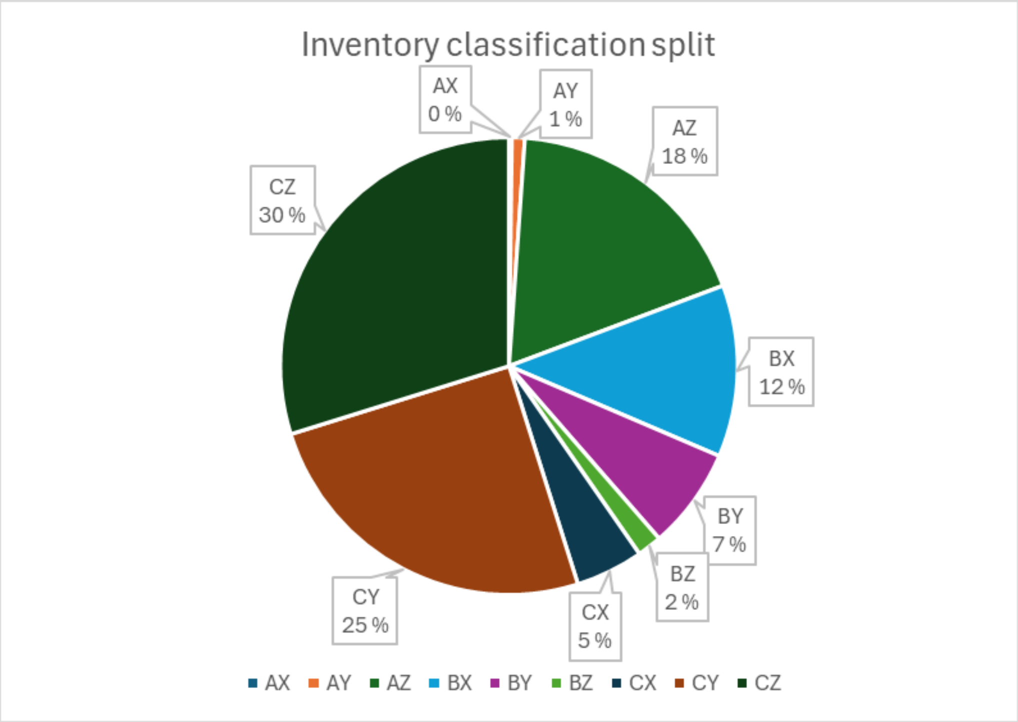
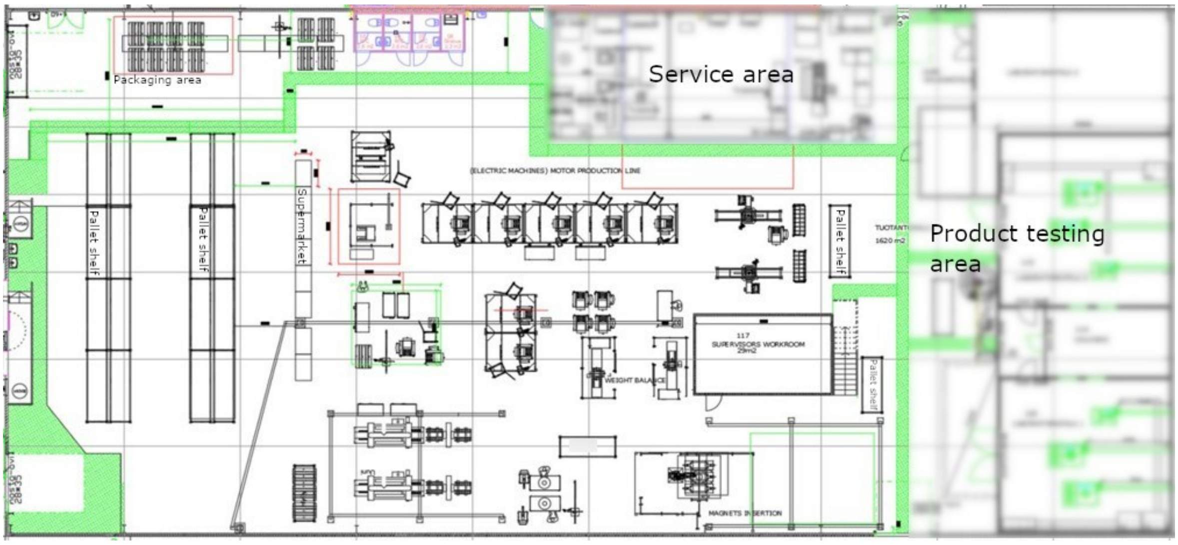


*Figure 22. Inventory classification split in the case company.*

In addition to classifying the parts, the classification enabled a review of the existing stock for materials that had become obsolete or unreasonable to store, as indicated by Pouri and Myerson. Given the case company's struggles with space constraints, clearing out these components is crucial, as is the classification of the components. The process revealed approximately 400 different obsolete materials that could be removed from the warehouse to free up space. Furthermore, the cleanup was not limited to manufacturing-related components. As the company has significant R&D activities, the warehouse also contains numerous project pallets and inventory reserved for these projects. The R&D projects were reviewed, and all inactive projects were removed from the warehouse, with related materials either released for production use, if applicable, or removed along with the project items. The same cleanup process was also conducted for components under the quality department. This cleanup is part of the Lean culture change to enable neat-looking operational facilities, which is a requirement for implementing visual cues for standardization. Without cleanup, the visual cues will be lost in the disorder and be far less effective.

After removing the phased-out and obsolete components to free up space in both the warehouse and production areas, the new warehouse layout could be defined (Picture 6), as the required physical space for component storage was determined. The new warehouse layout consists of a supermarket for the smaller components and pallet racking for palletized materials. The layout definition was guided by Lean principles aimed at minimizing transportation and motion waste, while considering the physical space constraints and modification possibilities of the existing facility.



*Picture 6. New layout of the case company main warehouse and SM production area.*

As the new storage system for materials previously held in the AWHS a supermarket was chosen. This would enable efficient storage of a large number of different small materials in a minimal floor space, addressing the lack of space identified as a problem in the current state analysis. The supermarket solution was also justified by the target of increasing material availability and control, which could be achieved by setting up the supermarket with a Kanban two-box system with sufficiently large coverage profiles. The two-box system also enhances FIFO-logic, as items are withdrawn from the shelf based on a pull principle. The quantities for each material per box were defined according to the inventory classification, along with consideration of incoming package quantities. The standard quantity of a full bin was labelled on the box with the material number, description, and barcode for efficient refilling and future inventory counting.

The supermarket utilizes a common solution of flow shelves, where a full box automatically slides into place when an empty box is removed (Picture 7). The empty boxes are placed on the bottom shelf, which flows in a different direction, indicating to the operator on the refill round (milk run) which materials need to be replenished. A naming code system based on shelf and shelf level was created for the supermarket, and a data table was developed to allow the direct identification of each material's location, enabling efficient material put-away.

*Picture 7. Supermarket shelf.*

Information on material locations in the supermarket also enables efficient reorganization of the supermarket for optimal material handling sequences. The space constraint is emphasized in the case company by the fact that empty bin flow shelves could only be implemented on every second supermarket shelf due to the need for available space for unique material numbers and a lack of available floor space for more shelves. The lack of floor space also forced the supermarket to be placed linearly instead of the most efficient aisle setup for picking and refilling, where the shelves are on both sides and the picker moves between the shelves, able to pick from both sides in parallel.

Following the inventory classification, a new warehousing approach was determined for the case company. As Hänggi et al. (2022) suggest, items with high to medium consumption are assigned to a Kanban system, either in the supermarket as a two-box system or, for larger pallet materials, with physical Kanban cards (Picture 8). The physical Kanban cards are placed on the pallet, indicating the picking location, material code, description, and alarm level, as illustrated in the example in Figure 10. Pallets also have a physical card placed between the items at the alarm level, so when the card is reached during picking, it is delivered to a Kanban mailbox, which serves as an indicator for replenishment. For all pallet materials, a fixed location was also defined, with the withdrawing location on the most accessible shelf levels and upper storage places serving as refill buffer locations to improve efficiency and FIFO implementation.

*Picture 8. Pallet Kanban and pull-out racks.*

Pull-out racks were acquired for the picking levels of pallet materials to improve working ergonomics and minimize the material handling equipment needed for the picking process. Pull-out racks also increase efficiency, as materials are more quickly accessible from the pallet. A warehouse map was created, enabled by fixed locations, to guide warehouse operators directly to the correct warehouse section. Regarding pallet materials, the issue of constantly having to handle the materials shipped for the supplier process before assembly was addressed by re-determining the supplier process flow. In the new process, materials are received at the long-term warehouse, where they are sorted and packed together upon arrival to eliminate the excess step of re-handling the materials for the supplier. The shipping process to the supplier was also updated to follow FIFO logic to stabilize the workflow for the operators. Components are only received at the main warehouse directly from the supplier and placed in allocated slots for these AZ materials, limiting the search area for these items. Dynamic location for the AZ materials was required due to the number of unique combinations available. With the dynamic location for these customer-based components, the required space could be decreased significantly, and material receiving, put-away, and retrieval improved.

To address availability issues related to C-parts, different approaches were reviewed to determine the most efficient solution, considering the lack of storage space and the need to minimize administrative work related to small batch sizes. Due to the large number of unique part numbers and multiple suppliers, establishing a traditional supplier Kanban setup was challenging. Therefore, a new supplier Kanban setup was established with one of the suppliers, where the supplier provides a self-service shop either inside the plant or outside the plant as a freight container. In this setup, the supplier owns the stock in the shop and is responsible for replenishment, while the customer has the freedom to decide which components they want to have in the shop and the coverage profile. Given the case company's volumes from the supplier, the shop is rent-free and incurs no extra costs. The ideology of the system is to leverage the accessibility and 100% On-Time Delivery (OTD) performance to review with the supplier whether other components can be acquired and provided by this supplier through the plant shop, thereby eliminating lead times.

For the case company, the only viable solution was an outdoor shop due to existing space constraints inside the plant. A key advantage of the shop container is that the products within are labelled with the case company's material numbers, rather than just the supplier's material codes, simplifying the work for warehouse operators in identifying and retrieving the correct components from the shop. As the components inside the shop are on the supplier's stock balance, this enables a larger safety stock at the plant without physical or financial constraints, ensuring material availability. For the supplier, all orders are automated through the self-service checkout, enabling them to arrange container replenishment as they wish while maintaining the agreed-upon availability level determined by the customer.

*Picture 9. Supplier shop from inside at the plant.*

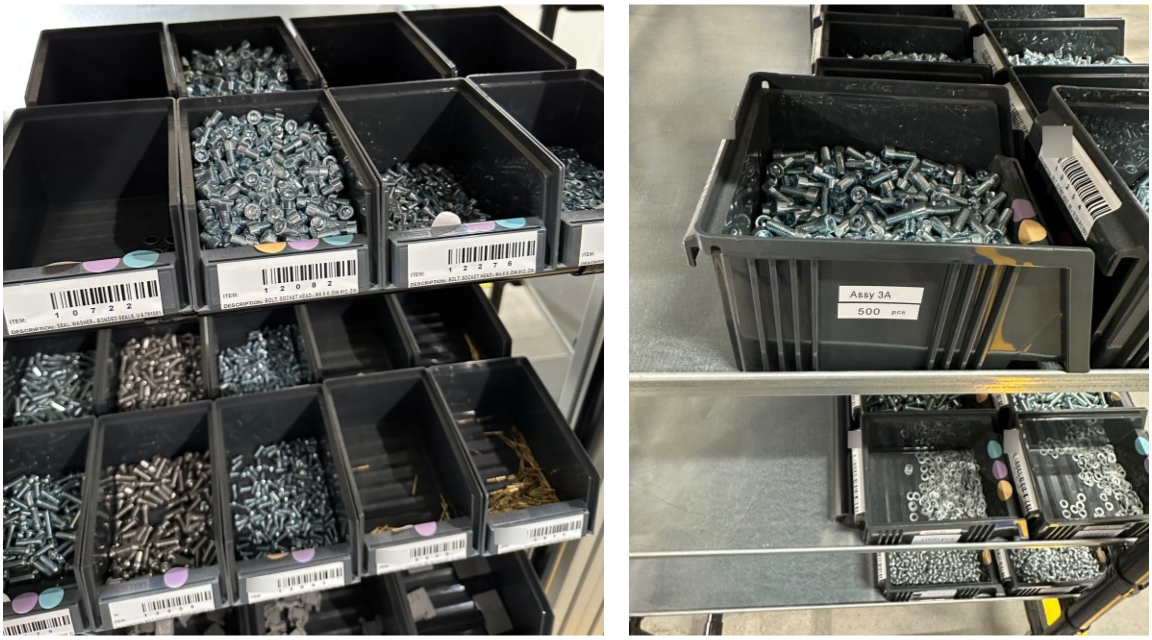
## 6.2 Assembly feeding system

The new one-piece flow with assembly station setup presents opportunities for a more efficient material feeding system compared to the existing setup. In accordance with Lean principles, as outlined by Tortorella et al. (2019, 3650) in the academic part, the existing logistics approach was challenged by initiating the design of a new material feeding method.

This began with an assessment of whether the current kitting method remained a valid approach for ensuring timely material preparation for the required 18 finished goods per shift. As the time study had already indicated, it was clear that the current AWHS would not be efficient enough to meet the new standards, as the system could not be further optimized and picking times could not be improved. Furthermore, the AWHS occupied a significant amount of scarce production area space and divided the layout, causing issues for the planned one-piece flow. As mentioned in Chapter 4.6  key factors have been identified as effective measures in the selection of a feeding policy, including product and component volume, variety, and size, component storage and material handling, production control methods, and the system of operational performance (Hua & Johnson 2010, 785–797; Kilic & Durmusoglu 2015, 63). Considering the case company's production volume, customization, and component storage, along with the other factors, it became evident that a hybrid feeding policy would be the most suitable solution. This is due to the small quantities of each finished good, the large variance in the parts used, and the fact that some components are very large, requiring material handling equipment for movement. Additionally, the system had to be flexible enough to accommodate all variants without changeovers, including the capability to regularly introduce new variants and products.

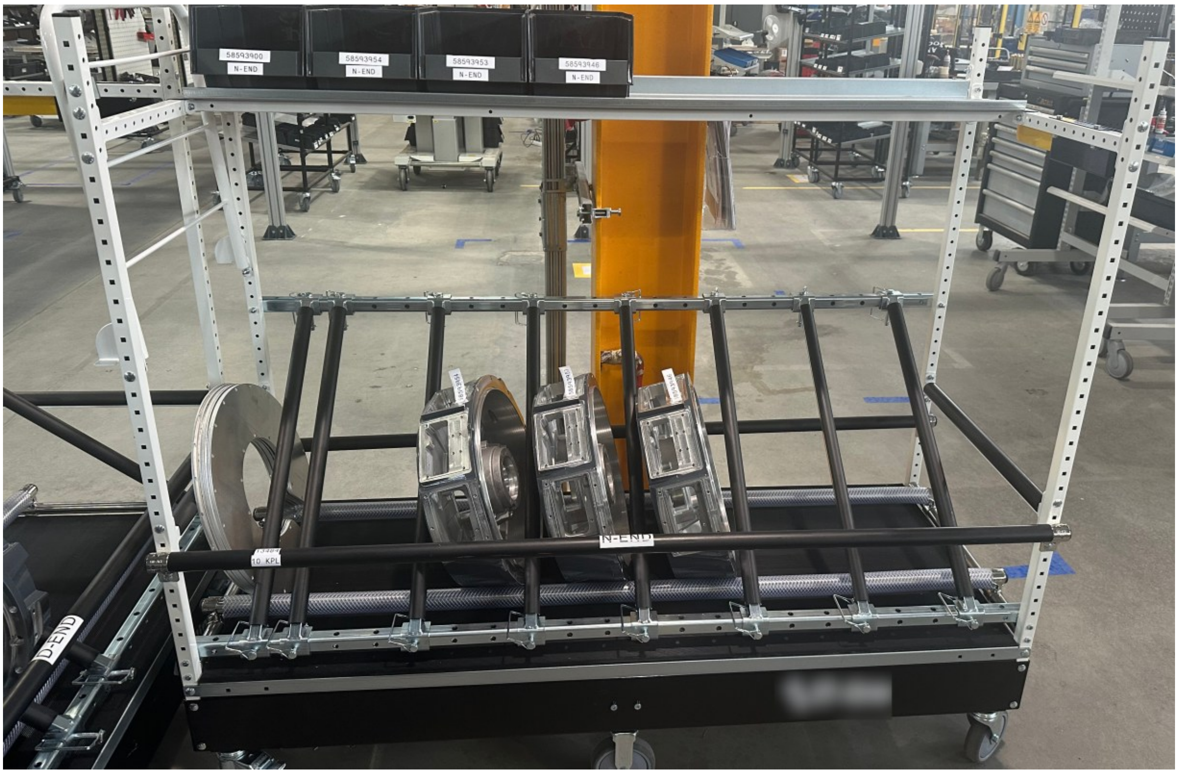
The new hybrid policy consists of line-side stocking, Kanban and kitting. For the stocking policy, only the most frequent components and small pieces from the X-components were assigned to line-side locations. This was done to keep the number of containers at each station reasonable due to space constraints. The stocked materials are stored at the assembly steps in flow shelves, similar to the supermarket, with components having a two-bin setup. For each stocked material, standard bin quantities were determined with sufficient coverage to create standardized refeeding routes and times, which are presented later in Chapter 6.3 The standard bin quantity was defined according to the average consumption based on the inventory classification and the incoming package size. This approach allowed for achieving the desired coverage profile for a certain period and enabled efficient replenishment, as each box is filled with one or more incoming packages to mitigate small piece counting and excess handling.

The line-side stocking of these materials was supported by the emphasis on material availability and control presented in the theoretical framework. Even though the allocated materials for each assembly station were limited, the high variance still resulted in a large number of different materials and bins being assigned to each assembly station. To counter the searching waste, a sticker coding system was developed (Picture 10) to indicate which materials were used in which product families. Each bin is labelled with material codes, a description, and barcodes, along with the family coding stickers. Bins also have a location naming convention, and a standard quantity labelled on the side for easy replenishment and identification of where to return the full bin.



*Picture 10. Labelling on the line-side stocked small pieces.*

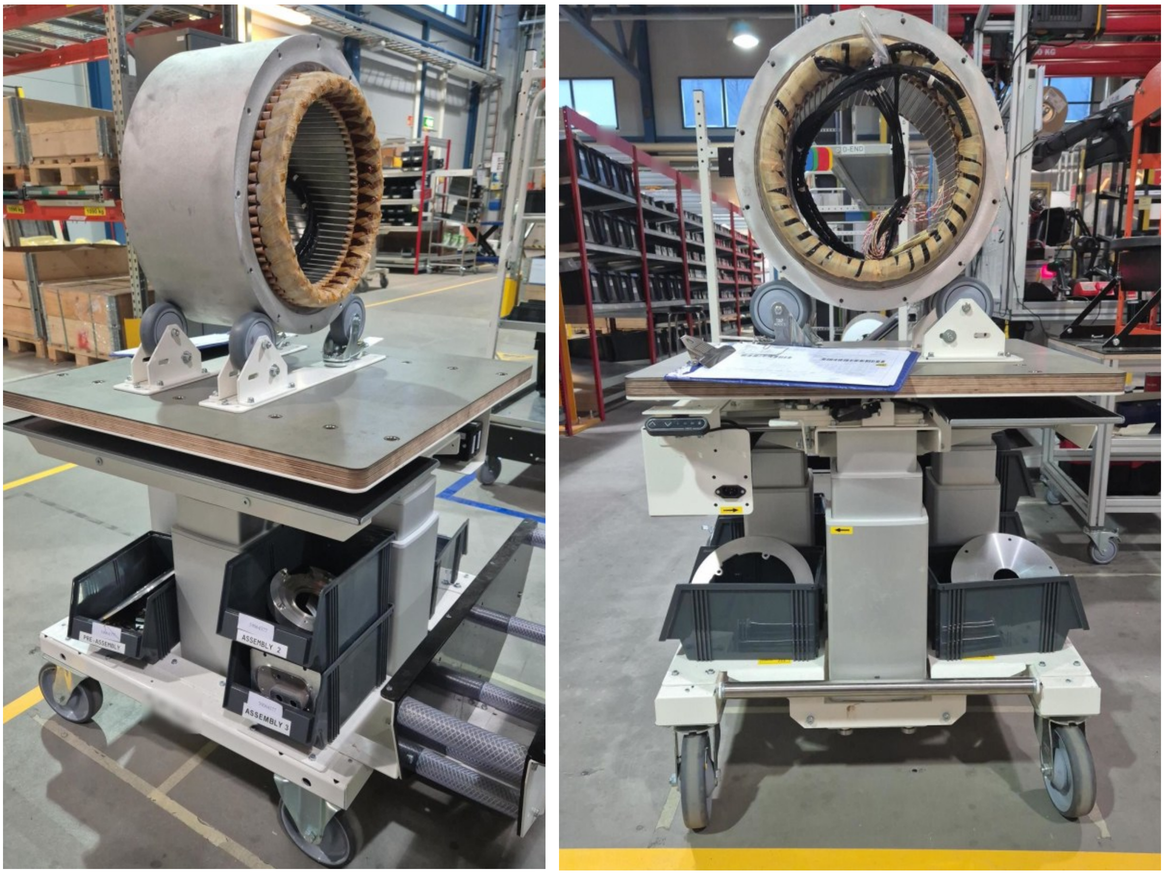
The line-side stocking of BX materials also incorporates some behavioural elements from Kanban, as certain components are delivered to line-side stocking locations using a Kanban setup. These BX materials undergo pre-assembly and therefore need to be prepared before the main assembly process. In the new feeding policy, the BX materials are initially delivered through a separate picking process, as they need to be fed to the sub-assembly process, marked in yellow in Figure 18, and processed before the main assembly. For the sub-assembly process, a kit of smaller parts is also created alongside the larger BX material, with the same unique identification code of the finished good as the assembly trolley kits traveling with the assembly trolley. After the sub-assembly process, the components are delivered to the main assembly process as line-side stocking material in the same delivery cart presented in Picture 11. These carts operate on a Kanban principle, having a predetermined coverage for a certain amount of finished goods at the main assembly station where they are used. The assembly operator initiates a physical signal indicating an empty cart while the spare cart is taken into use. This signal serves as an indication for logistics personnel to perform another round of picking for the sub-assembly process. The sub-assembly process has a determined buffer to cover a full shift, enabling a stabilized workflow for material feeding.



*Picture 11.Material delivery cart for sub assembly process.*

Due to the nature of the products and customer demand, kitting must also be employed to achieve an efficient material feeding policy. As pointed out by several academic sources, it is rather mandatory in a variant-heavy production environment. Furthermore, kitting enables a higher level of control, as control points can be placed within the kitting process, and the process can be stopped before the kit enters the assembly process. Due to line-side stocking, the kitting process is lighter and faster to perform, as time-consuming small piece counting and kitting have been removed, along with the waiting times associated with the AWHS. The materials and quantities needed to be picked are also significantly reduced, as the kit contains mostly medium- and low-volume items that vary based on the product configuration. The small piece kitting was also changed from one large kit, where the operator needs to search for the correct items according to the assembly order, to station-based kitting. The current kitting approach is a mix of stationary and moving kits, as the kits are created according to the usage at each station, but they travel with the finished good.

Each kit is labelled with the assembly station number where it is to be used and the unique identification number of the finished good to which it belongs (Picture 12).



*Picture 12. Assembly trolley with picking bins.*

Therefore, in the new feeding policy, instead of one large kit, multiple kits are picked according to the assembly order, so that each assembly station has its own kit, which contains all the necessary parts in addition to the line-side stocked materials. The kits are delivered to each station on the assembly trolley, which the product flows through the assembly process. The decision to use moving kits instead of stationary kits was driven by the lack of storage space at the stations to be fed directly, due to the high amount of line-side stocked items and lack of available floorspace at the stations. In addition, moving kits also have a smaller risk of being mixed up with other finished goods kits or components due to human error in choosing the wrong kit, increasing control in the process.

The AZ components are placed on the trolley to ensure that the correct unique part combinations are kitted together, minimizing the risk of mixing materials. AZ components also require lifting equipment for handling, minimizing the need for this equipment to be used only in picking and unloading finished goods from the assembly trolley. Physically larger items and more product-specific items were decided to keep as picked materials for several reasons. First, layout constraints necessitate that some of the items be stored further away from the assembly area, requiring a crane to move them. The second reason for picking was product control, to ensure that the correct parts would always be used when the parts have an effect on the fit, form, and functionality of the finished good. The third reason is the highlighted ergonomic improvement achieved when the large and heavy items are managed as picked materials. Due to the desired product and process control, some rather common and small parts were also defined as picked parts to ensure high quality and minimize error waste.

## 6.3 Standardizing the in-house logistics

Often, the most challenging step when implementing changes is ensuring their permanence. There are multiple reasons why new approaches are not permanently adopted, and operating models frequently revert to the original status quo after a period. In Lean methodologies, the human aspect has been generally recognized, along with the requirements for establishing new working models. Lean principles emphasize that, instead of just training individuals to adopt change, relevant personnel are not only trained but also provided with explanations of the rationale behind the changes. They are given tools to answer upcoming questions in daily operations independently or assigned a support resource to contact for resolving larger-scale issues. In addition to training, stability and repeatability are highly desired to create a well-functioning system that does not rely on a single person's capabilities or knowledge.

Repeatability is achieved through standardized operating procedures (SOPs) and working instructions for common tasks, as indicated by the CICMHE's principles in Chapter 2.2 For the case company, which has been struggling with inconsistencies and unorganized workflows, this was mandatory to even establish the new logistics changes presented in previous chapters. While designing the new in-house logistics, a key target was to create standardized processes with a clear workflow regarding when to perform tasks and by whom. For every SOP created, it was also tested with different logistics operators to identify potential missing information and address any arising questions related to the instructions or the process itself. The creation of SOPs also enabled a thorough review of existing and newly created processes, providing an opportunity to further eliminate excess activities and simplify the process to serve the core activities. Stabilized workflows were created for most of the tasks including for example standardized milk runs for the line-side stocked items and the milk runs for the supermarket and pallet Kanbans.

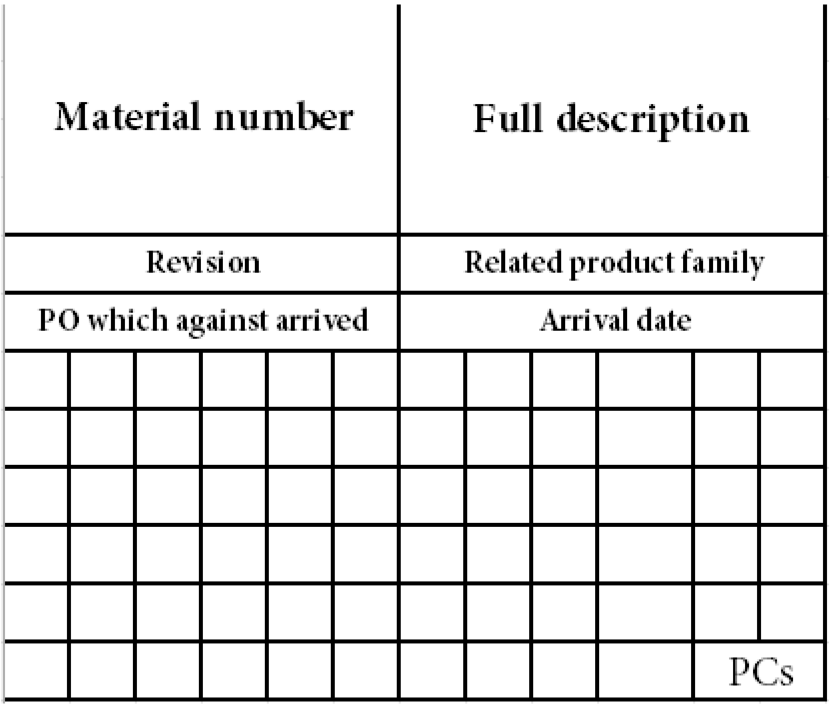
For each milk run, defined intervals were established, keeping in mind the need for flexibility. This allows warehouse operators to plan their daily routines independently, increasing work well-being and facilitating the adoption of the new operating model by removing the constant rush for certain tasks. Furthermore, the picking processes for the sub-assembly and main assembly are initiated using a Kanban-based pull principle with clear physical signals and adequate buffers. These physical signals serve as indicators that new pickings need to be performed within a specific timeframe. The new in-house logistics model also enables operational flexibility by defining intervals for action that allow production to be run in one, two, or three shifts per day, increasing operational flexibility in the long run.

Milk runs are conducted once per shift, with coverage profiles at assembly locations large enough to last one full shift without replenishment. The milk run is performed as presented earlier in Figure 15, The operator begins by collecting empty bins from the reverse-direction flow shelf level onto a material handling trolley, following a predetermined route through all the line-side material storage points. This route is a loop; after collecting empty bins, the same trolley travels through the central supermarket for refilling and then returns to the assembly line route to return the full bins. The route is defined according to Lean principles and the CICMHE's material handling principles, aiming to create the most straightforward loop from beginning to end, passing through the central supermarket. The milk run for the central supermarket is similar to the assembly line feeding milk run, except that the refilling is split into two phases. First, materials available from the plant shop (presented in Chapter 6.1 ), marked with a special label on each bin, are taken to the plant shop and refilled there. The remaining empty bins are taken to the incoming area, where they are refilled when the replenishment is received from the supplier or the long-term warehouse. After this, they are returned to the supermarket. Pallet Kanban replenishment is done based on the Kanban cards posted on the allocated locker. Warehouse operators move the full bins to the picking locations and order fulfilment for the buffer location from the long-term warehouse. After arrival, the Kanban card is placed back in its designated spot between the materials, and the pallet is placed in the buffer location.

Standardized milk runs provide structure, routines, and clear priorities regarding key activities and their required timing. Previously, warehouse operators were managed by the same manager as assembly operators, leading them to operate rather freely, as issues related to assembly operations took priority. As part of the standardization, a dedicated warehouse manager was chosen for the logistics operators, who would serve as a filter for requests from other departments to perform tasks outside of core warehousing activities. The warehouse manager would also be the key contact point for issues arising during warehouse processes, significantly reducing the amount of investigation and solution-finding required by operators compared to before. Dedicated managers are also crucial for Lean implementation and culture adoption, serving as responsible leaders and initiators for new iteration rounds of continuous improvement and waste analysis from existing operations, alongside increasing standardized operations and procedures.

Standardization and guidance are also provided through established daily routine meetings at the beginning of each shift. These meetings serve to identify key activities and assign task responsibilities for the day by the warehousing manager. In addition to reviewing the upcoming day, the daily meetings address potential issues and problems from the previous day, shifting them to the warehouse manager for further investigation and potential acquisition of additional resources and support from the management chain. These meetings also provide an opportunity for warehouse operators to engage and present improvement and development ideas. Daily meetings were established in every warehousing location, with the warehouse manager responsible for leading them. Furthermore, other managers were invited to the meetings as part of Gemba walks to identify potential improvements and challenge existing operating models as part of continuous improvement efforts.

A significant part of the standardization involved increasing the amount of relevant information accompanying the materials to reduce the need to handle papers as a means of information flow. Firstly, a put-away form was included to ensure that all relevant information for following FIFO principles was readily available (Picture 13). The cleanup performed in Chapter 6.1 has enabled a reduction in excess material handling by manually bundling materials. Materials can now be kept in their incoming packages and pulled from the buffer locations to the usage points according to Kanban principles. Furthermore, a new project was introduced to standardize the naming of items and supplier information to eliminate the current issue of identifying incoming materials. The goal is for materials to arrive in the same format regardless of the supplier, easing the receiving and put-away processes.



<table>
<tr><td colspan="6"><b>Material number</b></td><td colspan="6"><b>Full description</b></td></tr>
<tr><td colspan="6"><b>Revision</b></td><td colspan="6"><b>Related product family</b></td></tr>
<tr><td colspan="6"><b>PO which against arrived</b></td><td colspan="6"><b>Arrival date</b></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">PCs</td></tr>
</table>

*Picture 13. New material card for put away.*

Furthermore, changes were made to the ERP system to address issues of visibility regarding actual stock levels. Within the system, the actual warehouse stocks were separated from the production area. In the new process, as items are picked, they are also transferred in the ERP system to the production area using scanners. This provides a clear separation between stock allocated to production and stock physically available on the shelf. A project was also launched to implement a Kanban setup for the line-side stocked materials in the ERP system. This will provide clear indications through the ERP system regarding the status of these small pieces, both on the line and in the warehouse area.

One of the greatest challenges in the new warehouse and assembly feeding setup was preparing for the introduction of new components and products. As new components are introduced, how are they assigned to the correct feeding methods? Previously, in the case company, new components were simply placed in available space in the warehouse and then included in the kitting process, as all components were delivered in kits. Maintaining the required feeding capacity necessitates a revised approach, especially with the potential introduction of new materials such as class X. The inclusion of these materials as components in the kits would lack justification. Therefore, a new component introduction process was implemented. In the new process, relevant stakeholders are gathered before the release of the component to production to review key questions:

1. Does the component replace another material from the existing stock on a one-to-one basis?
2. In which classification category is the new component expected to be placed, based on its estimated annual usage volume?
3. What are the dimensions of the component?
4. What is the most effective warehousing method for the component?
5. What is the most effective assembly feeding method for the component?

These questions provide all the necessary information to make the correct decisions in in-house logistics. Firstly, they determine whether the change will require phase-outs and cleanups from the existing stock, enabling FIFO to be utilized to its full extent and existing stock to be phased out correctly. This point also enables the warehouse to clean up the existing warehouse location immediately. If the subsequent questions allow, it enables the placement of the new component in the corresponding location. The remaining questions are largely self-explanatory for creating an effective new material introduction process for warehousing and assembly feeding setup in in-house logistics.

# 7 Conclusions

## 7.1 Summary

In the case company, in-house logistics had not received sufficient attention and had evolved organically as the start-up-based company grew. This thesis was dedicated to improving and focusing on the logistics side of the company, thereby improving overall efficiency and productivity in both logistics and assembly operations. It has also been identified that the logistics side has been neglected while implementing changes in processes in assembly operations. Therefore, this thesis was implemented as part of a larger project aimed at changing the case company's operation model from job-shop/batch production to serial production for the high-runner product family. The goals of the thesis were to improve material availability on the production line, improve efficiency in warehousing while increasing FIFO logic utilization, and standardize the tasks of logistics workers. Lean and Kanban methodologies, along with various fundamental warehousing techniques, were used as tools to reach these goals.

The current state analysis of the case company identified several key challenges. These included unclear workflows, a lack of guidance, and inadequate management oversight regarding key activities in the warehouse. In addition, the company struggled with space constraints, leading to excessive material handling and constant searching within the warehouse. These issues were heavily related to a lack of information flow alongside the materials, as well as a lack of visualization in the warehouse environment. A third key problem was the constant generation of WIP stock, caused by a lack of correct materials in the assembly area, which further exacerbated spacing issues.

Firstly, a material classification was conducted for the case company, as it had not been previously implemented. Through classification and a review of existing stock, approximately 400 unique materials and 250 physical pallets could be cleared from the stock. Removing materials that were no longer needed enabled the establishment of fixed pallet locations, the creation of a warehouse map, and the implementation of visual cues in the warehouse area. This increased the efficiency of material placement and retrieval while significantly decreasing searching waste. Replacing the AWHS with the supermarket solution reduced the required floor space for small pieces by 65.5 % and resulted in annual savings of €53,500 through the elimination of the system's license. In addition, the average working capital expenditure (CAPEX) tied to materials was reduced by almost €270,000 per month due to reduced stock levels. Monthly working costs were reduced by €5,400 through the elimination of waiting times and improved working efficiency in picking, put-away, and reduction of WIP.

The largest contributors to these improvements were clearing out obsolete materials and increasing material availability through the two-box system, which provided physical control signals instead of relying solely on system-generated alerts to react to material shortages in advance. This physical control allowed for a reduction in actual stored quantities, as there was no need for "just in case" stock due to the Kanban quantities functioning as intended. Thirdly, it is crucial to identify the cost associated with storing materials and allocate it to the correct department. Previously, without this cost transparency, support functions had no incentive to reduce their stocks, as the costs were allocated to production. Putting a price tag on storage and allocating it to the relevant departments' budgets created an incentive for everyone to clean out and stop storing materials "just in case," a common practice, especially in small companies.

For the case company, transitioning from single/batch production to a one-piece flow in a serial production setup also required the definition of a new assembly feeding system. Previously, the picking process was cumbersome, with an average picking time of 68.5 minutes per finished good. Picking was conducted in two phases: larger components were gathered on a pallet, and small pieces were placed on a tray, where all components were thrown in without fixed locations. Both kits were combined and delivered to the assembly station, functioning as a stationary kit. The design target for the new assembly feeding system was to create a light and fast process that could be performed with the existing workforce to meet the needs of increased production capacity. As a result, the picking process was separated into multiple kits, according to the assembly steps. The kits are placed on the flowing assembly trolley and travel with it through the process. Station-based kits could not be implemented due to a lack of storage space at the assembly stations. On the other hand, the traveling kits offer far more control and a smaller risk of being mixed up with other kits, which was one of the identified goals of the case company.

By significantly reducing the amount of picked materials and increasing the use of common materials (Figure 23), the new assembly feeding system can provide a kit for assembly in 23 minutes. It is important to note that this performance level was achieved during the initial picking rounds testing the newly created setup. The picking layouts can still be improved by restructuring materials for the most efficient picking layout, which was not feasible during the thesis due to space constraints and a lack of reliable consumption data. As a result, the picking time for one finished good was reduced by 66.4 %. By discontinuing the use of the AWHS, multiple different kits could also be picked in parallel, further increasing efficiency and the picking process output.

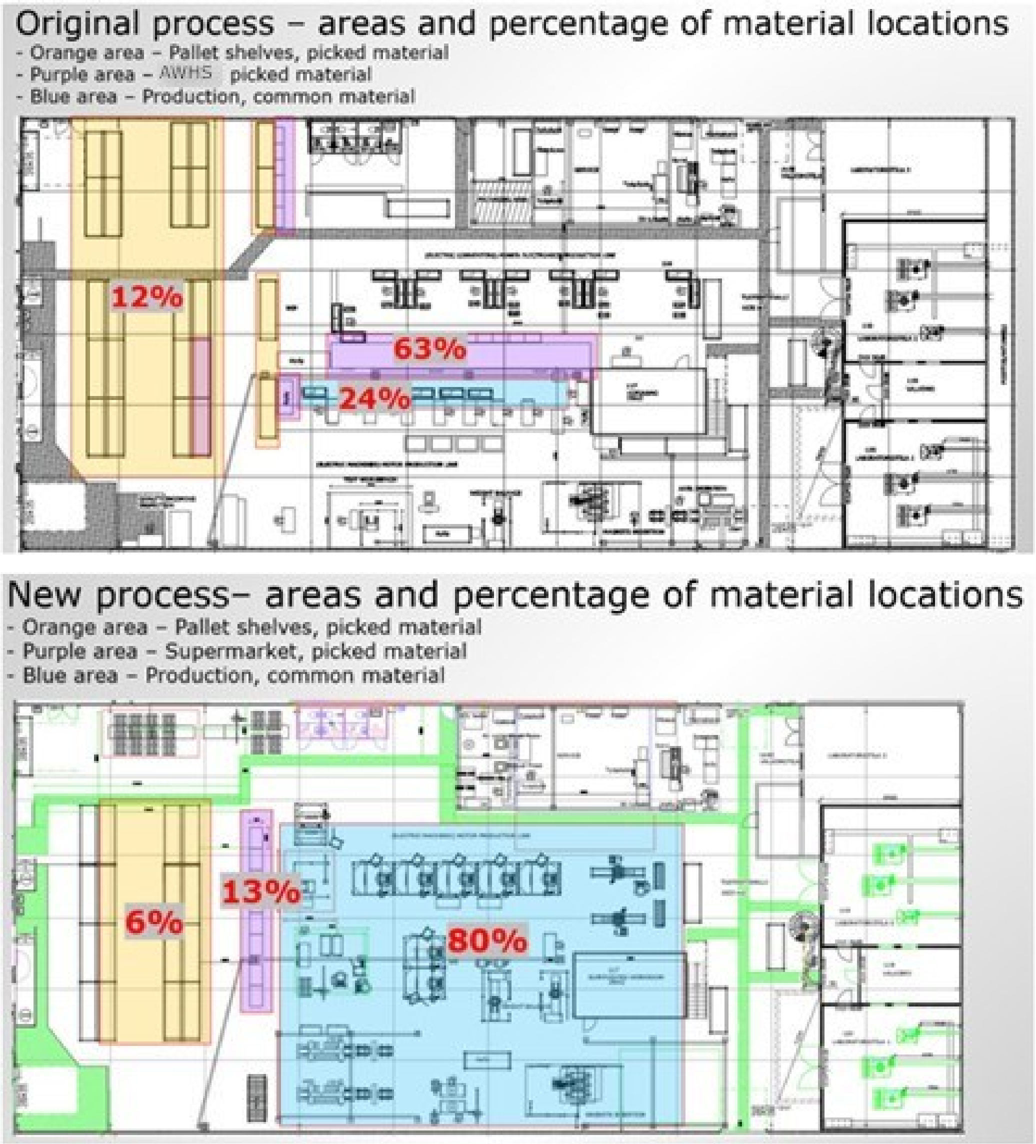


*Figure 23. Comparison of old assembly feeding process and the new process.*

Consequently, the new assembly feeding process has met its set target of being able to provide the required 18 units per shift or even outperform it. With only one picker, considering the effective working time, the 18 finished goods can be picked and delivered for assembly. In addition, WIP generation was reduced by around 70 % due to increased control in the picking process, and assembly efficiency was increased as no more part searching was required from the kits, as they had already been divided according to each assembly step and the number of items included in each kit was greatly reduced. Due to the two-bin system and the increasing use of common materials, small piece handling and counting were reduced, increasing efficiency in both logistics and assembly operations. The two-bin system also significantly increases FIFO implementation, which was identified as an important factor in the case company due to the nature of the products. FIFO was also greatly increased for the AZ components, as the shipping process to the supplier was changed to follow FIFO instead of the production plan. FIFO was also increased by removing the AWHS and by standardizing the identification information of materials during receiving, including relevant information such as purchase order numbers, arrival dates, and revisions to the identification tags. Furthermore, FIFO was increased through the introduction of a new material introduction process, which was also extended for revision changes, to ensure FIFO utilization to its full extent.

In its current state, the case company was struggling with workload, a lack of instructions, inadequate information flow, and a lack of standardized processes. By hiring a dedicated warehouse manager, creating SOPs, and changing the assembly feeding system to function based on pull demand with buffers, a significant change in warehouse performance was enabled. The operators are currently much more efficient, as there are common rules and responsibilities regarding daily tasks. The operators face far fewer problems in their daily activities, and when they do, they are aware of where to find support and move forward. Through all the standardization activities, warehouse personnel are far more productive, and they are aware of the priorities and when to perform each task. This has led to significantly increased job satisfaction, as the previously present sense of rush has been eliminated, and the operators have the freedom to influence their daily routines and when they perform each task.

Errors in receiving, put-away, and picking have also been reduced due to ongoing training alongside the introduction of new processes and working instructions for all daily tasks. Job satisfaction has also increased through the removal of unproductive labour, such as counting small pieces during picking and moving materials back and forth to create space or access certain materials due to an over-stacked warehouse. As a result of the improved working conditions and style, the warehouse operators are also far more proactive and are bringing up improvement ideas through the daily meetings to the warehouse manager for future improvements.

The effectiveness of the changes made overall in the warehouse, assembly feeding system, and standardization is highlighted by the fact that the assembly feeding has been returned to the warehouse and made a priority of the new in-house logistics system. This has removed the need for assembly operators to support warehouse functions. Even though the feeding has been returned to logistics, the common consensus among the warehouse operators is that the workload is far more reasonable in the new setup, and the changes made have improved their working conditions and workload.

This thesis is a prime example of the effectiveness of Lean and Kanban methodologies in a manufacturing environment on the logistics side. By implementing simple Lean and Kanban-based solutions, more can be achieved with less. Through implementation, the case company has gained multiple benefits. The expenses tied to in-house logistics have been significantly reduced. The bottleneck related to material feeding to assembly operations was eliminated, increasing the capacity to the preset requisite, which was even over-performed, having the ability to feed more than 18 pieces per shift if required. Job satisfaction has greatly increased, as roles and responsibilities are clear between warehouse operators and assembly operators. The increased control in the new assembly feeding system has reduced the costs tied to WIP and improved the overall appearance of the premises, as the amount of WIP lying around constantly has been reduced. Even though significant improvements were achieved, the case company is now at a critical point: whether it adopts the new status quo and resigns itself to it, or whether it adopts Lean as a culture and seeks more improvements through iteration and new cycles of reviewing current operations, seeking out waste, and eliminating it. This thesis was just the first step towards a Lean approach, and there is still much more to be achieved in the case company.

The main research question of this thesis was how to set up in-house logistics and warehousing in a manner that it can meet the preset capacity requirement. Supportive research questions were established, firstly, how to direct warehousing focus back to the core activity of warehousing and material feeding, and secondly, how to improve material availability, control, and FIFO-logic in the warehousing. This research met its goal and provided a robust way to set up in-house logistics to meet the required feeding capacity and performance. It is noteworthy that the solutions presented have facilitated an increase in capacity beyond the desired target, without necessitating additional workforce. This result could be reached by analysing the case company's current state, recognizing key issues, and then finding solutions for these issues. In the end, the result was achieved by changing the current assembly feeding system from kitting to a hybrid policy. In addition, a key decision driving the creation of the new assembly feeding system was increasing material availability, control, and FIFO. This enabled the creation of a highly reliable system with good control, which was achieved through implementing physical signals in the processes and implementing pull drives to the processes. For the second research question, key decisions were to create SOPs for processes, implement a dedicated manager for the function, and train the personnel about Lean principles and who their customer is, and what brings value to them. A significant tool was also creating a clear picture of responsibilities alongside eliminating the constant unnecessary sense of rush from the logistics side, which was caused by poor initial information flow and support processes.

In its entirety, it can be stated that this thesis has answered all the research questions. The paper provides practical solutions to the research questions, which are also adaptable for other cases, and not just for the case company, through explained and justified decision-making. This study also gives a good indication of how to establish an in-house logistics department alongside manufacturing operations in a smaller company, such as a startup, where roles and responsibilities are often unclear. The thesis provides a good basis for the case company's in-house logistics to build on for future development.

## 7.2 Future research topics

While significant changes have been implemented at the case company, this represents only the initial phase, and further substantial improvements can be achieved through incremental enhancements. For instance, the existing sticker coding system could be optimized by implementing a pick-to-light system, which would directly indicate the materials required for a specific finished good. A pick-to-light system would also enhance control, reducing error waste in both assembly stations and the picking process by minimizing the potential for human error. Furthermore, the system would improve efficiency by immediately identifying the correct bins for material retrieval, eliminating the need for manual searching. It is acknowledged that searching waste is typically most pronounced at the outset of a new process, until operators develop muscle memory for fixed bin locations and internalize the sticker coding scheme. A more critical area for future research involves the standardization of components. During the material classification process, a preliminary review by the engineering department revealed that the number of distinct components could be reduced through the standardization of small piece components. This would yield several benefits, including increased lot sizes, reduced space requirements at assembly stations and in the supermarket, the potential to introduce additional components to the assembly stations, and a further reduction in picking time.

As emphasized in the current state analysis, the case company experiences challenges related to information flow, resulting in various problems and excessive paper handling. A key area for future research is the review and correction of existing Bills of Materials (BOMs), alongside addressing other systemic deficiencies in information flow. Reviewing BOMs for highly customized goods carries the well-documented risk, as noted in academic literature, that root cause fixes are neglected, and flawed mechanisms are accommodated, leading to the accumulation of problems in the future. If these BOMs are corrected, it would enable more accurate material classification, further reducing inventory levels, freeing up space, and decreasing tied-up CAPEX. Moreover, reliable data from material classification would facilitate more sophisticated inventory analysis and further optimization of logistics, for example, through dynamic inventory planning and optimized inventory quantities within the case company. Another area for future systems-related research would involve establishing a connection with the supplier's local shop to enable automatic receipt of withdrawn goods upon checkout, a feature that was not feasible to implement during this research and currently requires a separate manual step for receiving goods at the case company. In terms of digitalization, transitioning from physical Kanbans to digital Kanbans is another potential avenue for future exploration, as suggested by multiple academic sources.

From the case company's perspective, one of the most critical areas for future research is the development of a structured Lean culture. To enhance the likelihood of successful Lean adoption, an iterative cycle framework could be developed. This framework would delineate a systematic process for conducting waste analysis, identifying potential solutions, and implementing them within a defined timeframe. Furthermore, it would integrate this process into the company's core operational activities. This would mitigate the risk of neglecting continuous improvement efforts due to the demands of competing priorities and other development projects. A study focused on developing such a framework would provide a valuable opportunity for the case company to assess the extent to which the new approaches outlined in this thesis have been effectively integrated into the organization and to evaluate the effectiveness of their ongoing continuous improvement initiatives.

## 7.3 Comparison to existing academic literature

The primary objective of academic research is to generate and validate new knowledge. However, the practical implementation of established theories and best practices is an equally crucial endeavour, serving as a rigorous test of their real-world functionality and revealing any unforeseen factors that may influence the underlying hypothesis. This thesis contributes to the latter, by implementing established best practices within the context of a specific case company. The findings of this study align with those of previous Lean and Kanban implementation studies, further validating their effectiveness as methodologies for enhancing efficiency in manufacturing environments. The case study approach provides novel insights into the application of these techniques in a high-variation environment, enabling serial production with a diverse product mix. This supports the hypothesis advanced by Kemppainen et al. (2008, 717–718) and Helkiö and Tenhiälä (2013, 217) that new technologies facilitate more flexible manufacturing strategies without significant compromises, as argued by Haynes and Wheelwright. Nevertheless, as these authors suggest, certain trade-offs may be necessary. In the case company, for example, traveling kits were implemented instead of stationary kits, and it was not possible to implement line-side stocking for all materials as initially planned. It is important to note that, given the specific decision-making criteria of the case company, these solutions were deemed justified due to the enhanced level of control they afforded.

In addition to advanced manufacturing technologies, a less frequently discussed enabler of more versatile production strategies lies in enhanced value recognition and more efficient organizational structures. This entails segmenting production processes into smaller, more manageable units, fostering the concept of internal customers, and acknowledging value creation at each stage. The case company exemplifies this principle, as its initial state involved assembly operators being responsible for material preparation, which, from a Lean perspective, constitutes waste, given that the assembly operator's primary value lies in assembling finished goods. Conversely, the warehouse operators' value resides in facilitating the assembly operators' value creation by ensuring the timely delivery of the necessary components. This attention to detail across different roles fosters an efficient value chain and a robust value creation process. While this concept may be challenging to recognize in smaller organizations, it is essential for larger companies to maintain competitiveness and efficiency. Therefore, it is a valuable point to recognize and understand in growing companies such as the case company.

Within a broader context, the recognition of internal customers in the manufacturing environment is often underemphasized. It is crucial to delineate core and support functions, with the support functions' primary focus being to serve the core functions. Failure to recognize this distinction can lead to detrimental process changes if the customers are not properly identified. Often, attempts to simplify tasks may inadvertently increase workload in other areas. Without proper customer and value recognition, there is a risk of adding waste to core functions while attempting to ease the operation of support functions, a phenomenon observed in the analysis of the case company's current state. Due to its case study-based approach, this research has certain limitations. For example, similar studies should be conducted in high product mix environments to assess the replicability of these practices and to determine whether comparable results can be achieved, thereby enabling the generalization of the findings. Furthermore, it would be desirable to test the implicated solutions in other warehousing environments, testing the statement of Bozer (2012) that every warehousing function is at the core the same.

While existing literature offers numerous case examples of Lean and Kanban solution implementations, this thesis contributes novel insights to the field. Primarily, this paper serves as a readily accessible repository of ideas for enterprises grappling with logistical challenges and space constraints, offering practical guidance on improving warehousing operations. Furthermore, this study provides valuable information on enhancing in-house logistics, increasing capacity, and maintaining the existing product mix without significant trade-offs. The paper presents multiple easily implementable improvement ideas that can be readily adapted to diverse scenarios. The research also emphasizes decision drivers beyond the commonly prioritized efficiency improvements, which is particularly desirable for environments characterized by high risks, where stringent control is paramount.

This paper addresses the relatively underexplored topic of implementing Lean practices in manufacturing environment warehouses. Existing literature predominantly concentrates on retail warehousing and logistics or manufacturing environments, often relegating the logistics and warehousing aspects to a secondary position. Additionally, the paper indicates how to enable, from a logistics perspective, the highly desirable one-piece material flow in a variant-heavy manufacturing environment with high customization. This case study provided similar implications as highlighted by Mourato et al. (2021, 1946) that internal logistics efficiency will increase overall productivity in other departments as well by eliminating waiting waste. For the case company, WIP generation was greatly reduced, and material availability increased in the assembly operations, which eliminated the common situation of waiting for new materials in material shortage situations.

Beyond the practical implementation examples, several generalizable insights can be derived from this research that are not commonly emphasized in existing literature. Much of the literature neglects the importance of providing adequate training in Lean methodologies to warehouse and in-house logistics personnel within the manufacturing environment, often focusing primarily on assembly workers. However, neglecting these personnel undermines the Lean approach, as the process cannot be considered Lean if all components of the process are not Lean. Therefore, it is essential to ensure that all relevant personnel receive adequate training, regardless of their role or department within the manufacturing operation.

A second significant insight is that improvements and changes can be implemented effectively even without perfect data and information. Organizations should not be paralyzed by a lack of comprehensive data to inform decision-making. Instead, they should fully leverage existing data and information possible. Data collection procedures can be implemented during the change process, and changes need not be perfect solutions from the outset. Multiple iteration cycles should be conducted after the initial implementation to identify and refine successful and unsuccessful solutions. Furthermore, the change process itself may reveal unforeseen patterns and highlight gaps in the data, enabling further opportunities for continuous improvement.

# References

Ahmadi-Javid, A. & Ardestani-Jaafari, A. 2021. The unequal area facility layout problem with shortest single-loop AGV path: how material handling method matters. International Journal of Production Research. 59(8): 2352–2374.

Ahmed, W. 2022. Understanding alignment between lean and agile strategies using Triple-A model. International Journal of Productivity and Performance Management. 71(5): 1810–1828.

Azzi, A., Battini, D., Faccio, M. & Persona, A. 2012. Sequencing procedure for balancing the workloads variations in case of mixed model assembly system with multiple secondary feeder lines. International Journal of Production Research. 50(21): 6081–6098.

Barnes, R.M. 1968. Motion and Time Study: Design and Measurement of Work. Wiley.

Battini, D., Faccio, M., Persona, A. & Sgarbossa, F. 2009. Balancing–sequencing procedure for a mixed model assembly system in case of finite buffer capacity. International Journal of Advanced Manufacturing Technology. 44(3–4): 345–359.

Battini, D., Faccio, M., Persona, A. & Sgarbossa, F. 2010. “Supermarket warehouses”: stocking policies optimization in an assembly-to-order environment. International Journal of Advanced Manufacturing Technology. 50(5–8): 775–788.

Battini, D., Faccio, M., Persona, A. & Sgarbossa, F. 2011. New methodological framework to improve productivity and ergonomics in assembly system design. International Journal of Industrial Ergonomics. 41(1): 30–42.

Baudin, M. 2004. Lean Logistics: The Nuts and Bolts of Delivering Materials and Goods. New York: Productivity Press.

Belay, M.A., Welo, T. & Helo, P. 2014. Approaching Lean Product Development Using System Dynamics: investigating Front-Load Effects. Advances in manufacturing. 2(2): 130–140. Web.

Benjaafar, S., Heragu, S.S. & Irani, S.A. 2002. Next Generation Factory Layouts: Research Challenges and Recent Progress. Interfaces (Providence). 32(6): 58–76.

Berg, J.P. & Zijm, W.H.M. 1999. Models for warehouse management: Classification and examples. International Journal of Production Economics. 59(1): 519–528.

Berhan, E., Kitaw, D., Gobachew, A.M. & Haasis, H. 2021. ABC/XYZ Analysis for Kanban System Implementation in Pharmaceutical Supply Chain: A Case of Ethiopian Pharmaceutical Supply Agency. International Journal of Information Systems and Supply Chain Management. 14(3): 63–78.

Bonvik, A.M., Couch, C.E. & Gershwin, S.B. 1997. A comparison of production-line control mechanisms. International Journal of Production Research. 35(3): 789–804.

Bozer, Y. & McGinnis, L.F. 1992. Kitting versus line stocking: A conceptual framework and a descriptive model. International Journal of Production Economics. 28(1): 1–19.

Bozer, Y. 2012. Developing and Adapting Lean Tools/Techniques to Build New Curriculum/Training Program in Warehousing and Logistics. 1–37.

Caputo, A.C. & Pelagagge, P.M. 2008. Analysis and optimization of assembly lines feeding policies. Proceeding MITIP Conference. Prague. 12–14 November 2008.

Caputo, A.C. & Pelagagge, P.M. 2011. A methodology for selecting assembly systems feeding policy. Industrial Management + Data Systems. 111(1): 84–112.

Carlson, O. & Hensvold, B. 2008. Kitting in a high variation assembly line: a case study at Caterpillar BCP-E. Master thesis. Lulea University of Technology.

Chaouiya, C., Liberopoulos, G. & Dallery, Y. 2000. The extended kanban control system for production coordination of assembly manufacturing systems. IIE Transactions. 32(10): 999–1012.

Che, M.N.B. & Abdul, S.A.B. 2014. Analysis and Reduction of the Waste in the Work Process Using Time Study Analysis: A Case Study, Applied Mechanics and Materials. 660: 971–975.

Chica, M., Bautista, J. & de Armas, J. 2019. Benefits of robust multi objective optimization for flexible automotive assembly line balancing. Flexible Services and Manufacturing Journal. 31(1): 75–103.

Choi, W. & Lee, Y. 2002. A dynamic part-feeding system for an automotive assembly line. Computers & Industrial Engineering. 43(1): 123–134.

Coelho, F., Macedo, R., Relvas, S. & Barbosa-Póvoa, A. 2022. Simulation of in-house logistics operations for manufacturing. International Journal of Computer Integrated Manufacturing. 35(9): 989–1009.

Corakci, A.M. 2009. An Evaluation of Kitting Systems in Lean Production. Master thesis. University of Borås/School of Engineering.

Curcio, D. & Longo, F. 2009. Inventory and internal logistics management as critical factors affecting the supply chain performances. International Journal of Simulation & Process Modelling. 5(4): 278–288.

de Koster, R., Le-Duc, T. & Roodbergen, K.J. 2007. Design and control of warehouse order picking: A literature review. European Journal of Operational Research. 182(2): 481–501.

de los Mozos, E.Á. & López, N.G. 2020. Short-term logistics management at a multinational corporation. Procedia Manufacturing. 51: 1696–1702.

Dharmapriya, U.S.S. & Kulantunga, A.K. 2011. New Strategy for Warehouse Optimization – Lean Warehousing. Proceedings of the 2011 International Conference on Industrial Engineering and Operations Management. January 22–24. 513–518.

Ding, F.Y. 1992. Kitting in JIT Production: a kitting project at a tractor plant. Industrial Engineering. 24(9): 42–43.

Drira, A., Pierreval, H. & Hajri-Gabouj, S. 2007. Facility layout problems: A survey. Annual Reviews in Control. 31(2): 255–267.

Dysko, D. 2012. Gemba Kaizen- Utilization of human potential to achieving continous improvement of company. The International Journal of Transport & Logistics. 1–10.

Emde, S. & Boysen, N. 2012a. Optimally routing and scheduling tow trains for JIT-supply of mixed-model assembly lines. European Journal of Operational Research. 217(2): 287–299.

Emde, S. & Boysen, N. 2012b. Optimally locating in-house logistics areas to facilitate JIT-supply of mixed-model assembly lines. International Journal of Production Economics. 135(1): 393–402.

Fabri, M. & Ramalhinho, H. 2023. The in-house logistics routing problem. International Transactions in Operational Research. 30(2): 1144–1168.

Fabri, M. & Ramalhinho, H. 2024. Assessing the In-house Logistics flows in the automotive industry. Computers & Industrial Engineering. 187: 109822.

Faccio, M., Gamberi, M. & Persona, A. 2013a. Kanban number optimisation in a supermarket warehouse feeding a mixed-model assembly system. International Journal of Production Research. 51(10): 2997–3017.

Faccio, M., Gamberi, M., Persona, A., Regattieri, A. & Sgarbossa, F. 2013b. Design and simulation of assembly line feeding systems in the automotive sector using supermarket, kanbans and tow trains: a general framework. Journal of Management Control. 24(2): 187–208.

Faccio, M. 2014. The impact of production mix variations and models varieties on the parts-feeding policy selection in a JIT assembly system. International Journal of Advanced Manufacturing Technology. 72(1-4): 543–560.

Field, K.A. 1997. Point-of-use storage saves TI millions. Modern Materials Handling. 52(7): 42–44.

Frazelle, E. 2002. Supply Chain Strategy: The Logistics of Supply Chain Management. New York, N.Y: McGraw-Hill.

Freitas, A.M., Silva, F.J.G., Ferreira, L.P., Sá, J.C., Pereira, M.T. & Pereira, J. 2019. Improving efficiency in a hybrid warehouse: a case study. Procedia Manufacturing. 38: 1074–1084.

Garcia-Diaz, A. & MacGregor Smith, J. M. 2024. Facilities Planning and Design. 2nd ed. 2024. [Online]. Cham: Springer Nature Switzerland.

George, M. 2002. Lean Six Sigma: Combining Six Sigma with Lean Speed. New York: McGraw-Hill.

Gross, J.M. & McInnis, K.R. 2003. Kanban made Simple Demystifying and Applying Toyota's Legendary Manufacturing Process. New York: AMACOM.

Hanson, R. & Medbo, L. 2012. Kitting and time efficiency in manual assembly. International Journal of Production Research. 50(4): 1115–1125.

Hayes, R. & Wheelwright, S. 1979. Link Manufacturing Process and Product Life Cycles. Boston: Harvard Business School Press.

Helkiö, P. & Tenhiälä, A. 2013. A contingency theoretical perspective to the product-process matrix. International journal of operations & production management. [Online] 33 (2): 216–244.

Henderson, R. & Kiran, A.S. 1993. Kitting elimination supports just-in-time principles. Industrial Engineer. Norcross, Ga. 25(3): 46.

Heragu, S.S. 2022. Facilities Design. Boca Raton, FL: CRC Press.

Hines, P., Holweg, M. & Rich, N. 2004. Learning to evolve: A review of contemporary lean thinking. International Journal of Operations & Production Management. 24(10): 994–1011.

Hsu, V.N., Lee, C.Y. & So, K.C. 2007. Managing components for assemble-to-order products with lead-time-dependent pricing: The full-shipment model. Naval Research Logistics; Naval Research Logistics. 54(5): 510–523.

Hua, S.Y. & Johnson, D.J. 2010. Research issues on factors influencing the choice of kitting versus line stocking. International Journal of Production Research. 48(3): 779–800.

Hänggi, R., Fimpel, A. & Siegenthaler, R. 2022. LEAN Production - Easy and Comprehensive: A Practical Guide to Lean Processes Explained with Pictures. Berlin, Heidelberg: Springer Berlin / Heidelberg.

Imai, M. 2012. Gemba kaizen A Commonsense Approach to a Continuous Improvement Strategy, Second Edition. New York, NY. McGraw Hill.

Jármai, K. & Voith, K. 2020. Special Optimization Process for Warehouse Layout Design. In: Anonymous Singapore: Springer Singapore Pte. Limited, 194–205.

Jimenez-Partearroyo, M., Medina-López, A. & Juárex-Varón, D. 2024. Towards industry 5.0: evolving the product-process matrix in the new paradigm. The Journal of technology transfer. [Online] 49 (4): 1496–1531.

Karhunen, J., Pouri, R. & Santala, J. 2004 Kuljetukset Ja Varastointi : Järjestelmät, Kalusto Ja Toimintaperiaatteet. Helsinki: Suomen logistiikkayhdistys.

Kemppainen, K., Vepsäläinen, A.P.J. & Tinnilä, M. 2008. Mapping the structural properties of production process and product mix. International Journal of Production Economics. 111(2): 713–728.

Kilic, H.S., Durmusoglu, M.B. & Baskak, M. 2012. Classification and modeling for in-plant milk-run distribution systems. International Journal of Advanced Manufacturing Technology. 62(9-12): 1135–1146.

Kilic, H.S. & Durmusoglu, M.B. 2012. Design of kitting system in lean-based assembly lines. Assembly Automation. 32(3): 226–234.

Kilic, H.S. & Durmusoglu, M.B. 2015. Advances in assembly line parts feeding policies: a literature review. Assembly Automation. 35(1): 57–68.

Klassen, R. D. & Menor, L. J. 2007 The process management triangle: An empirical investigation of process trade-offs. Journal of operations management. [Online] 25 (5): 1015–1034.

Kovács, G. 2020. Combination of Lean value-oriented conception and facility layout design for even more significant efficiency improvement and cost reduction. International Journal of Production Research. 58(10): 2916–2936.

Kumar, M., Tsolakis, N., Agarwal, A. & Srai, J.S. 2020. Developing distributed manufacturing strategies from the perspective of a product-process matrix. International Journal of Production Economics. 219: 1–17.

Kumar, P., Rajan, A.J. & Balan, K.N. 2014. VED & ABC Analysis of Inventories for a Wind Turbine Company. Applied Mechanics and Materials. 591: 27–32.

Lage Junior, M. & Godinho Filho, M. 2010. Variations of the kanban system: Literature review and classification. International journal of production economics. [Online] 125 (1): 13–21.

Lai, K. & Cheng, T.C.E. 2016. Just-in-Time Logistics. London: Routledge.

Lean Enterprise Institution -LEI Lean Thinking and Practice. Retrieved [16.9, 2024] Available at: https://www.lean.org/lexicon-terms/lean-thinking-and-practice/.

Li, S.G. & Kuo, X. 2008. The inventory management system for automobile spare parts in a central warehouse. Expert Systems with Applications. 34(2): 1144–1153.

Limère, V., Landeghem, H.V., Goetschalckx, M., Aghezzaf, E. & McGinnis, L.F. 2012 Optimising part feeding in the automotive assembly industry: deciding between kitting and line stocking. International Journal of Production Research. 50(15): 4046–4060.

Manos, A. & Vincent, C. 2012. The Lean Certification Handbook. Milwaukee, Wisconsin: ASQ Quality Press.

Manzini, R., Gamberi, M., Regattieri, A. & Persona, A. 2004. Framework for designing a flexible cellular assembly system. International Journal of Production Research. 42(17): 3505–3528.

Manzini, R., Persona, A. & Regattieri, A. 2006. Framework for designing and controlling a multicellular flexible manufacturing system. International Journal of Services and Operations Management. 2(1): 1–21.

Martins, R., Pereira, M.T., Ferreira, L.P., Sá, J.C. & Silva, F.J.G. 2020. Warehouse operations logistics improvement in a cork stopper factory. Procedia Manufacturing. 51: 1723–1729.

Material Handling Institute -MHI. NA. The Ten Principles of Material Handling. College Industry Council on Material Handling Education (CICMHE). Retrieved [14.8.2024] Available at: Ten Principles for .pdf

McDermott, C.M., Greis, N.P. & Fischer, W.A. 1997. The diminishing utility of the product/process matrix: A study of the US power tool industry. International Journal of Operations & Production Management. 17(1): 65–84.

Mourato, J., Pinto Ferreira, L., Sá, J.C., Silva, F.J.G., Dieguez, T. & Tjahjono, B. 2021. Improving internal logistics of a bus manufacturing using the lean techniques. International Journal of Productivity and Performance Management. 70(7): 1930–1951.

Muñuzuri, J., Larrañeta, J., Onieva, L. & Cortés, P. 2005. Solutions applicable by local administrations for urban logistics improvement. Cities. 22(1): 15–28.

Myerson, P. 2012. LEAN Supply Chain Logistics Management. New York, McGraw-Hill. 270 s.

Niemann, J.Ö., Reich, B. & Stöhr, C. 2024. Spaghetti Diagram. In: Anonymous Germany: Springer Berlin / Heidelberg.

Ohno, T. 1988. Toyota Production System - Beyond Large- Scale Production. Productivity Press.

Pandya, B. & Thakkar, H. 2016. A review on inventory management control techniques: ABC-XYZ analysis. REST Journal on Emerging Trends in Modelling and Manufacturing. 2(3): 82–86.

Pereira, C.M., Anholon, R., Rampasso, I.S., Quelhas, O.L.G., Leal Filho, W. & Santa-Eulalia, L. 2021. Evaluation of lean practices in warehouses: an analysis of Brazilian reality. International Journal of Productivity and Performance Management. 70(1): 1–20.

Persona, A., Battini, D., Manzini, R. & Pareschi, A. 2007. Optimal safety stock levels of subassemblies and manufacturing components. International Journal of Production Economics. 110(1): 147–159.

Pouri, R. 1983. Varastoinnin Tekniikka. Helsinki: Oy Rastor Ab.

Praveen, M., Simha, J. & Venkataram, R. 2016. Techniques for Inventory Classification: A Review. International Journal for Research in Applied Science & Engineering Technology (IJRASET). 4(X): 508–518.

Pyzdek, T. 2021. ‘Spaghetti Diagrams’, in The Lean Healthcare Handbook. [Online]. Cham: Springer International Publishing. 25–28.

Raghavan, V.A., Yoon, S. & Srihari, K. 2014. Lean transformation in a high mix low volume electronics assembly environment. International Journal of Lean Six Sigma. 5(4): 342–360.

Raghuram, P. & Arjunan, M.K. 2022. Design framework for a lean warehouse – a case study-based approach. International Journal of Productivity and Performance Management. 71(6): 2410–2431.

Ritvanen, V., Inkiläinen, A., von Bell, A. & Santala, J. 2011. Logistiikan Ja Toimitusketjun Hallinan Perusteet. Saarijärvi: Suomen Huolintaliikkeiden Liitto ry & Suomen Osto- ja Logistiikkayhdystys LOGY Oy.

Salhieh, L., Altarazi, S. & Abushaikha, I. 2019. Quantifying and ranking the “7-Deadly” Wastes in a warehouse environment. TQM Journal. 31(1): 94–115.

Satoglu, S.I., Durmusoglu, M.B. & Dogan, I. 2006. Evaluation of the conversion from central storage to decentralized storages in cellular manufacturing environments using activity-based costing. International Journal of Production Economics. 103(2): 616–632.

Sayer, N. & Williams, B. 2007. Lean for Dummies. Hoboken: Wiley.

Scholz-Reiter, B., Heger, J., Meinecke, C. & Bergmann, J. 2012. Integration of demand forecasts in ABC-XYZ analysis: practical investigation at an industrial company. International Journal of Productivity and Performance Management. 61(4): 445–451.

Schrotenboer, A.H., Wruck, S., Roodbergen, K.J., Veenstra, M. & Dijkstra, A.S. 2017. Order picker routing with product returns and interaction delays. International Journal of Production Research. 55(21): 6394–6406.

Sendil Kumar, C. & Panneerselvam, R. 2007. Literature review of JIT-KANBAN system. International Journal of Advanced Manufacturing Technology. 32(3-4): 393–408.

Sharma, S. & Shah, B. 2016. Towards lean warehouse: transformation and assessment using RTD and ANP. International Journal of Productivity and Performance Management. 65(4): 571–599.

Sheldon, D. 2008. Lean Materials Planning and Execution: A Guide to Internal and External Supply Management Excellence. E-kirja. Ft. Lauderdale, J. Ross Publishing Inc. 271 s.

Spencer, M.S. & Cox, J.F. 1995. An analysis of the product-process matrix and repetitive manufacturing. International Journal of Production Research. 33(5): 1275–1294.

Stavrulaki, E. & Davis, M. 2010. Aligning products with supply chain processes and strategy. The International Journal of Logistics Management. 21(1): 127–151.

Stephens, M.P. 2019. Manufacturing Facilities Design & Material Handling. West Lafayette, Indiana: Purdue University Press.

Stojanović, M. & Regodić, D. 2017. The Significance of the Integrated Multicriteria ABC-XYZ Method for the Inventory Management Process. Acta Polytechnica Hungarica. 14(5): 29–48.

Sugimori, Y., Kusunoki, K., Cho, F. & Uchikawa, S.1977. Toyota production system and Kanban system Materialization of just-in-time and respect-for-human system. International Journal of Production Research. 15(6): 553–564.

Swart, A.D. 2016. The Current Understanding of Lean Warehousing Principles in a Third Party Logistic Provider in South Africa.

Tortorella, G.L., Fettermann, D., Cauchick, M.P.A. & Sawhney, R. 2020. Learning organisation and lean production: an empirical research on their relationship. International Journal of Production Research. 58(12): 3650–3666.

Toyota Motor Corporation. 1998. The Toyota Production System—Leaner Manufacturing for a Greener Planet.

Tuohy, G. 2009. Ten Ways To Improve Material Handling Efficiency. Food Logistics. s. 29– 30.

van Zelst, S., van Donselaar, K., van Woensel, T., Broekmeulen, R. & Fransoo, J. 2009. Logistics drivers for shelf stacking in grocery retail stores: Potential for efficiency improvement. International Journal of Production Economics. 121(2): 620–632.

Vinodh, S. & Balaji, S.R. 2011. Fuzzy logic based leanness assessment and its decision support system. International Journal of Production Research. 49(13): 4027–4041.

Vrat, P. 2011. Inventory models and human body food supply chain: some managerial insights. Industrial Engineering Journal. 2(2): 8-16

Vrat, P. 2014. Materials Management an Integrated Systems Approach. New Delhi: Springer India.

Wang, F., Ng, H.Y. & Ng, T.E. 2018 Novel SKU Classification Approach for Autonomous Inventory Planning. IEEE. 1441–1445.

Wright, C. 2017. Fundamentals of Assurance for Lean Projects - an Overview for Auditors and Project Teams. Place of publication not identified: IT Governance Publishing.

Zhang, X., Ou, J. & Gilbert, S.M. 2008. Coordination of stocking decisions in an assemble-to-order environment. European Journal of Operational Research. 189(2): 540–558.