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Statistical Approaches to Enhancing Inventory Control and Reducing Variability in Supply Chains

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ABSTRACT:
Efficient inventory management and OTD performance are cornerstones of supply chain operations, influencing both operational efficiency and customer satisfaction. This study investigates factors affecting a company's OTD performance, focusing particularly on inventory variability and associated risks. The research combines statistical modeling of finished goods inventory levels and the state of component inventories with qualitative insights gathered from interviews to identify process inefficiencies and bottlenecks.

While previous studies have extensively addressed OTD and inventory management, much of the research has focused either on theoretical models or isolated case studies. Few studies have integrated statistical analysis and qualitative methods to provide a comprehensive view of risks and inefficiencies impacting OTD. This thesis bridges that gap by combining quantitative data analysis with process mapping based on interview findings.

Mixed methods approach is an ideal choice for this study because it allows for a holistic approach, integrating quantitative data for patterns and trends with qualitative insights to understand the underlying causes and contexts of the OTD process challenges. Quantitative analysis was conducted using deviations in orders from suppliers and customers across multiple part numbers, applying normal distribution models to evaluate inventory variability. Qualitative data was gathered through three interviews with key personnel, which helped identify bottlenecks and map critical processes affecting order-to-delivery performance.

The findings revealed inventory level fluctuations and highlighted key factors influencing OTD performance. These included challenges such as material management and transportation. The interviews provided valuable insights into these operational issues, enabling the identification of critical bottlenecks and process inefficiencies. This forms the basis for improvements in inventory management and operational planning to mitigate risks affecting OTD performance.

The implications of these findings for supply chain optimization are significant. By integrating statistical and qualitative analysis, the research offers a comprehensive framework for enhancing order-to-delivery performance. The combination of variability assessment and process perspectives supports the development of targeted strategies to reduce inefficiencies, ensuring timely deliveries and operational flexibility in dynamic market conditions.

KEYWORDS: Order-To-Delivery process, optimization, logistics, variance, supply chain management

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ABSTRACT:
Tehokas varastonhallinta ja tilaus-toimistus-prosessin suorituskyky ovat toimitusketjun toiminnan kulmakiviä, jotka vaikuttavat sekä operatiiviseen tehokkuuteen että asiakastyytyväisyyteen. Tämä tutkimus tarkastelee tekijöitä, jotka vaikuttavat yrityksen OTD-suorituskykyyn, keskittyen erityisesti varastojen vaihteluun ja siihen liittyviin riskeihin. Tutkimuksessa yhdistetään valmiiden tuotteiden varastotasojen ja komponenttivarastojen tilan tilastollinen mallinnus sekä haastattelujen avulla kerätyt laadulliset havainnot prosessien tehottomuuksien ja pullonkaulojen tunnistamiseen.

Vaikka aiemmat tutkimukset ovat laajasti käsitelleet tilaus-toimitus-prosessia ja varastonhallintaa, suuri osa tutkimuksesta on keskittynyt joko teoreettisiin malleihin tai erillisiin tapaustutkimuksiin. Harvat tutkimukset ovat yhdistäneet tilastollisen analyysin ja kvalitatiiviset menetelmät tarjotakseen kokonaisvaltaisen näkemyksen tilaus-toimitus-prosessista vaikuttavista riskeistä ja tehottomuuksista. Tämä tutkielma täyttää tämän aukon yhdistämällä määrällisen datan analyysin ja prosessikartoituksen, joka perustuu haastattelun tuloksiin.

Monimenetelmällinen lähestymistapa on hyvä valinta tähän tutkimukseen, koska se mahdollistaa kokonaisvaltaisen lähestymistavan yhdistämällä määrällisen analyysin trendien ja ilmiöiden tarkasteluun sekä laadullisen analyysin haasteiden taustasyiden ja kontekstien ymmärtämisen tilaus-toimitus-prosessin haasteista. Määrällinen analyysi suoritettiin hyödyntämällä tilausten poikkeamia toimittajilta ja asiakkailta useiden osanumeroiden osalta, soveltaen normaalijakauman malleja varastovaihteluiden arvioimiseksi. Laadullinen aineisto kerättiin kolmen avainhenkilön haastatteluista, jotka auttoivat tunnistamaan pullonkauloja ja kartoittamaan kriittisiä prosesseja, jotka vaikuttavat tilaus-toimitus-suorituskykyyn.

Tulokset paljastivat varastotasojen vaihtelun ja nostivat esiin keskeiset tekijät, jotka vaikuttavat tilaus-toimitus-prosessin suorituskykyyn. Näihin kuului erilaisia haasteita kuten, materiaalihallinta ja kuljetukset. Haastattelut tarjosivat arvokkaita näkemyksiä näistä operatiivisista ongelmista, jolloin voitiin tunnistaa kriittiset pullonkaulat ja prosessien tehottomuudet. Tämä muodostaa perustan parannuksille varastonhallinnassa ja operatiivisessa suunnittelussa tilaus-toimitus-suorituskykyyn vaikuttavien riskien vähentämiseksi.

Näiden havaintojen vaikutus toimitusketjun optimointiin on merkittävä. Yhdistämällä tilastollinen ja laadullinen analyysi, tutkimus tarjoaa kattavan viitekehyksen tilaus-toimitus-suorituskyvyn parantamiseen. Määrällisen vaihtelun arvioinnin ja prosessinäkökulmien yhdistäminen tukee kohdennettujen strategioiden kehittämistä tehottomuuksien vähentämiseksi, mikä varmistaa ajantasaisen toimituksen ja operatiivisen joustavuuden dynaamisissa markkinaolosuhteissa.

KEYWORDS: Order-To-Delivery process, optimization, logistics, variance, supply chain management

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1 Introduction

This thesis begins by outlining the background and purpose of the research, followed by a discussion of the problem statement and research questions, definitions and limitations. Additionally, the overall structure of the study, offering a clear explanation of how the research has been carried out.

1.1 Study purpose

The logistics performance of a contract manufacturing company is crucial in ensuring efficient lead times within the OTD process, as any delays can impact customer satisfaction and operational costs. Ioncor Oy, a case company specializing in battery systems, faces logistical challenges that hinder timely order fulfillment, particularly in areas such as material handling inefficiencies, stockouts, inventory inaccuracies and delays in transportation. These issues impact the company's ability to meet customer demand on time and efficiently manage resources. Despite advancements in logistics theories and OTD optimization models, gaps remain in understanding how the integration of logistical elements such as inventory management, transportation, and material handling collectively impacts OTD efficiency. For example, delays in transportation can affect inventory turnover and inaccuracies in stock levels can lead to late deliveries, ultimately reducing overall OTD performance. Prior research primarily focuses on individual logistics components, often overlooking the significance of their interdependencies within the manufacturing process, especially in focused industrial sectors like battery manufacturing (Christopher, 2016).

This study seeks to address these gaps by examining Ioncor Oy's OTD process to identify specific areas of inefficiency and explore potential optimization strategies. The research aims to provide actionable insights into how logistics coordination can be improved to reduce lead times, thereby enhancing overall productivity and cost-effectiveness. By investigating the current OTD workflow and identifying the logistical factors most responsible for delays, the study contributes valuable knowledge for optimizing supply chain performance in contract manufacturing. The goal is to help Ioncor Oy—and similar companies—achieve a more streamlined and competitive logistics process that supports timely and reliable deliveries.

1.2 Problem statement and research questions

The primary problem addressed by this study is the identification and analysis of logistics-related inefficiencies, such as delays in material handling, inaccurate inventory levels, and transportation bottlenecks, impacting lead times in the order-to-delivery (OTD) process within a contract manufacturing environment. The research centers on Ioncor Oy's logistics and aims to isolate specific factors that cause delays and inefficiencies in the OTD process. Current logistical challenges include delays stemming from bottlenecks in material handling, inventory management and transportation, all of which influence the overall efficiency and effectiveness of the company's supply chain operations. Addressing these issues is crucial to enhancing customer satisfaction and achieving timely and cost-effective production cycles, which are vital for competitive advantage in contract manufacturing. To explore these logistics challenges in detail, the research seeks to answer the following questions:

1. What are the key logistics-related factors affecting to manage lead times in the OTD process?
2. What is the current status of Ioncor Oy's OTD process?
3. How can the lead-time of the OTD process be optimized within the supply chain and logistics system in a contract manufacturing company?

Through these questions, the study assess the current OTD process's performance, identify underlying causes of inefficiency and propose methods for optimization. The insights gained from answering these questions aim to contribute significantly to the efficient coordination of logistics processes, thus enhancing both cost-effectiveness and operational effectiveness within Ioncor Oy.

1.3 Definitions, assumptions and limitations

To ensure clarity, this section defines key terms central to this thesis, specifically in the context of the order-to-delivery (OTD) process within contract manufacturing.

Order-to-Delivery (OTD) Process: Refers to the series of logistics-related steps that transform a customer order into a delivered product. This includes stages like order processing, inventory management, material handling, and transportation. (Christopher, 2016).

Lead time: The duration from when an order is placed to when it is delivered. This study focuses on lead time as a key performance metric within the OTD process, aiming to understand the logistics factors that affect it. (Mentzer et al., 2001.)

Bottlenecks: Points within the OTD process where delays or inefficiencies restrict the flow, often resulting in increased lead times and reduced operational efficiency (Goldratt, 1990).

Logistics performance: Encompasses metrics such as delivery reliability, inventory turnover, and throughput. The performance metrics, especially those measured by key performance indicators (KPIs), help quantify the efficiency and effectiveness of logistics processes within the OTD context. (Gunasekaran et al., 2001.)

Contract manufacturing refers to a business model where a company outsources its production to a third-party manufacturer under a formal agreement. This allows companies to focus on core activities like design and marketing while leveraging cost efficiencies and scalability provided by the manufacturer. (Christopher, 2016.)

This study operates under several key assumptions to support the analysis and conclusions. Firstly, it is assumed that all data utilized in the research is accurate and representative of the case company’s current processes. The responses obtained from surveys and interviews are presumed to be truthful and reflective of the participants' genuine experiences and opinions. Furthermore, the documentation and descriptions of the case company’s existing OTD processes are considered to accurately represent actual operational practices. Lastly, it is assumed that the optimization methods proposed in this study functions as intended and yield measurable improvements when applied under the outlined conditions. These assumptions are critical for the validity of the study but may introduce limitations if proven incorrect.

This study's limitations define the focus and ensure the feasibility of the analysis. The research centers on Ioncor Oy’s logistics processes, specifically examining the order-to-delivery (OTD) process for product X. Broader supply chain factors, such as external suppliers, customers and third-party logistics providers, are excluded from the scope unless they directly impact the logistics activities under study. Additionally, the analysis does not cover external influences like global supply chain disruptions, geopolitical events, natural disasters or macroeconomic factors. While these elements significantly impact the logistics environment, thoroughly analysing them would require extensive data beyond the study's scope.

Data collection is limited to the autumn of 2024, meaning that any seasonal variations or changes in logistics practices outside this timeframe may influence lead times differently than observed within this period. Additionally, limitations related to potential biases of the interviewees should be acknowledged, as their perspectives may not fully represent all operational dynamics or alternative viewpoints.

The methodology applied involves process analysis and improvement methods but does not include the implementation or measurement of specific continuous improvement methodologies such as Six Sigma or Lean. Consequently, the study may identify areas with potential for improvement but does not empirically validate the effects of optimization methods.

The findings focus on the specific context of Ioncor Oy and therefore, may have limited generalizability to other industries or organizational settings. While the results could offer valuable insights for logistics improvement in similar contract manufacturing companies, their applicability to different environments is constrained.

1.4 Structure of the thesis

This thesis is structured into six main chapters, each designed to address different aspects of the research, from establishing the background and purpose to presenting findings and recommendations for the case company.

The first chapter, Introduction, provides an overview of the research context, objectives and research questions. This chapter also outlines the study's definitions, limitations and scope, clarifying the focus on Ioncor Oy's order-to-delivery (OTD) process and key logistics factors impacting lead times.

The second chapter, Literature Review, explores existing research and theories related to the OTD process, focusing on key concepts in logistics, including material and inventory management, transportation efficiency and supply chain integration. This chapter also reviews process optimization methods, such as Lean and Six Sigma and examines case studies on OTD process optimization in different industries to establish a theoretical foundation for this research.

The third chapter, Research Methodology, explains the methods used to investigate and analyse the logistics performance in the OTD process. This includes the selection of interview planning and data analysis methods that provide insight into identifying bottlenecks and inefficiencies.

The fourth chapter, Empirical Part, introduces the case company, describes its current logistics processes and identifies specific bottlenecks affecting lead times. This chapter also presents the results of variance analysis and insights from interviews with key stakeholders, highlighting areas where logistics inefficiencies hinder OTD performance.

2 Literature review

By consolidating research on logistics integration, process optimization and performance measurement in contract manufacturing, the literature review aims to provide a comprehensive understanding of current knowledge and highlight the gaps this study intends to address. It underscores the need for empirical research on how multiple logistics elements interact to impact OTD efficiency.

The primary research gap this study addresses is the lack of empirical insights into the combined impact of logistics components (material handling, inventory, and transportation) on OTD process efficiency within contract manufacturing. While Lean and Six Sigma methods have been studied in logistics broadly, there is a shortage of research on how these process improvement methods, alongside tailored variance metrics, can be specifically applied to contract manufacturing to improve OTD process performance. This study seeks to bridge this gap by examining the nuanced interactions and optimization potential within this sector’s logistics framework.

2.1 Theorethical backround of the OTD process

The Order-to-Delivery (OTD) process is a critical element in industries such as automotive manufacturing, where it plays a pivotal role in managing the interactions between manufacturers, dealers and customers (Brabazon & MacCarthy, 2017). This process, is although vital for ensuring customer satisfaction and operational efficiency, has not been the subject of as extensive research as other areas like product development. The OTD process, particularly in high-volume sectors such as the automotive industry, is a complex system characterized by multiple interactions and dependencies between customers, suppliers and logistics service providers (LSPs). (Brabazon & MacCarthy, 2017.)

The OTD process can be viewed as a triadic system comprising the customer, supplier and LSP. Each actor in this triad influences the overall performance of the process, necessitating a triadic performance management approach. This involves assessing performance based on multiple dimensions beyond just lead time, including factors such as on-time delivery, lead time flexibility and adaptability. (Çakanyıldırım & Luo, 2017.) While lead time reduction has received substantial attention in past research, it is often considered less critical than meeting the promised delivery date or ensuring flexibility to adapt to changes in customer demand (Ghasemi et al., 2022).

The configuration of an OTD process is also influenced by the environment in which it operates. Traditional order-by-order environments, where each order is processed individually, differ from more modern configurations that use long-term delivery schedules with call-offs. (Svensson et al., 2019.) These latter configurations are increasingly common in industries like automotive and white goods manufacturing. In this type of OTD process, the supplier's sub-process is triggered not by individual customer orders but by a delivery schedule, which introduces additional challenges for performance management and adaptability. (Forslund, Mattsson & Jonsson, 2008)

From a supply chain perspective, the OTD process is a cross-company business process that integrates several sub-processes (Svensson, Gustafsson & Guillaume, 2019). These sub-processes include ordering, delivery, transportation and goods receipt, each with distinct performance metrics and interfaces between actors in the supply chain. For instance, the ordering sub-process begins when the customer identifies the need to order and concludes when the supplier receives the order. The delivery sub-process starts when the supplier receives the order and ends when the goods are available for shipping, followed by the transportation and goods receipt sub-processes. (Corradini et al., 2020.)

One of the key performance measures traditionally associated with the OTD process is lead time, defined as the time between recognizing the need for an order and receiving the ordered goods. However, beyond lead time, on-time delivery has emerged as a critical measure. (Sillanpää, 2011.) On-time delivery focuses on ensuring that the delivery date and quantity correspond precisely to what was agreed upon. Other important performance dimensions include lead time variability (the consistency of lead times), lead time adaptability (the ability to adjust lead times to changing conditions) and lead time flexibility (the ability to meet varying customer delivery demands). (Holopainen, Saunila & Ukko, 2023.)

The OTD process in the battery industry is a multi-faceted and dynamic system that requires careful coordination between different actors. The efficiency of the process is determined not only by reducing lead times but also by ensuring that deliveries are made on time, with the required flexibility to meet fluctuating customer demands.

2.2 Key theories and concepts in logistics

Logistics plays a vital role in the overall efficiency and effectiveness of supply chain management, impacting an organization's ability to compete in today’s dynamic marketplace. As businesses strive to optimize their operations, a deep understanding of key theories and concepts in logistics becomes essential. (Hofmann & Rüsch, 2017.) This section explores foundational ideas, including materials management, inventory management models and transportation systems, each of which contributes to streamlined processes and improved cost efficiency. By effectively implementing these theories and concepts, organizations can enhance productivity, reduce operational costs and improve customer satisfaction, ultimately driving profitability and growth. Understanding these key areas helps logistics professionals navigate complex supply chains and adapt to evolving market demands. (Bhat, 2009, p. 1.)

2.2.1 Theory of material management

The concept of materials management has gained significant recognition in recent years due to the need for production and operations managers to develop an organized body of knowledge concerning the planning, acquisition and utilization of materials in production processes (Patrucco, Ciccullo & Pero, 2020). This has led to the establishment of materials management as a distinct discipline. Managing materials efficiently is crucial for most organizations, as the costs associated with purchasing, storing, transporting and delivering materials account for more than half of the total product cost. Thus, improving productivity, particularly through effective materials management, is key to staying competitive, as it offers considerable potential for cost reduction. (Relich, Nielsen, & Gola, 2022.)

The main objectives of materials management focus on enhancing cost efficiency. These include achieving low prices, high inventory turnover, minimizing acquisition and ownership costs, ensuring continuity of supply, maintaining consistent quality, reducing payroll costs and fostering good relations with suppliers. (Alnaim & Kouaib, 2023.) The goal is to improve overall productivity and profitability by effectively managing material resources. (Bhat, 2009.)

Materials management covers a broad range of processes critical to the smooth functioning of production and business operations. This is especially true in industries like automotive manufacturing, where inventory management and just-in-time (JIT) systems are essential for maintaining efficient supply chains, minimizing costs and ensuring uninterrupted production. Additionally, materials management helps maintain accurate inventory levels, minimizes freight costs and improves quality control. (Suryatej & Sandeep, 2024.) MRO (maintenance, repair, and operations) inventory management is a critical component, as efficiently managing MRO parts is necessary to reduce downtime and optimize operational performance (Nair, 2012).

In production companies, materials management is an essential area of activity. Without well-planned and properly managed processes, such as material procurement and delivery systems, businesses would struggle to function effectively. One of the significant challenges in materials management is maintaining optimal inventory levels, as excessive stock can increase costs and reduce productivity. (Tliche et al., 2020.) Innovative solutions like real-time inventory tracking and JIT systems can help resolve this issue by optimizing inventory levels and reducing unnecessary expenses (Bookbinder & Ülkü, 2021).

The procurement process is one of the most critical aspects of materials management. In logistics, procurement is more comprehensive than simply purchasing, as it also involves market research, cost control and sourcing alternative materials to reduce costs. (Letunovska et al., 2023.) Effective procurement processes enable companies to gain a competitive edge by supporting their core operations. In addition, procurement logistics plays a vital role in ensuring smooth material flow, balancing service levels and associated costs. (Kanecka, 2020.)

To support comprehensive materials management, several computer-based systems, such as Material Requirements Planning (MRP 1) and Manufacturing Resource Planning (MRP 2), have been developed. These systems help minimize inventory while ensuring an adequate supply of materials for production processes. JIT systems, often integrated with MRP and Distribution Requirements Planning (DRP), are designed to optimize material flows and manage supply chains holistically. Purchasing, as a key component of inbound logistics, has become increasingly important as companies look globally for reliable, high-quality suppliers. The sourcing and acquisition of production inputs directly impact product pricing and customer satisfaction (Gourdin, 2001).

2.2.2 Inventory management models

Inventory management is a critical aspect of any business, ensuring that companies maintain adequate stock levels to meet customer demand while minimizing costs (Kumar et al., 2022, p. 27). Effective inventory management strikes a balance between avoiding stock shortages, which can lead to production delays or lost sales and minimizing holding costs, such as storage fees and potential inventory losses. By using various inventory management models, businesses can optimize their operations, reduce waste and improve customer satisfaction. (Stojkanovic et al, 2021, pp. 193-194.) Table 1 provides an overview of commonly used inventory models, highlighting their key features, benefits and relevant references.

Model	**Key features**	**Benefits**
EOQ	Optimizes order quantity to minimize ordering and holding costs.	Balances costs while ensuring suffiecient stock levels.
JIT	Orders materials only when needed, reducing inventory levels.	Minimizes holding costs and fees up capital.
ABC Analysis	Classifies inventory by consumption value.	Focuses on critical items for cost reduction and efficiency.

Table 1. Common inventory management models (Haekal & Setiawan, 2020; Emar et al., 2021; Stojkanovic et al., 2021; Kumar et al., 2022).

Inventory management is essential for multiple reasons. It ensures that businesses can meet customer demand promptly. If stock levels are too low, companies may face stockouts, leading to delayed orders, lost sales and dissatisfied customers. Maintaining appropriate stock levels ensures that products are always available when needed, enhancing customer satisfaction. (Kumar et al., 2022, p. 27.)

Inventory management helps reduce costs. Excess inventory results in higher holding costs, such as storage fees, insurance and the risk of obsolescence or spoilage. On the other hand, frequent ordering can increase logistics and handling costs. (Stojkanovic et al, 2021, p. 194.) Effective inventory management models, such as EOQ, help businesses find the optimal balance between ordering and holding costs, minimizing both and thereby increasing operational efficiency (Haekal & Setiawan, 2020, p. 77). For instance, JIT models aim to keep inventory levels as low as possible, which helps companies reduce storage costs and improve efficiency (Stojkanovic et al, 2021, p. 193).

Inventory management aids in better decision-making. Detailed records of available, ordered and consumed inventory provide businesses with essential data to plan for future demand, make informed production schedules and allocate resources effectively (Amos & Magad, 1995, p. 13). By having a clear understanding of inventory levels, businesses can respond more flexibly to market changes and avoid over- or understocking (Stojkanovic et al, 2021, p. 194).

Proper inventory management maximizes profitability by ensuring that products are available for sale without overcommitting resources to excess stock. Models like ABC analysis allow companies to focus their attention on high-value items, ensuring that the most critical products are always available while reducing investment in lower-priority items. (Kumar et al., 2022, p. 27.) This targeted approach helps businesses reduce waste and improve their return on investment (Stojkanovic et al, 2021, p. 194).

The Economic Order Quantity (EOQ) is one of the oldest and most well-known inventory management models. The EOQ model helps companies optimize order quantities and frequencies to minimize total costs, including ordering and holding costs. The model aims to balance the cost of placing orders (ordering costs) and the cost of storing inventory (holding costs). If orders are placed too frequently in small quantities, ordering costs increase. Conversely, if too much inventory is ordered at once, holding costs rise. (Emar et al., 2021, p. 1161.) EOQ helps businesses determine the ideal order quantity that minimizes these costs while ensuring enough stock is available to meet demand (Haekal & Setiawan, 2020, p. 77).

Just-in-Time (JIT) is a modern inventory management strategy focusing on precise timing of orders and inventory storage (Hanh & Reineke, 2019). The core idea of JIT is to order and store materials or products only when they are needed for production or sales, minimizing inventory levels. This reduces holding costs and frees up capital that would otherwise be tied up in inventory. (Geng et al., 2019.) The success of the JIT model depends on accurate demand forecasting and strong supplier relationships to ensure materials are available exactly when required (Schmidt et al., 2022).

JIT requires careful planning and monitoring. Maintaining minimal stock levels can be risky if demand fluctuates unexpectedly or suppliers fail to deliver on time. While JIT reduces inventory costs, it can lead to production delays if materials are not available when needed. (Mazanai, 2012.) The system, also known as the Toyota Production System (TPS), is especially popular in manufacturing industries, where maximizing efficiency and minimizing waste are critical. (Stojkanovic et al, 2021, pp. 193-194.)

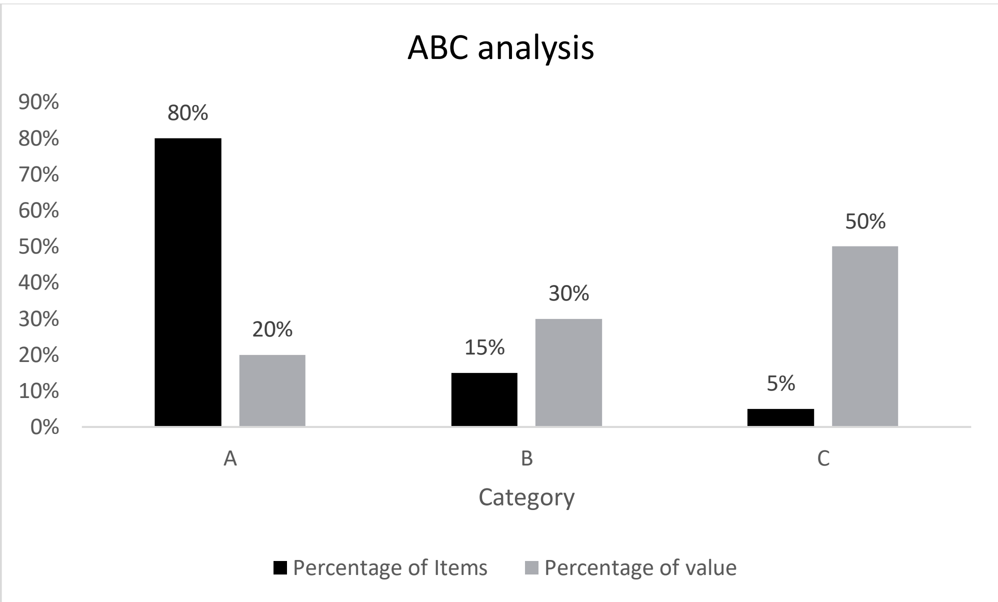

Figure 1. ABC analysis (Baluyot, 2022).

ABC analysis (Figure 1) is another popular inventory management technique in which products are classified based on their consumption value. Products in the A category are the most valuable and require close monitoring, while B and C category products are of lesser importance. This method follows the 80/20 rule, where 20% of the items (A category) account for 80% of the inventory's total value. (Emar et al., 2021, p. 1161.) ABC analysis helps companies focus resources more effectively by closely managing the most critical items, which reduces costs and improves product availability (Kumar et al., 2022, p. 27).

Inventory management is crucial for businesses, ensuring they meet customer demand while controlling costs. Key strategies like EOQ, JIT and ABC analysis help optimize inventory levels. EOQ balances ordering and holding costs, JIT minimizes stock to reduce expenses and ABC analysis prioritizes high-value items. Together, these models enhance decision making, improve operational efficiency and ensure product availability, leading to greater customer satisfaction and increased profitability. Exploring these approaches allows businesses to adapt to market changes effectively.

2.2.3 Transportation systems efficiency and optimization

The selection, routing and optimization of transportation systems play a critical role in the operations and logistical efficiency of manufacturing companies. In manufacturing, transportation is not merely a supporting function but an integral part of the production process, directly affecting cost-efficiency, production flow and customer satisfaction. The effectiveness of transportation systems and optimized routes help manage both the logistics of raw materials and finished goods, enhancing competitiveness and reducing costs. (Sied, 2024.)

Efficient transportation systems are essential for ensuring the timely availability of raw materials and components. When transportation is optimized, a company can leverage just-in-time methods, where raw materials arrive at the production site exactly when needed. This reduces inventory costs and minimizes the amount of capital tied up in stock, thus improving cost efficiency and reducing the risk of production delays (Chunawalla, 2016).

Additionally, the optimization of transportation systems can significantly impact delivery times and logistics costs. For instance, the choice of transportation mode is primarily influenced by two parameters: cost and transit time (Ghiani, Laporte & Musmanno. (2013), pp. 318-320). A manufacturing company might opt for simpler unimodal transportation, but in more complex supply chains, multimodal solutions are often utilized. Multimodal transport, where more than one transportation mode is used without changing the load unit, provides flexibility and cost savings, especially in international trade. (Archetti et al., 2022.)

Transportation optimization affects a manufacturing company's cost efficiency at multiple levels. Efficiently planned transport can reduce excess costs, such as fuel expenses, vehicle maintenance costs and labor wages. Moreover, route optimization, for example using algorithms like the Vehicle Routing Problem (VRP) model, can minimize vehicle mileage, reducing total costs and improving environmental performance. (Muniz-Villamizar et al., 2018.)

Cost efficiency also extends to optimizing transshipment costs, the expenses incurred when transferring goods between different transportation modes. Accurate estimation of these costs is critical for assessing when multimodal transportation becomes more cost-effective than unimodal options. (Archetti et al., 2022.)

In manufacturing, the optimization of transportation also has a direct effect on customer satisfaction. Fast and reliable deliveries enhance the company’s competitiveness and strengthen customer relationships. Optimized transport routes and the right combination of transportation modes ensure that products are delivered to customers on time, a critical aspect of supply chain management. (Zijm et al., 2019, p. 469.)

Furthermore, when companies optimize transportation systems by using multimodal solutions, such as intermodal transportation, they can take advantage of the strengths of different transport modes, such as speed, cost efficiency and flexibility. This is particularly important in international business, where distances and complexity increase. Efficient multimodal networks improve delivery reliability and optimize resources, ensuring the best possible service for the customer. (Archetti et al., 2022.)

The selection, routing and optimization of transportation systems are key factors in the success of manufacturing companies. They have a significant impact on production continuity, cost efficiency and customer satisfaction. Properly optimized transportation systems ensure the efficient supply of raw materials, reduce the need for inventory, shorten delivery times and improve product reliability, all of which enhance a company's competitiveness in the market. (Zijm et al., 2019, p. 469.)

2.3 Role of integrated supply chain for logistics performance

Effective supply chain management plays a critical role in balancing various organizational goals, such as maintaining operational efficiency, reducing costs and achieving financial stability while also promoting long-term growth and flexibility. A well-managed supply chain involves integrating both internal and external processes to ensure seamless communication, coordination and flow of goods and information across the entire network. This approach is essential in today's globalized marketplace, where supply chains, rather than individual companies, often determine competitive advantage. As highlighted in contemporary literature, the integration of supply chain operations and the development of collaborative partnerships are essential for enhancing overall supply chain performance and achieving sustainable business success. (Mangan, Lalwani & Butscher, 2008.)

By aligning internal processes, such as production, inventory management and logistics, companies can minimize inefficiencies and delays. Similarly, external integration, involving closer ties with suppliers and customers, enables better communication and coordination across the supply chain, leading to improved operational efficiency and customer satisfaction. (Mangan, Lalwani & Butscher, 2008.) This focus on both internal and external integration is crucial for organizations seeking to optimize their supply chains and respond effectively to the challenges posed by global competition and fluctuating market demands.

The following sections explores the impact of supply chain integration on operational efficiency and the role of constraint management in logistics, highlighting key strategies and technologies that can enhance supply chain performance.

2.3.1 The impact of supply chain integration on efficiency

Supply chain integration has a significant impact on operational efficiency, as it encompasses various communication channels and linkages within the supply network. However, integration should not be confused with collaboration. While integration refers to the alignment and linking of business processes, collaboration involves developing partnerships over time. Integration can exist without collaboration but it serves as an enabler for collaboration. (Mangan, Lalwani & Butcher, 2008.)

Internal integration focuses on integrating communication and information systems within an organization to optimize efficiency. Traditionally, companies have been organized into functional silos, where each department operates independently. This structure can lead to inefficient information flows, delays and errors, as each department optimizes its processes without considering the overall organizational performance. (Mangan, Lalwani & Butcher, 2008.)

For instance, ERP (Enterprise Resource Planning) systems are key enablers of internal integration. They consolidate different functions within an organization, eliminating non-value-adding activities that hinder efficiency. By improving communication and minimizing unnecessary tasks, these systems lead to better service quality and reduced lead times. ERP implementation also exposes inefficiencies within the organization, helping to streamline operations further (Mangan, Lalwani & Butcher, 2008).

External integration involves collaboration between a company and its suppliers, customers and service providers. Backward integration connects the company with its suppliers, particularly first-tier and sometimes second-tier suppliers, while forward integration links the company with its customers and service providers. Full supply chain integration, which includes both suppliers and customers, is rare but represents an ideal state where the entire supply chain operates seamlessly. (Mangan, Lalwani & Butcher, 2008.)

External integration often relies on technologies such as Electronic Data Interchange (EDI), which automates the transfer of order information between supply chain partners. This streamlines processes and reduces the likelihood of errors. Like ERP systems, external integration requires well-designed organizational structures and processes. While integration focuses on products and processes, collaboration is built around relationships. (Mangan, Lalwani & Butcher, 2008.)

Supply chain integration also plays a crucial role in mitigating the risk of supply chain disruptions. It enables supply chain partners to access each other’s capacity and inventory data, improving planning and scheduling. When supply chain members have better visibility into each other's resources and plans, they can more effectively anticipate and address potential disruptions. This upstream and downstream flow of information is essential for minimizing supply chain disruptions and ensuring timely deliveries. (Krajewski, Malhotra & Ritzman, 2022.)

Beyond improving efficiency, supply chain integration can provide a significant competitive advantage. It helps optimize resource utilization and enhances overall supply chain performance. Supplier involvement in product design allows them to provide high-quality components that can be used efficiently in manufacturing. Similarly, customer involvement in production and distribution brings valuable feedback, helping companies identify process inefficiencies and develop better solutions. (Quang et al., 2015.)

Research shows that supply chain integration directly influences a company's competitive performance and customer satisfaction. Integration with both suppliers and customers improves schedule attainment, competitive positioning and customer satisfaction. Similarly, internal integration is positively linked to improved performance and efficiency. (Zhao et al., 2012.) This underscores the importance of collaboration and information sharing among supply chain partners to ensure smooth and efficient operations.

Supply chain integration is crucial for improving efficiency and competitiveness. It connects internal and external processes, enhances information flows and minimizes disruptions within the supply chain. Technologies like ERP and EDI can streamline processes, but their successful implementation requires careful planning and organizational design. Supply chain integration not only improves internal operations but also fosters better collaboration with suppliers and customers, leading to enhanced performance and customer satisfaction. (Mangan, Lalwani & Butcher, 2008; Krajewski, Malhotra & Ritzman, 2022; Zhao et al., 2012.)

Contract manufacturing, also referred to as third-party manufacturing, is defined as a production arrangement where one company (the "contractor") agrees to produce goods on behalf of another company (Brennan & Vecchi, 2011). This approach allows the contracting company to focus on its core competencies, such as product design and development, while leveraging the contractor's production capabilities. The significance of contract manufacturing has grown, particularly in industries like electronics and pharmaceuticals, as it enables companies to reduce production costs, improve scalability and increase flexibility. (Qrunfleh & Tarafdar, 2014.)

Contract manufacturing enhances supply chain efficiency by optimizing logistics. By partnering with established contractors, companies can benefit from existing networks and distribution channels. (Sridharan & Simatupang, 2013.) For instance, Kumar et al. (2017) found that firms using contract manufacturing could achieve "considerable cost savings" by avoiding the need to invest in their own production facilities, which allows for greater investment in innovation and market growth.

Contract manufacturing facilitates better inventory and supply chain management. Qrunfleh and Tarafdar (2014) note that outsourcing production can "lead to improved logistics performance" especially when manufacturers are geographically closer to end markets. However, managing these external relationships can present challenges, including issues related to product quality and coordination throughout the supply chain (Sridharan & Simatupang, 2013).

The increasing reliance on contract manufacturing reflects its vital role in modern supply chains, as companies strive to streamline production processes and enhance responsiveness to market dynamics.

2.3.2 Theory of constraints in logistics

The Theory of Constraints (TOC), developed by Eli Goldratt, is a management approach designed to identify and address constraints or bottlenecks that limit the performance of a system. It has broad applications across various industries, including logistics, where it helps improve overall supply chain performance by focusing on the weakest link. This theory views processes as interconnected parts of a whole, rather than isolated functions. By identifying and managing the bottleneck, TOC allows organizations to optimize their operations and achieve higher profitability and efficiency. (Krajewski, Malhotra & Ritzman, 2022, pp. 241-242.)

In logistics, TOC emphasizes that systems consist of interconnected processes, much like the links in a chain, where the performance of each part affects the entire system. If one link is weak, the whole system suffers. The central principle of TOC is that every logistics system has at least one constraint that limits its overall throughput. This constraint, whether physical (e.g., limited production capacity), market-related (e.g., lack of demand) or managerial (e.g., poor planning or resource allocation), is the point at which improvement efforts should focus. (Krajewski, Malhotra & Ritzman, 2022, pp. 241-242; Kacmary & Fedorko, 2015, p. 14.)

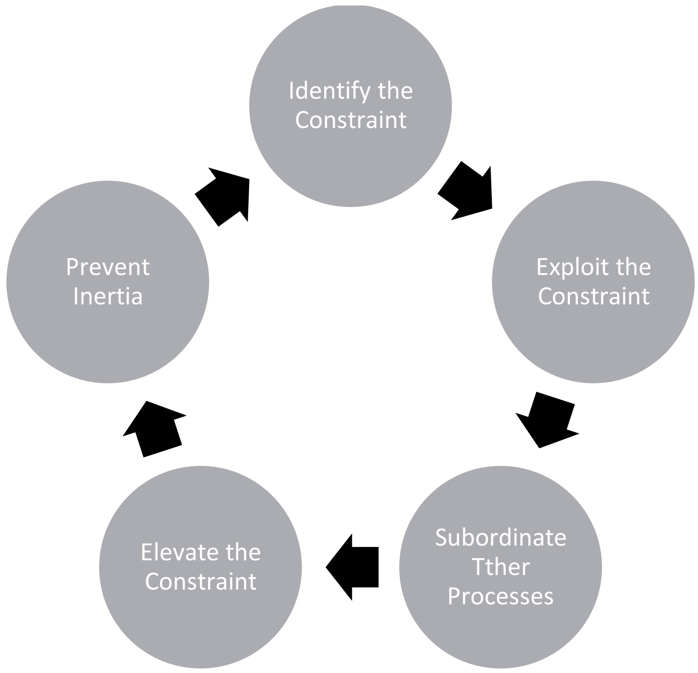

Figure 2. TOC process (Goldratt, 1986).

TOC outlines a structured, five-step process for addressing these constraints (Figure 2):

1. Identify the Constraint: The first step is to identify the constraint that limits the system's overall performance. In logistics, this could be related to production capacity, warehouse space, transport availability, or market demand. These bottlenecks are the key factors restricting throughput, and the overall performance of the system depends on managing them effectively.

2. Exploit the Constraint: Once the constraint is identified, it is essential to make the most out of its capacity. In logistics, this means optimizing the bottleneck so that it works on the right products or services to maximize profitability. Inefficiencies often arise from producing the wrong product mix or scheduling resources incorrectly, leading to wasted capacity at the bottleneck.
3. Subordinate Other Processes: In this step, the goal is to align all other processes to support the constraint. This could involve changing metrics and decision-making rules across the supply chain. For example, other departments or functions should adjust their workflows to ensure that the constraint operates without unnecessary interruptions.
4. Elevate the Constraint: If the capacity of the constraint remains insufficient, it must be increased. This might involve redesigning processes, investing in additional resources, or working with suppliers to boost production. In logistics, this could mean reconfiguring transportation routes or introducing new technology to increase capacity at the bottleneck.
5. Prevent Inertia: Once the constraint is addressed, a new bottleneck may appear elsewhere in the system. Continuous improvement is essential in TOC, meaning that after resolving one constraint, organizations must return to step one and identify the next limiting factor. This cycle of identifying and managing constraints ensures that firms continue to optimize their operations. (Kacmary & Fedorko, 2015, p. 14).

TOC has several practical applications in logistics, particularly in improving the flow of materials and managing inventories. Three notable methods include:

- Drum-Buffer-Rope (DBR) Scheduling: This method ensures smooth production flow by synchronizing the pace of operations (the "drum") with available capacity, while buffers are used to manage variability, and the "rope" ensures materials are only released when needed. DBR helps minimize overproduction and excess inventory, common challenges in logistics. (Krajewski, Malhotra & Ritzman, 2022, p. 242.)

- Buffer Management: In logistics, managing buffers—whether they are inventory or time buffers—helps ensure that supply chain disruptions don’t cause bottlenecks. Proper buffer management involves adjusting buffer sizes based on demand variability and lead times, helping maintain a steady flow of goods and services. (Krajewski, Malhotra & Ritzman, 2022, p. 242.)
- VAT Analysis: This approach analyzes how goods and services flow through different stages of production and distribution, helping firms understand where constraints are likely to occur. VAT (V = volume, A = assembly, T = transportation) analysis identifies where value is added and where delays or bottlenecks might occur, providing a framework for addressing them. (Kacmary & Fedorko, 2015, p. 14.)

In logistics, constraints can occur at multiple levels, including suppliers, customers and within the firm itself. For instance, a shortage of raw materials from suppliers may limit production capacity, creating a bottleneck in the firm’s ability to meet customer demand. Likewise, logistical constraints like limited warehouse space or transport delays can disrupt supply chain efficiency. According to TOC, firms must manage these constraints strategically, not just by increasing capacity but by coordinating decisions across departments and aligning resources to meet overall demand. (Krajewski, Malhotra & Ritzman, 2022, p. 241.)

TOC emphasizes that every resource in the system, including capital investments, labor and in-process materials, is inventory and must be managed effectively. Any product or service that does not lead to a sale increases inventory and operational costs without improving throughput. Therefore, logistics managers must ensure that bottleneck resources are fully utilized to maximize system throughput. If bottlenecks are not managed properly, they result in imbalanced capacity, where some areas of the system operate at full capacity while others lag, reducing overall efficiency. (Krajewski, Malhotra & Ritzman, 2022, p. 242.)

The Theory of Constraints provides a comprehensive framework for improving logistics performance by focusing on bottlenecks. By applying TOC's five-step process, firms can systematically address constraints, optimize capacity and improve overall throughput. This leads to better resource utilization, lower operational costs and increased profitability. TOC's holistic approach encourages businesses to consider the interconnectedness of their supply chain and continuously seek improvements across all levels, ensuring long-term success in an ever-changing market environment.

2.4 Process optimization methods

Process optimization refers to the practice of improving the efficiency and effectiveness of operations to achieve the best possible performance within an organization. This involves identifying inefficiencies, reducing waste, improving workflow and enhancing overall system performance. In logistics, the need for process optimization is particularly acute due to rising global demand, increasing costs and competitive pressures. As a result, logistics managers are tasked with finding ways to enhance operational performance and deliver more value to customers. Table 2 shows optimization models that can be implemented in logistics.

Optimization Model	**Description**	**Benefits**
Lean Logistics	Focuses on minimizing waste, improving flow and increasing efficiency in logistics operations.	Reduces lead times, minimizes waste and improves overall system efficiency
Six Sigma	A data driven methodology that seeks to eliminate defects and variations in processes.	Improves quality, reduces costs and increases customer satisfaction by minimizing errors.
Total Quality Management	Focuses on continuous improvement, quality control and customer satisfaction in every aspect of logistics.	Enhances customer satisfaction and ensures long-terms operational improvements.
Theory of Constraints	Concentrates on identifying and managing	Identifies and removes bottlenecks, improving

	bottlenecks to optimizeflow and performance in the supply chain.	throughput and system performance.
Just-in-Time	Focuses on inventory control and reducing excess stock to improve operational efficiency.	Reduces inventory costs, increases product availability and enhances operational flexibility.

Table 2. Optimization models (Gourdin, 2001).

Various methodologies, including Lean logistics and Six Sigma offer valuable tools for optimizing logistics processes, improving speed, reducing costs and increasing flow within the supply chain. By leveraging these tools, organizations can create more efficient, cost-effective logistics systems that deliver higher value to customers and enhance overall business performance. (Gourdin, 2001.)

2.4.1 Role of Lean logistics in waste reduction and efficiency enhancement

Lean logistics is a refined approach to logistics management that draws its principles from the Toyota Production System (TPS), seeking to eliminate waste and inefficiencies across the supply chain. The goal is to streamline logistics operations by improving speed, reducing costs and maximizing customer value. As lean concepts move beyond their traditional application in manufacturing, they have been successfully adapted to logistics and supply chain management, shaping how modern companies manage their resources and processes. (Brewer, Button & Hensher, 2001.)

The core of lean logistics lies in understanding the inefficiencies that exist in current systems and then eliminating them through both radical and incremental changes. The lean methodology focuses on the identification of non-value-adding activities, often referred to as muda, which hinder optimal performance. This philosophy is operationalized through tools like value stream mapping, which allows businesses to visually represent all processes involved in the logistics system, from the receipt of goods to final delivery, identifying waste and areas for improvement along the way. This detailed understanding is vital for the development of a logistics system that operates at peak efficiency. (Brewer, Button & Hensher, 2001.)

A fundamental aspect of lean logistics is the focus on waste reduction, where waste is not limited to material resources but also includes time, space and human capital. According to lean theory, excess inventory is one of the most prominent forms of waste in logistics. Excess inventory ties up capital, consumes storage space and can obscure underlying inefficiencies in the system. By maintaining only the necessary inventory required to meet immediate customer needs, lean logistics ensures that resources are utilized effectively, reducing storage costs and enhancing flow across the supply chain. (Goldsby & Martichenko, 2005.)

The lean philosophy also introduces six key potential sources of waste in logistics: transportation, space and facilities, time, packaging, administration and knowledge (Goldsby & Martichenko, 2005). While each of these elements is necessary for efficient logistics operations, they become sources of waste when mismanaged. For instance, inefficient transportation routes can lead to longer delivery times and increased fuel consumption, while poorly designed warehouse layouts waste valuable space and lead to inefficient use of labor. Similarly, time wasted due to delays in processes, such as waiting for shipments or inefficient administrative procedures, reduces the overall velocity of the supply chain.

Moreover, lean logistics extends its focus beyond operational costs by emphasizing the concept of total cost. This approach urges logisticians to consider all aspects of cost simultaneously, rather than focusing solely on specific elements like transportation or warehousing. For many industries, inventory carrying costs can account for a significant portion—up to 40%—of total logistics expenses, making the reduction of excess inventory critical for improving overall financial performance. (Goldsby & Martichenko, 2005.) Many organizations struggle to adopt the total cost approach fully, often making decisions based on more visible, traditional cost drivers such as transportation and warehousing without understanding the hidden costs of inefficient inventory management or excess handling.

In addition to optimizing internal logistics processes, lean systems also address external linkages with suppliers and customers. Lean logistics encourages collaboration across the entire supply chain, aiming to reduce waste not only within a company but also in its interactions with partners. By fostering more efficient relationships, companies can ensure that their supply chains function smoothly, from procurement to final delivery. (Krajewski, Malhotra, & Ritzman, 2022.)

A notable feature of lean logistics is its focus on continuous improvement, also known as kaizen. This Japanese concept emphasizes that improvement is an ongoing process, with the goal of identifying inefficiencies and incrementally enhancing processes over time. Lean systems are built on the premise that hidden problems, such as excess capacity or inventory, conceal deeper inefficiencies. By minimizing these "buffers" companies expose the real issues within their processes, allowing them to make targeted improvements. In the context of inventory management, lean systems advocate for maintaining low inventories to reveal operational bottlenecks and inefficiencies that would otherwise remain obscured. (Krajewski, Malhotra, & Ritzman, 2022.)

The eight wastes (Figure 3) commonly identified in lean systems—overproduction, inappropriate processing, waiting, transportation, motion, inventory, defects and underutilization of employees—are all prevalent in logistics as well (Krajewski, Malhotra, & Ritzman, 2022). In urban logistics, for example, overproduction can occur when orders are prepared too early, leading to congestion and delays in distribution centers (Esceder & Tanco, 2020). Unnecessary transportation and extra motion are often the result of poor route planning or inefficient warehouse layouts, where products are not stored in a logical order, causing longer search and retrieval times. Similarly, defects, such as incorrect order fulfillment or damaged goods, lead to costly rework, returns and customer dissatisfaction.

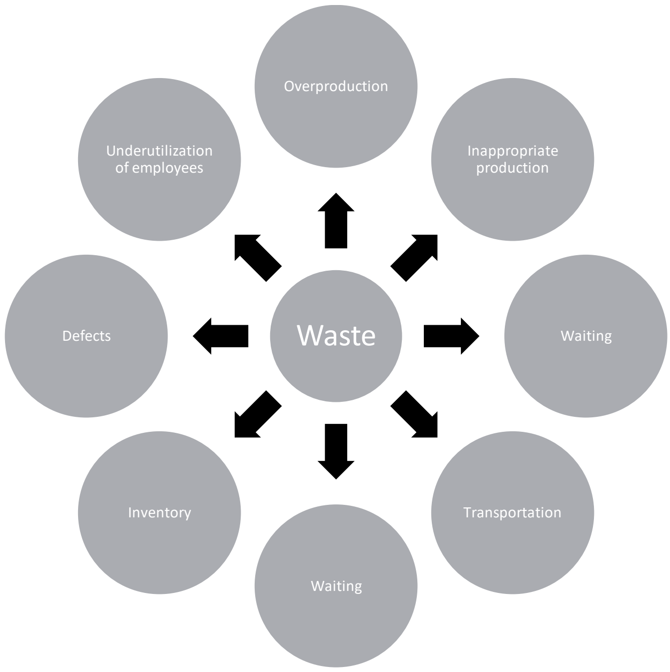

Figure 3. Waste identification (Roosen & Pons, 2013).

One of the more subtle forms of waste identified in lean logistics is the underutilization of employee skills and knowledge. In many logistics operations, workers' potential is often overlooked, as tasks are designed around specific processes rather than tapping into employees' abilities to improve those processes. Lean logistics aims to correct this by empowering employees to participate in continuous improvement initiatives and contribute to more efficient workflows. (Esceder & Tanco, 2020.)

Lean logistics is not a one-size-fits-all solution, but its principles can be adapted to various industries and supply chain environments. It calls for a holistic view of logistics, where the focus is on eliminating waste at every stage, from procurement and production to distribution and delivery. By streamlining processes, reducing unnecessary inventory and fostering a culture of continuous improvement, companies can achieve significant cost savings, improve service levels and enhance customer satisfaction.

Lean logistics offers a strategic framework for optimizing logistics systems by focusing on waste reduction, improving flow and aligning resources more effectively. Through a deep understanding of inefficiencies and the application of tools like value stream mapping, organizations can drive both radical and incremental improvements in their logistics operations. By adopting the lean approach, companies can not only reduce costs but also enhance overall supply chain performance, ensuring that their logistics systems provide maximum value to both customers and the business itself.

2.4.2 Role of six sigma to improve process quality improvements

Six Sigma is a robust management methodology that aims to understand and eliminate the negative effects of variation in organizational processes. This structured approach is built upon a framework of trained professionals who employ statistical process control tools alongside the "voice of the customer" to identify and solve problems. At its core, Six Sigma promotes the reduction of process variability to achieve a defect rate of no more than 3.4 defects per million opportunities. This goal is grounded in the concept of maintaining high levels of quality and performance, ensuring that products and services meet customer expectations consistently. (Krajewski, Malhotra & Ritzman, 2022.)

Central to the Six Sigma methodology is the DMAIC (Figure 4) model—define, measure, analyze, improve and control. This step-by-step process enables organizations to systematically tackle quality issues:

- Define: Clearly articulate the problem and the goals for improvement.
- Measure: Collect relevant data to understand current performance levels.
- Analyze: Identify root causes of defects and variations in the process.
- Improve: Develop and implement solutions to eliminate root causes and enhance process performance.
- Control: Establish controls to sustain the improvements and ensure processes remain consistent over time.

Six Sigma projects rely on this structured approach to achieve meaningful process enhancements and drive organizational growth. (Cudney & Kestle, 2011.)

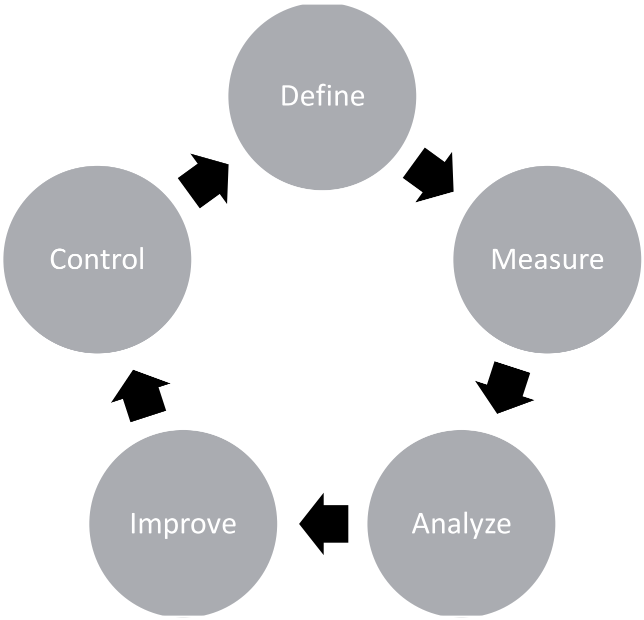

Figure 4. DMAIC process (Alwan & Abeer, 2016).

At the heart of Six Sigma is the principle of variation reduction. Variability can lead to inconsistent outputs, customer dissatisfaction and ultimately lost sales. For example, if the average order-to-delivery cycle time fluctuates between two and eight days, this variability can erode customer confidence and contribute to excess inventory costs. By understanding and controlling the variations in supply chain processes, organizations can mitigate reliance on safety stocks, which are maintained as buffers against uncertainties in supplier quality, transportation reliability, and customer demand patterns. (Goldsby & Martichenko, 2005).

One of the key aspects of Six Sigma is its customer-centric focus. The methodology emphasizes understanding customer needs and aligning processes to meet those expectations effectively. By reducing variability in product design, production and administrative processes, organizations can achieve higher levels of customer satisfaction. This focus on the customer not only drives continuous improvement but also enhances organizational performance by fostering a culture that prioritizes quality. (Nave, 2002.)

The implementation of Six Sigma offers numerous benefits, including:

- Reduced Defects: By systematically identifying and eliminating root causes of defects, organizations can achieve lower rates of defective products. In this study, reducing defects is particularly crucial for improving the quality of the process and product.
- Increased Customer Satisfaction: Higher quality products and services lead to improved customer experiences and loyalty. This aligns with the case company´s goal of enhancing customer retention.
- Enhanced Process Capability: By improving process throughput and capability, organizations can optimize their operations and reduce waste. For the case company, this means addressing bottlenecks in logistics processes.
- Stronger Team Communication: Six Sigma fosters collaboration and teamwork, enhancing communication across departments. This is significant in the context of cross functional teams within the case company.
- Long-Term Financial Benefits: Cost reductions from decreased defects and improved efficiency translate into greater profitability. For the case company, this could mean reduced operational costs and better financial outcomes (Revere et al., 2003.)

Six Sigma is a powerful framework for process quality improvement that emphasizes the reduction of variation, enhanced customer satisfaction and a disciplined approach to problem-solving. By employing the DMAIC methodology, organizations can achieve significant improvements in quality and performance, leading to long-term success. While some may view Six Sigma as merely a fad, its principles and practices remain integral to achieving high levels of process performance and quality in today’s competitive business landscape. (Näslund, 2008.)

Six Sigma also aligns closely with the principles of Total Quality Management (TQM), which emphasizes customer satisfaction, employee involvement and continuous improvement. TQM and Six Sigma share a common goal: to enhance process performance and quality. While TQM takes a broader approach, Six Sigma focuses specifically on data-driven decision-making and the statistical analysis of processes to minimize defects and variability. Both methodologies recognize that high-quality services and products lead to increased profitability and that quality must be integrated into every aspect of production. (Krajewski, Malhotra & Ritzman, 2022.)

2.4.3 Effect of process mapping and workflow analysis on efficiency

Process mapping is a crucial tool in analysing and improving industrial processes. This method involves five key stages: studying the process flow, identifying waste, assessing whether the process can be rearranged for greater efficiency, considering better flow patterns or transportation routes, and finally determining if all activities are necessary. The process begins with a preliminary analysis, followed by a detailed recording of all relevant aspects of each step. The result is a process map that captures the space used, distance moved, time taken, number of people involved and other key observations. After compiling this data, the total distance, time and people involved are calculated. This serves as the basis for further analysis and improvement, often using techniques like the 5W1H method, which asks questions about the necessity and execution of each activity. The goal of this approach is to eliminate unnecessary steps, simplify others and reorganize activities to reduce waste. (Brewer, Button & Hensher, 2001, pp. 180-181.)

While process mapping seems like a basic management tool, many organizations operate without it. This often happens because companies start small, and their processes evolve incrementally over time, leading to confusion and redundancy. In contrast, a coordinated and planned system can be easily documented and mapped to identify process owners and critical touchpoints, also known as "moments of truth." These moments of truth are crucial and must be coordinated, managed and measured. For example, the process of moving raw materials into a production facility requires careful planning to ensure smooth operations. (Goldsby & Martichenko, 2005, p. 121.)

Value Stream Mapping (VSM) is a tool used to identify waste and highlight opportunities for Lean improvements. Rather than focusing on working harder, it emphasizes working smarter by providing a visual representation of the entire system, including inputs, processes and outputs. VSM shows the connections within the system and challenges the current state of activities. It identifies sources of non-value-added waste in the value stream and serves as the foundation for an improvement plan. This plan envisions the desired future state of the process, helping to develop a collection of improvement actions or “events”. (Plenert, 2007, p. 234.)

Process maps are widely used in continuous improvement projects because it is difficult to improve a process without understanding its steps and who owns them. Developed by Frank and Lillian Gilbreth in the early 20th century, process maps or flowcharts, are graphical displays of the steps, events and operations that make up a process. These maps help organizations identify value-added and non-value-added steps, providing a common understanding of the process and its inputs and outputs. They can also be used to evaluate process capabilities and measurement analysis. A high-level process map that outlines only the core steps can be a good starting point to establish process boundaries and gain stakeholder buy-in. Process maps can include decision points and dependencies between groups or individuals, often visualized using swim lanes. Traditional process maps are created through interviews, brainstorming sessions, and observations, but variations can arise based on factors like shifts, individual workers or seasons. (Tarantino, 2022, pp. 59-66.)

Process maps make workflows visible, helping organizations understand the work better and achieve their goals. They assist teams in clarifying how their work contributes to customer value, fits into the overall workflow and connects to the primary operations of the enterprise. Process maps improve communication, strengthen teamwork and support process ownership transfer. They also provide a foundation for continuous improvement by visualizing the relationship between different activities. This helps to assess how local changes impact broader workflows across the organization. (Dameli, 2011, pp. 31-32.)

Process mapping and workflow analysis offer organizations powerful tools to improve efficiency and identify sources of waste. These methods clarify processes, streamline operations and create a foundation for continuous improvement. Through detailed analysis, organizations can assess their current state, develop improvement plans and ensure that activities provide maximum value to the customer.

2.5 Previous research on OTD process optimization

Research indicates that supply chain integration (SCI) and on-time delivery (OTD) significantly impact contract manufacturing performance. SCI can influence cost efficiency, with customer and supplier integration having varying effects on return on contract manufacturing. (Kim & Schoenherr, 2018.) OTD is crucial for customer satisfaction and competitive advantage, with top suppliers consistently improving delivery windows and reliability (Kumar & Sharman, 1992). Implementing lean thinking methodologies, live tracking tools and cross-functional team approaches can substantially improve OTD performance in make-to-order situations (Ramachandran & Neelakrishnan, 2017). Contract manufacturing can lead to reduced inventory levels across industries, potentially enhancing overall supply chain efficiency (Cheng et al., 2012).

These findings suggest that focusing on SCI, OTD and contract manufacturing strategies can offer significant benefits to supply chain management performance in contract manufacturing companies, including cost reduction, improved customer satisfaction, and increased operational efficiency. This section delves into the existing literature surrounding OTD process optimization, categorized into two key subsections.

2.5.1 Comparing research approaches of OTD optimization

Previous studies on order-to-delivery (OTD) optimization, such as those by Mishra and Singh (2019) and Tortorella and Fettermann (2018), provide valuable insights into different aspects of the OTD process. These studies offer unique perspectives but also exhibit certain limitations that this research seeks to address.

Mishra and Singh (2019) offer a thorough overview of key elements within the OTD process, including order processing, inventory management and deliveries. Their research highlights the critical role of integration among logistics operations in improving process efficiency. They emphasize that the effectiveness of the OTD process heavily depends on how well various departments and functions are interconnected. However, their analysis remains superficial, lacking a detailed examination of the interactions among these elements and their collective impact on the OTD process. Challenges such as information sharing and collaboration are discussed at a general level, without practical solutions.

Aspect	**Mishra and Singh**	**Tortorella and Fettermann**
Focus	Integration of logistics operations in the OTD process.	Integration of Lean principles and industry 4.0.
Key findings	Highlighted the importance of interdepartmental connectivity.	Showed how Lean reduces waste and industry 4.0 enhances efficiency.
Limitations	Superficial analysis of interconnections between elements.	Limited consideration of the OTD process as a whole.
Relevance to current study	Insights on challenges in integratino and collaboration.	Opportunities for synergy between Lean and industry 4.0.

Table 3. Comparison of logistics integration and industry 4.0.

Conversely, Tortorella and Fettermann (2018) explore the integration of Lean principles and Industry 4.0, uncovering opportunities to enhance operational performance. Their study emphasizes the role of Lean methodologies in reducing waste and improving efficiency, which is particularly relevant to OTD optimization. However, their findings overlook the comprehensive management of the OTD process, including the dynamics between different logistics elements. This raises the risk of implementing Lean and Industry 4.0 strategies in isolation, without considering their interconnections with other aspects of the OTD process. Table 3 illustrates the differences and overlaps between these studies.

Building on these insights, this study explores how logistics elements—material handling, inventory management, and transportation—interact as a dynamic system influencing each other. The objective is to analyze these interactions to improve OTD process efficiency and customer satisfaction.

The research examines how internal communication, information sharing, and collaboration support integration and improve the fluidity of the OTD process, addressing challenges identified in prior studies.

This approach aims to provide actionable recommendations that foster integration and cooperation while addressing challenges in OTD optimization. By bridging research gaps, the study seeks to deliver practical and theoretical contributions for improving the OTD process.

2.5.2 Case studies of OTD optimization in various industries

Optimizing on-time delivery (OTD) has become a critical success factor across industries, with companies implementing innovative strategies to improve efficiency in their delivery processes. Companies have adopted diverse strategies to enhance their delivery processes and improve efficiency. Table 4 summarizes key cases studies from industries such as automotive, technology, manufacturing, e-commerce and pharmaceuticals, highlighting the strategies, outcomes and references for each company.

Company	Industry	Key strategies	Outcome
Toyota	Automotive	Toyota production system (TPS) focusing on lean production and flexible processes.	Reduced waste, short lead times, improved supply chain flexibility, better OTD.
Dell	Technology	Vendor-managed inventory (VMI), pull mechanism driven by customer demand.	Low inventory, optimized material flow, reduced supply chain disruptions, improved OTD.
General Electric	Manufacturing	Six Sigma methodology for quality improvement and defect minimization.	Enhanced quality and delivery precision, improved OTD performance.
Amazon	E-commerce	Automation in logistics and data analytics for optimized deliveries.	Rapid, accurate delivery, optimized supply chain in real-time, improved OTD
Pfizer	Pharmaceutical	Predictive delivery strategies and data based inventory management.	Enhanced delivery precision, improved OTD in a complex supply chain.

Table 4. Case studies of OTD optimization acrtoss different industries (Liker, 2004; Kapuscinski et al., 2004; Pyzdek & Keller, 2010).

Toyota is renowned for its Toyota Production System (TPS), which emphasizes production flow and short lead times. TPS allowed Toyota to optimize its OTD process by reducing waste, enhancing flexibility and focusing on creating customer value. Toyota's production model is based on lean thinking, where production is designed to meet demand through a "pull" system, minimizing inventory levels and ensuring efficient deliveries. (Liker, 2004.)

A key takeaway from Toyota’s approach is that flexible production lines capable of handling multiple product types simultaneously improve supply chain performance significantly. This flexibility allows Toyota to respond swiftly to customer needs, enhancing both OTD accuracy and quality. Toyota’s system highlights that short lead times and flexible processes are essential to improving OTD in various industries. (Liker, 2004.)

Dell’s business model revolves around fulfilling customer orders quickly and efficiently. Dell developed a vendor-managed inventory (VMI) system where suppliers manage their inventories and deliveries according to Dell's target inventory levels. The system ensures low inventory levels and optimizes material flow. Dell uses a pull mechanism driven by customer demand, ensuring that only the necessary products are withdrawn, reducing excess inventory, and streamlining OTD. (Kapuscinski et al. 2004.)

The lesson from Dell’s case is the importance of transparent, real-time communication throughout the supply chain. Dell shares detailed forecasts with its suppliers, improving decision-making and enabling better inventory management strategies. This reduces supply chain disruptions and enhances OTD accuracy. Dell’s approach demonstrates that collaboration and data sharing between companies and suppliers are key to sustaining OTD improvements over time. (Joan, 1998.)

General Electric (GE) implemented the Six Sigma methodology to enhance its OTD performance by focusing on quality improvement and minimizing defects. GE realized that moving from lower quality standards to a Six Sigma level could significantly reduce waste and ensure timely deliveries. Six Sigma enabled GE to identify and remove bottlenecks in the delivery process, ensuring all processes operated efficiently and on schedule. (Pyzdek & Keller, 2010.)

The benefits GE achieved through Six Sigma, including improved quality and delivery precision, are clear indicators that systematic, data-driven process management can enhance OTD. GE's example emphasizes the importance of continuous process improvement and measurement in optimizing supply chains. (Pyzdek & Keller, 2010.)

Amazon revolutionized OTD in e-commerce by automating its logistics systems and using data analytics to predict and optimize deliveries. Amazon's extensive use of automation in warehouses and finely tuned delivery algorithms allows the company to ensure rapid and accurate product delivery to customers.

Amazon's strategy is built on quick deliveries and precise storage and shipment decisions informed by vast amounts of customer and order data. This enables the company to optimize its entire supply chain in real time, reducing delays and improving OTD performance. Amazon demonstrates that data-driven decisions and automation can yield substantial advantages in supply chain management. (Liker, 2004.)

In the pharmaceutical industry, Pfizer has successfully developed flexible supply chains that allow for the rapid and accurate delivery of medications. Delivery precision is critical in this sector, and Pfizer has adopted predictive delivery strategies and data-based inventory management to enhance its OTD performance.

Pfizer's case underscores that, in complex supply chains like those in the pharmaceutical industry, precise forecasting and flexible delivery mechanisms are crucial to OTD improvements. Pfizer shows that strict quality requirements and accurate delivery processes can reduce delays and increase customer satisfaction (Pyzdek & Keller, 2010).

Companies from various industries, such as Toyota, Dell, General Electric, Amazon, and Pfizer, have successfully optimized their OTD processes through different strategies. By applying these principles, companies in various sectors can develop OTD strategies and optimize their supply chains to meet customer demand more effectively.

3 Research methodology

This study used a mixed-methods approach to examine logistics performance, integrating both qualitative and quantitative data to gain a holistic understanding of logistics processes and their efficiency. A mixed-methods approach is particularly valuable in logistics studies, as it allows for the exploration of complex, multifaceted issues that cannot be fully captured through a single data type (Creswell & Plano Clark, 2017). By combining qualitative insights into the workflow and operational challenges with quantitative metrics that measure actual performance, the study can provide a deeper understanding of both the "how" and the "how much" of logistics operations (Bryman, 2016). The integration of qualitative data allows for a comprehensive understanding of operational dynamics, while quantitative data offers measurable evidence of performance, ensuring that both subjective and objective aspects of logistics are considered (Tashakkori & Teddlie, 2003). Figure 5 illustrates the mixed-methods research methodology for studying logistics performance.

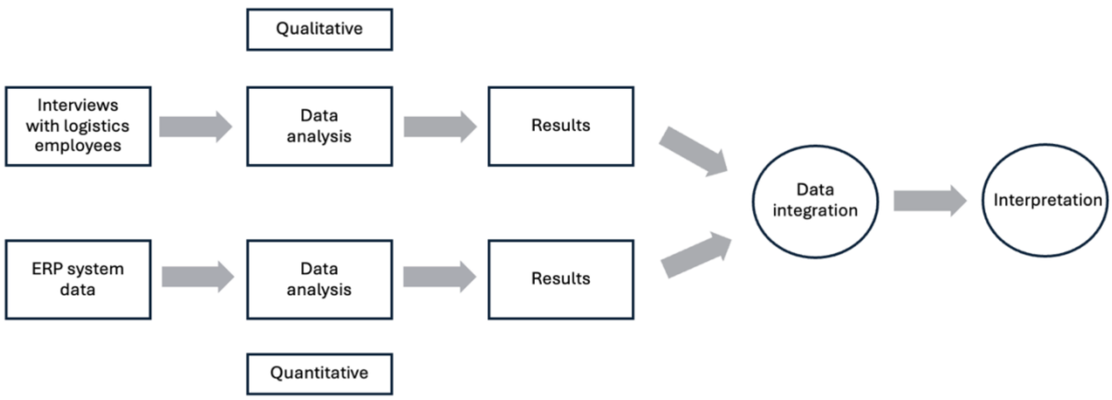

Figure 5. Mixed-methods research methodology (Opoku & Ahmed, 2013).

To achieve this aim, qualitative data was gathered through interviews with employees directly involved in logistics tasks, providing firsthand perspectives on process steps and identifying potential bottlenecks. This was complemented by quantitative data from the company's ERP system, which provided objective metrics on logistics performance over time. The combination of these data types allowed for an in-depth analysis of logistics efficiency, capturing both process nuances and measurable outcomes and ultimately facilitated a thorough assessment of current performance against desired logistics standards.

3.1 KPI metrics for measuring logistics performance

To measure logistics performance effectively, data was gathered exclusively from the company's ERP (Enterprise Resource Planning) system. This system provided a centralized source of historical and real-time data relevant to logistics operations, ensuring that the analysis was based on accurate and comprehensive information. The table 5 shows KPIs which were used to measure logistics and OTD performances.

KPI	Description	Unit of measurement
Component stock impact (1)	Evaluates the impact of component stock on logistics performance using mathematical equation 2.	Dimensionless
Component stock impact (2)	Evaluates the impact of component stock on logistics performance using mathematical equation 3.	Dimensionless
Ready product stock	Assesses the effect of ready product stock on logistics performance.	Dimensionless

Table 5. KPIs for logistics and OTD performance.

The data was sourced directly from the ERP system, where it is systematically recorded as part of daily logistics tracking. This data includes a range of metrics relevant to logistics performance, capturing essential information on activities, timelines, and resource utilization within the company's supply chain processes.

For consistency and relevance, the data used spans from the beginning of the current year, supplemented with records from the most recent three months. This offers a comprehensive view of logistics performance. This approach provided a solid foundation for identifying trends and any potential areas of improvement in logistics operations.

3.2 Planning and conducting interviews

The interviews for this study were conducted in a setting conductive to open discussion, typically within the participants' work environment to capture an authentic representation of their workflow. The factors identified from the interview data were analysed using thematic analysis. During this process, the data was coded and grouped based on recurring themes, enabling the systematic identification of key challenges and factors. This choice of setting allowed participants to feel comfortable and accurately describe their tasks within the real context of their work. To ensure a representative sample, the following details of the interviews are presented in the table 6.

Participant role	Years of experience	Mode of interview	Duration
Transportation engineer	2	Online	60 minutes
Material planner	4	Online	50 minutes
Production planner	2	Online	60 minutes

Table 6. Interview participants details.

A total of 3 interviews were conducted, ensuring coverage across key roles directly involved in logistics operations. Interviews were scheduled at times convenient for each participant to minimize disruption to their daily responsibilities and maximize engagements.

The sample size was deemed sufficient as the information gathered during the interviews aligned with existing background data, confirming the reliability of the findings. Additional interviews were unnecessary, as perspective from different departments were consistent and no significant themes emerged. To support this conclusion of the sample size, the mathematical equation 1 was applied.

(1) The sample size is determined using the following formula

$$n = \frac{N}{1+N(e^2)} \qquad (1)$$

where [n is the sample size, N is the population size (8) and e is the margin of errors (0,10) (Yamane, 1967)].

While the theoretical sample size suggests 8 participants, practical constraints and the observations data saturation justified the use of a smaller sample. The themes identified during the 3 interviews were consistent with prior knowledge, confirming the adequacy of the sample size for the scope of this study.

To obtain an in-depth understanding of the processes, I selected participants who were actively performing the tasks under examination within their respective teams. By focusing on individuals directly involved in these specific roles, I aimed to gain insights into the day-to-day activities and challenges they face, ensuring that the process descriptions would accurately reflect actual practices. I interviewed one person per team, selecting representatives with the most relevant experience and knowledge.

The interviews were conducted in a semi-structured format. I prepared initial draft versions of the process flow, outlining my preliminary understanding of the tasks involved. During each interview, we reviewed these drafts together from start to finish, allowing the participants to identify inaccuracies and provide corrections. This collaborative review enabled us to refine the process descriptions and identify any bottlenecks, ensuring the accuracy and applicability of the information gathered.

When reviewing the initial process flow diagrams, participants were asked to indicate the steps they perceived as time-consuming or problematic. During these discussions, certain recurring bottlenecks emerged, such as delays in communication or uneven availability of resources. These insights were further refined by asking participants to provide specific examples of challenges they encountered and how they affected their workflows

Each interview lasted approximately 60 minutes, allowing enough time for a thorough review of the processes without overwhelming the participants. While I did not record the interviews on video, I took detailed notes throughout the discussions. Additionally, I created process diagrams based on these notes, mapping out the workflows and highlighting bottlenecks. The process diagrams not only visualized the workflows but also highlighted key bottlenecks and challenges. These diagrams served as a foundation for further analysis, illustrating the dependencies between tasks and the critical points where delays occurred.

The key factors identified in the interviews, such as resource availability and inter-team communication, are directly linked to the research objectives of optimizing the OTD process. These factors highlight areas that require improvement and provide a clear foundation for the recommendations aimed at addressing the existing challenges.

3.3 Data analysis and integration

To prepare the data for analysis, I began with three separate datasets, each requiring specific cleaning and transformation steps to ensure accuracy and relevance. First, I filtered each dataset to include only records within the desired date range, from beginning of August 2024 to the end of October 2024. This step was essential for maintaining consistency in the analysis period.

Next, I removed any data entries with zero values, as these indicated the absence of events and would skew the analysis if included. In the dataset for material consumption, I also eliminated positive entries, as these represented counter-transactions (e.g., returns) that did not reflect actual usage. The table 7 presents the types of data extracted from the ERP system.

Dataset	**Data extracted**	**Purpose**
Material Consumption	Received materials, delivery dates and quantities	Tracking incoming materials and their reception dates
Call off from customer	Customer orders, requested quantities and latest requested delivery date	Analyzing customer demand and ensuring timely order fulfilment based on customer delivery requirements
Material receptions	Received materials, delivery dates and quantities	Tracking incoming materials and their reception dates

Table 7. ERP data for logistics analysis.

Values that deviated significantly from the expected behaviour of the normal distribution were excluded, as their variability was unrealistic and could distort the results. The Z-scores of these outliers were notably large, indicating that they deviated from the mean by several standard deviations. Z-scores greater than 3 suggest that these values were statistically unusual and likely the result of exceptional events, such as sudden demand spikes or disruptions in the supply chain. Additionally, values with units other than PCE were also excluded from the analysis, as they would have introduced inconsistency into the data. These values were not included in the calculations, as they were not representative of normal inventory behaviour and could lead to erroneous forecasts in inventory management. Excluding the outliers helped ensure that the calculated mean and standard deviation reflect a more realistic and predictable inventory behaviour.

To structure the data for detailed analysis, I sorted entries based on part numbers and organized them into separate tabs or sheets according to each part. I then calculated the daily variance for each part's activity within the selected timeframe, aggregating all variances to obtain an overview of fluctuations across the dataset. With these variance values, I applied the formula for determining optimal stock levels, which served as a foundation for assessing inventory needs.

After preparing and cleaning the data, I used the results from mathematical equation (1), (2) and (3) to create a normal distribution model and a box plot to visually represent the inventory variability. The normal distribution allowed me to assess how inventory levels fluctuate around the mean. I also performed a visual check to ensure the normal distribution followed a bell curve, confirming that the data adhered to a typical pattern of variation. The box plot helped identify the spread of data, revealing both the interquartile range and potential outliers, further enhancing the understanding of inventory behaviour.

Spreadsheet was used for data preparation and initial calculations, as its spreadsheet functions facilitated the organization and sorting of data across different part numbers. For more complex statistical analysis, I used spreadsheets macros, where I applied variance calculations to accurately assess daily fluctuations. This approach enabled me to derive reliable stock level estimates based on the observed variances, supporting inventory management and performance evaluation.

4 Study results and analysis

The empirical section analyses the current state of the case company's logistics and delivery process, assessing related bottlenecks and delay factors. This section is based on concrete observations and metrics that provide insights into the efficiency of the supply chain and areas in need of improvement.

4.1 Introduction of the case company

Ioncor Oy is a newly established company, emerging from Valmet Automotive’s Electric Vehicle Systems (EVS) business line. Officially launched on October 1, 2024, Ioncor is one of Europe’s leading independent manufacturers of battery modules and systems, with a key focus on electrifying vehicles and machinery across various industries. The company continues to build on the battery expertise and manufacturing capabilities developed under Valmet Automotive, which achieved over EUR 1.2 billion in gross sales and EUR 200 million in turnover in 2023. (Ioncor, n.d.)

Ioncor operates seven sites across Finland (Salo, Turku, Uusikaupunki) and Germany (Bad Friedrichshall, Kirchardt, Munich, Weihenbronn), employing 1,400 professionals. Initially, its core business revolves around the automotive sector, serving leading OEMs like Volvo and Mercedes-Benz with battery systems for electric vehicles. However, Ioncor is also strategically expanding into non-automotive sectors such as trucks, buses, construction, agriculture, material handling and forestry. (Ioncor, n.d.)

At the heart of Ioncor's product offerings is a scalable, modular battery platform, designed to meet the needs of diverse industries through highly reliable, stackable and durable battery solutions. The company’s modular battery packs and systems are built to perform in the harshest environments while offering optimal space efficiency and energy density. The Energy Pack Concept, for example, is tailored for applications requiring fast charging and long service life, ideal for buses and trucks. (Ioncor, n.d.)

Under its independent brand identity, Ioncor is positioned as a lifetime partner in electrification for its customers, providing a comprehensive suite of services from engineering and testing to contract manufacturing. The company is poised to contribute significantly to the decarbonization and electrification megatrend, leveraging its experience with demanding OEMs to deliver battery solutions not only for land-based vehicles but also for sectors like construction, mining and off-highway applications. (Ioncor, n.d.)

4.2 Current state of logistics and process descriptions

The battery industry, driven by the global demand for energy storage and electric vehicles, depends on a highly structured and coordinated logistics and production process to ensure that customer demands are met efficiently. This process, visualized through a swimlane diagram, encompasses various departments such as production planning, material management, transportation planning and logistics, each playing a critical role in moving from customer order to product delivery. To better understand this complex process, we walk through the different phases outlined in the swimlane diagram (Figure 5), delving deeper into specific stages where detailed actions are laid out in the process map.

The process starts with the customer submitting a call-off, which is essentially an order request specifying the required quantities and delivery deadlines for battery products. This triggers the internal workflow across various teams, setting the entire supply chain into motion.

Once the call-off is received, the internal systems, particularly the production planning and material management teams, take over to ensure that the customer’s request can be fulfilled on time. This leads us into the production planning phase, a critical step to align resources with customer demands.

The production planning team plays a central role in the supply chain by organizing and executing the manufacturing schedule based on the customer's call-off. This process is represented in the process map (Figure 6) by several key steps.

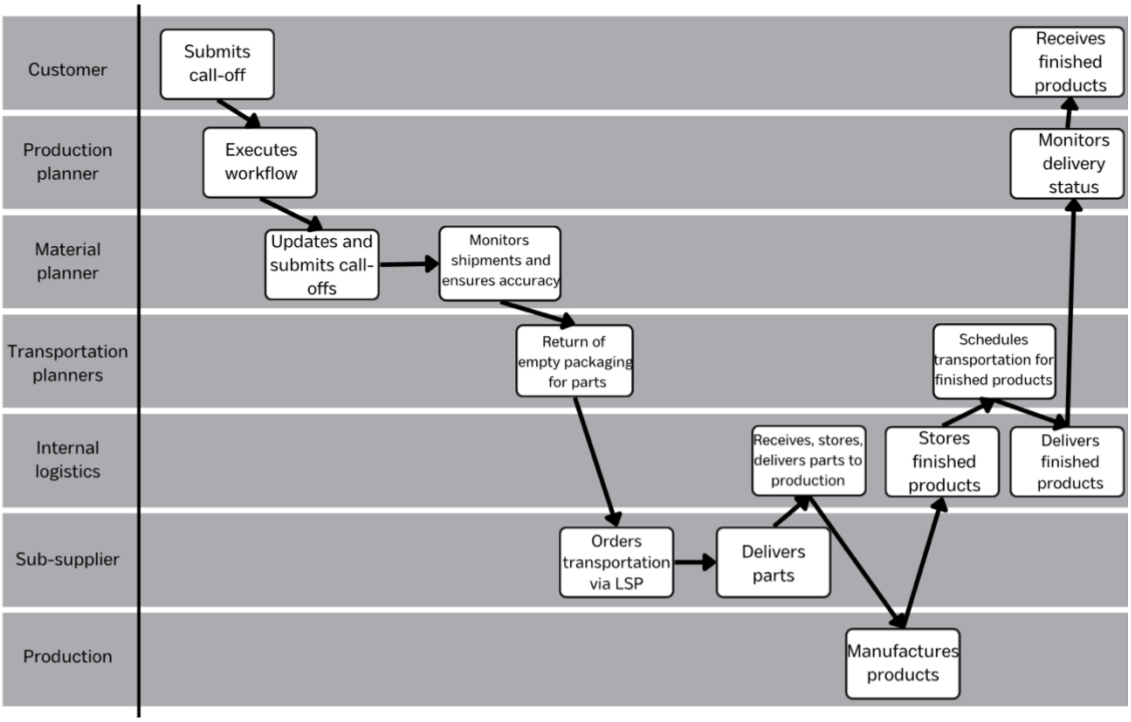

Figure 6. Swimlane chart of process flow.

The planners use tools like ERP and spreadsheet to create a detailed production/supply plan, which outlines what materials and resources are required and when. This ensures that production is align with the requested delivery date from the customer. It involves a Material Requirements Calculation in ERP, where the necessary raw materials and components are evaluated based on current inventory levels and future demand forecasts.

After the planning phase, the next step involves using a ERP to generate the actual production schedule. This ensures that the timeline is feasible, considering equipment availability, workforce and supply of raw materials.

Once the schedule is finalized, the production planners continuously monitor the workflow to ensure that all activities are proceeding on time. They handle any unexpected disruptions by adapting the plan, addressing delays or issues that may arise.

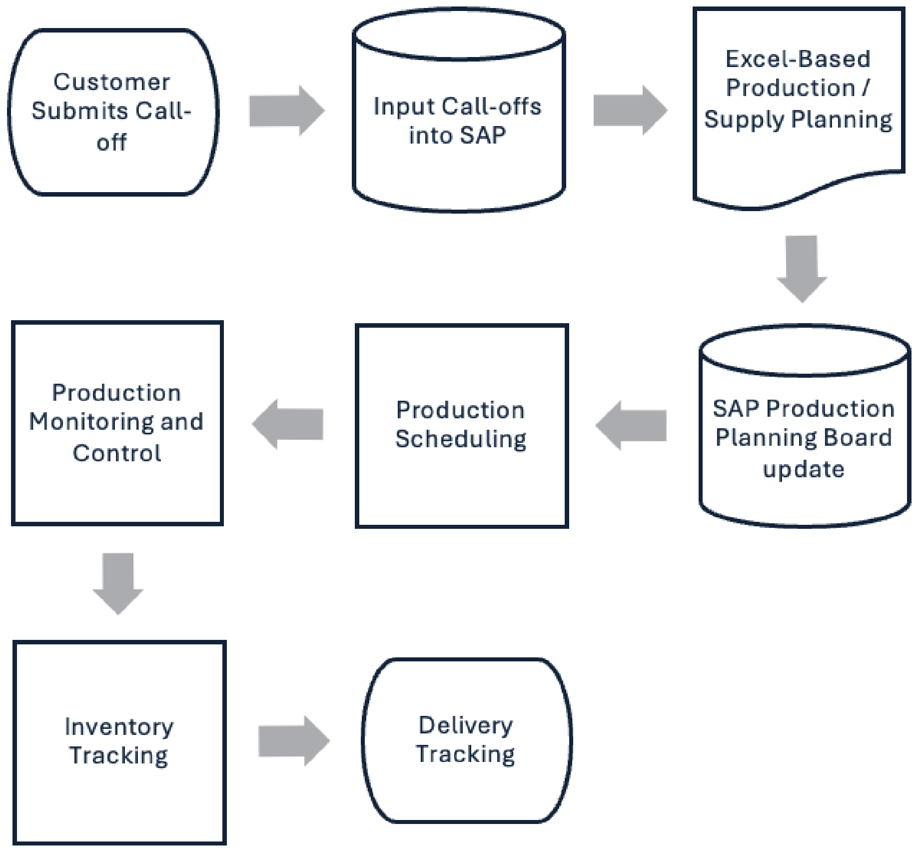

Figure 7. Work flow of production planner.

Production planning sets the groundwork for the entire process, ensuring a smooth transition from order reception to manufacturing execution. This phase also leads directly to the material management process (Figure 7), where the necessary inputs for production are secured.

The material planning team is responsible for updating and submitting the call-offs to the sub-supplier, ensuring that the requirements set during the production planning phase are communicated to sub-suppliers. This step links closely with the earlier production planning stages as it translates the theoretical production schedule into actionable procurement activities.

Material planners also monitor the incoming shipment of materials to make sure everything is in line with production needs. According to the process map, material planners are tasked with managing the follow-up with Suppliers: addressing issues, delays, and modifications as they occur. This follow-up ensures that any unforeseen supply chain challenges are mitigated in real-time, minimizing the risk of production stoppages.

Once the materials are ordered, the material management team continues to monitor the shipments, ensuring that the deliveries align with the production schedule. Here, they must verify that the right materials arrive in the correct quantities and are delivered on time. This process is crucial for maintaining the flow of production.

At this point, we move into the logistics and transportation phase, where the parts are moved from suppliers to the warehouse, ready to be moved into the production line.

The sub-suppliers, responsible for providing key components to produce batteries, play a crucial role in the logistics chain. Once they receive the orders, they arrange transportation through Logistics Service Providers (LSPs) to deliver parts to the manufacturing facility. Before sub-suppliers are ready to order transportation for parts, the transportation team ensures the return of empty packaging from previous deliveries, making sure that these are returned to the suppliers for reuse. This reverse logistics step helps promote sustainability and ensure packaging is available when needed for the next delivery cycle.

Upon arrival, the internal logistics team manages the receipt, storage, and delivery of parts to the production line. The warehouse team ensures that the parts are properly stored and made available to production as needed. This stage is crucial for inventory management, as outlined in the process map, which involves maintaining accurate records of stock levels and ensuring that parts are available without excess storage costs. Once all parts are available, the production team takes over to manufacture the battery products. This step is the culmination of the efforts of the earlier stages of planning, material management and logistics. Production must be carried out efficiently to meet quality standards and deadlines set by the customer’s call-off. Any delays in material delivery or production scheduling would affect the entire process, leading to potential late deliveries.

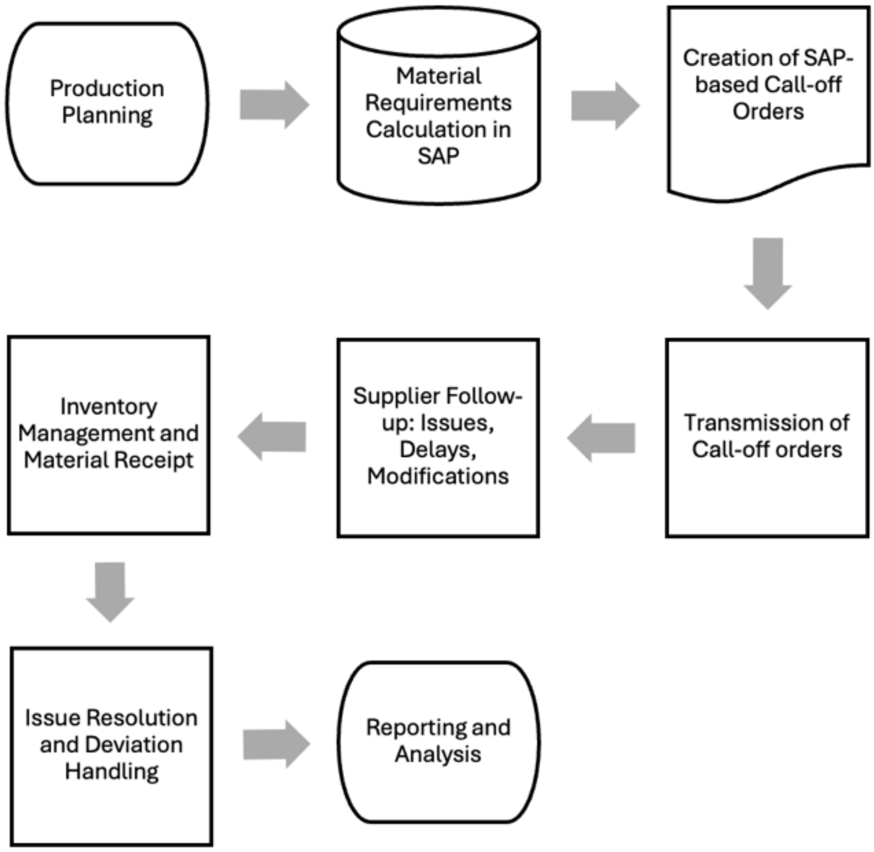

Figure 8. Work flow of material planner.

After production, the finished products are transferred to the warehouse for storage. This is a short-term step where the internal logistics team ensures that the finished products are safely stored and prepared for dispatch. Inventory management at this stage is crucial to ensure that the products are labeled and ready for shipment when the transportation team schedules the next phase.

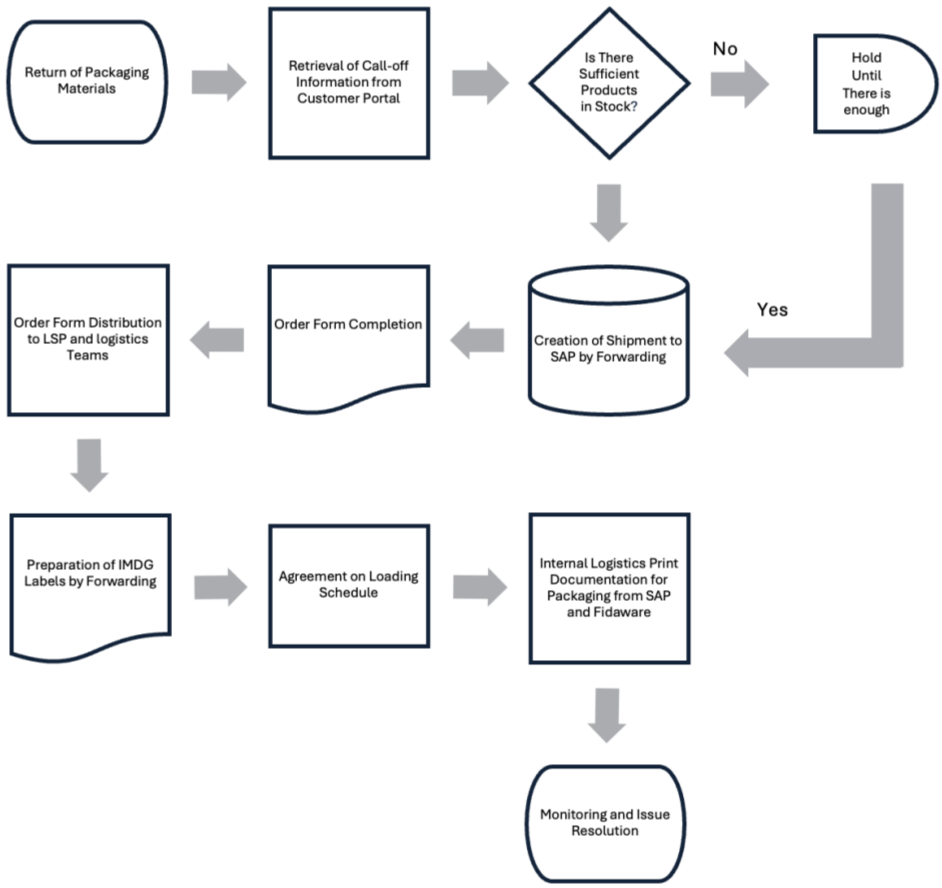

Figure 9. Work flow of transportation engineers.

Next, the transportation team schedules the shipment of finished products. This process (Figure 9) involves coordinating with logistics service providers to arrange timely deliveries. Forwarding creates the shipment in the ERP and IMDG labels. The warehouse team copy the necessary documents and dispatches the finished products, ensuring they are loaded and shipped according to the customer's specifications.

The transportation team monitors the shipment status to ensure that everything proceeds according to schedule. Any delays or issues in transit are addressed to avoid disruptions in the final delivery stage.

While the shipment is in transit, the production planning team continues to monitor the delivery status. This oversight ensures that the customer's requirements are being met, and any last-minute changes or updates are accounted for. Once the customer receives the finished products, the delivery process is complete.

The entire process concludes with reporting and analysis, as outlined in the process map. This stage involves evaluating the overall performance of the supply chain, identifying any issues that may have occurred and using this information to improve future workflows. Continuous improvement is key to maintaining an efficient and responsive supply chain in the battery industry.

The logistics and production process in the battery industry is a complex, multi-step workflow that requires precise coordination across several departments. From customer order submission to final delivery, each phase builds on the previous one, ensuring that production aligns with demand and materials are available when needed. The use of production planning tools, material management systems and efficient logistics coordination ensures that the entire supply chain operates smoothly. By combining insights from the swimlane diagram and the process map, we see how these interdependent steps function together to meet customer demands and deliver products efficiently.

4.3 Key bottlenecks and delay factors in the OTD process

In the highly interconnected supply chain environment, timely delivery of products or On-Time Delivery (OTD) is crucial for maintaining customer satisfaction and operational efficiency. Delays in OTD can stem from various underlying issues and root cause analysis using a Fishbone diagram (Figure 9), helps in identifying the key contributors. These factors can be categorized into six primary areas: Materials Management, Production Planning, Collaboration and Communication, Transportation, Warehousing and Systems and IT. Each category represents a distinct set of risks that collectively impact the efficiency of the OTD process.

Materials Management is often a critical area of concern in achieving OTD targets. Delays here are primarily caused by supplier-related issues, such as supplier downtimes, operational inefficiencies or material quality problems. Raw material shortages further exacerbate the problem, especially when suppliers fail to meet demand or deliver defective goods. Additionally, errors in procurement processes, such as incorrect call-offs or misrouted RFQs, can delay the receipt of necessary materials. When raw materials are delayed or unavailable, the production schedule is thrown off course, triggering a chain reaction that affects the entire delivery timeline.

Moving further along the supply chain, Production Planning plays a vital role in determining the accuracy and timeliness of product manufacturing. Issues such as incorrect production quantities or challenges in adapting to call-off modifications can create bottlenecks. These discrepancies can lead to either overproduction or underproduction, both of which result in delays. Overproduction ties up storage space and resources, while underproduction leaves customers waiting for finished goods. Moreover, poor planning often leads to secondary effects, such as the misallocation of resources and inefficiencies in downstream processes, which further disrupt on-time delivery.

The effectiveness of Collaboration and Communication is equally critical to ensuring smooth operations across the supply chain. Delayed communication, whether internal or external, often leads to misunderstandings and misaligned expectations regarding production and delivery schedules. For example, Incoming Quality Control (IQC) can take parts for inspection without immediately updating inventory balances, which can disrupt stock levels. Similarly, a lack of timely communication with clients or suppliers regarding changes in production or delivery timelines can have significant consequences, as it leaves parties unaware of necessary adjustments. Poor communication also impacts critical change management, hindering the ability to adapt efficiently to sudden shifts in demand or operational challenges.

Transportation poses another major bottleneck for OTD performance. Delayed shipments, whether caused by the supplier or due to external factors such as weather or customs delays, are among the most common reasons for late deliveries. In addition, transportation schedules that are overly tight or lack flexibility do not leave room for unforeseen delays. Packaging returns present another logistical challenge, as empty containers or packaging materials need to be returned efficiently to ensure smooth production flow, especially for Just-in-Time manufacturing systems. When transportation teams are unable to coordinate these returns, subsequent shipments and deliveries suffer, resulting in cumulative delays and rising expenses.

Warehouse operations also have a significant influence on the OTD process. In Warehousing, improper receipt of goods—such as receiving incorrect quantities or goods that do not meet quality specifications—can create delays both in production and in shipping finished products. Furthermore, component degradation, particularly of sensitive materials stored improperly, can further complicate warehouse management. If goods are incorrectly loaded or misallocated within the warehouse, the delivery schedule is directly impacted, as shipments may either be delayed or incorrectly fulfilled. These inefficiencies contribute to further bottlenecks down the line.

Lastly, Systems and IT infrastructure forms the backbone of modern supply chain operations. Issues such as system downtime, incorrect inventory balances and data entry errors during the receipt or dispatch of goods can lead to major delays. Moreover, data security vulnerabilities or errors in electronic data interchange (EDI) processes can disrupt the flow of information, leading to missed deliveries or incorrect shipments. Without accurate and reliable IT systems to track inventory, production and transportation schedules, the entire supply chain becomes prone to delays and miscoordination.

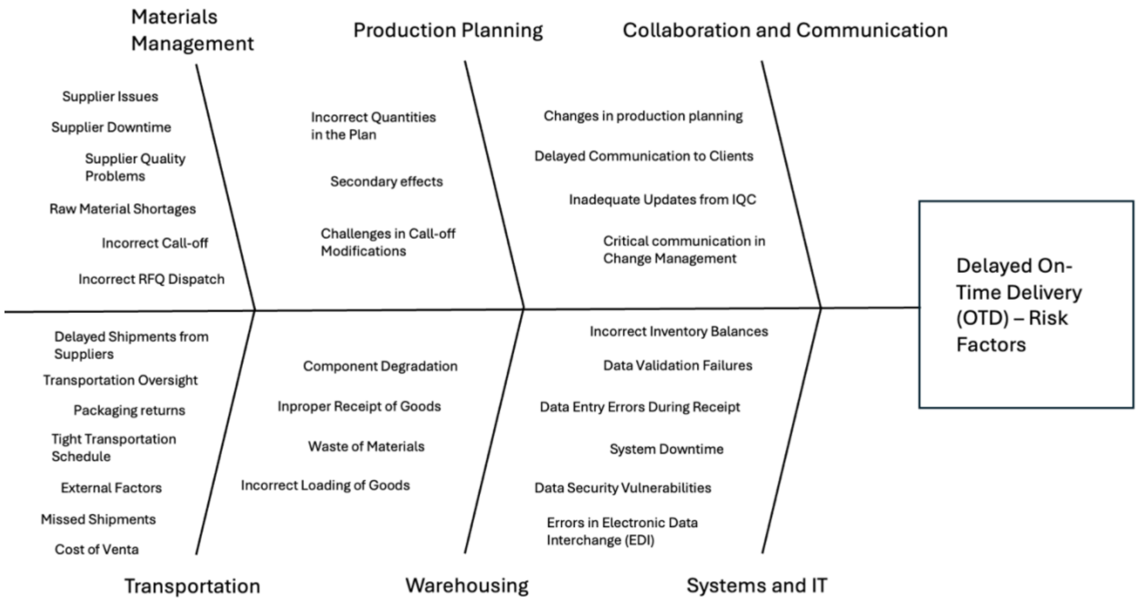

Figure 10. Fishbone risk factors.

The Fishbone diagram (Figure 10) highlights the complexity and interdependence of various factors that contribute to OTD delays. The primary root causes across the OTD process include supplier reliability issues, production planning inaccuracies, communication breakdowns, transportation bottlenecks, warehouse inefficiencies and IT system failures. These issues not only delay the production and delivery of goods but also create a ripple effect, compounding delays as they propagate through the supply chain. Addressing these root causes requires a coordinated, multi-disciplinary approach—improving supplier relations, enhancing communication protocols, optimizing transportation scheduling and ensuring the robustness of IT systems. Such improvements are mitigatinf the risks of OTD delays, resulting in a more efficient and resilient supply chain.

4.4 Analysis of KPIs for finished product inventory

Ready product stock is a critical component of a company's supply chain, directly affecting operational efficiency and customer service levels. Accurate forecasting and management of inventory levels are influenced by various factors, such as demand fluctuations and uncertainties in the delivery processes. This study explores how normal distribution can be used to estimate ready product inventory levels based on call-off variances, which represent the variability in supplier deliveries (p) and customer-driven demand (pp).

The call-off variances were calculated separately for both the supplier and the customer. Based on these variances ready product stock levels were analysed using a mathematical equation (2).

(2) The variable is examined for each part number individually

$$A = \sqrt{\sigma_p{}^2 + \sigma_{pp}{}^2}, \qquad (2)$$

where [σ_p = standard deviation of the supplier´s call-off variance, σ_{pp} = standard deviation of the customer´s call-off variance](M. Savolainen, personal communication, October 31, 2024).

These values from mathematical equation (2) were then used to form a normal distribution. A normal distribution model (Figure 10) is an essential tool in understanding how inventory levels might fluctuate around an expected value. The mean (μ) gives us an indication of the expected inventory level, while the standard deviation (σ) helps assess the degree of variation around this mean. Since the analysis was conducted for individual part numbers, exceptionally large variances and millilitre units were excluded from the calculations to avoid excessive uncertainty and to ensure realistic results.

Using the normal distribution, we determined how much the inventory level could deviate from the predicted mean at different probabilities. The normal distribution had a mean of 261 units and a standard deviation of 90 units, it could be predicted that the inventory level would, with 68% probability, be between 171–351 units ($\mu \pm \sigma$), with 95% probability between 81–441 units ($\mu \pm 2\sigma$). This provides an estimate of the possible variation in inventory levels and helps make informed decisions about inventory management.

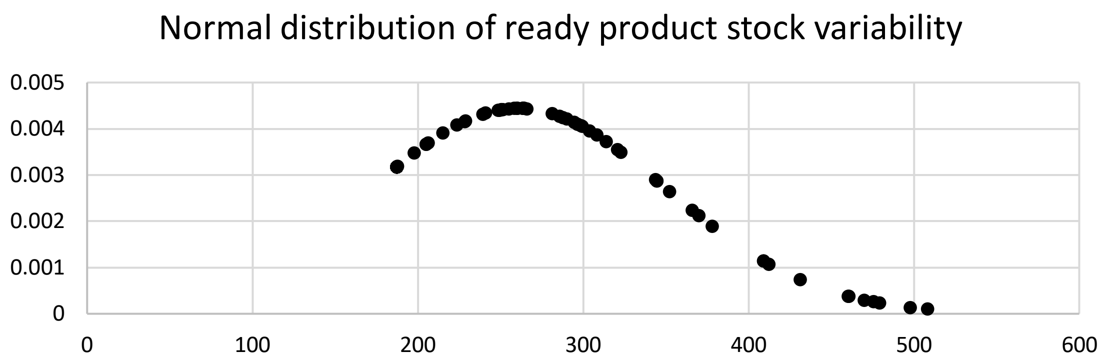

Figure 11. Normal distribution of ready product stock variability.

The box plot in Figure 11 provides insights into the distribution of inventory levels. The median is located slightly below the centre of the box, suggesting that the data is somewhat skewed. This indicates that inventory levels are generally lower, but occasional spikes can occur. The interquartile range (IQR) is of medium width, reflecting a relatively consistent inventory level, though some variation is present.

The whiskers are relatively short, extending about 1.5 times the height of the box above the upper quartile, which shows that the inventory levels do not fluctuate significantly. There is no whisker below the box, indicating a stable lower bound for inventory levels. Furthermore, no outliers are visible in the plot, implying that the inventory data has been stable, with no extreme deviations.

The slight asymmetry of the box plot, with the median closer to the bottom of the box, suggests that inventory levels are generally on the lower side, though spikes can occur. This indicates some potential for variability, but the overall trend appears stable.

Figure 12 shows that inventory levels are stable with moderate fluctuations, without any significant risks. The data suggests that inventory remains consistent, but occasional increases in stock levels may occur.

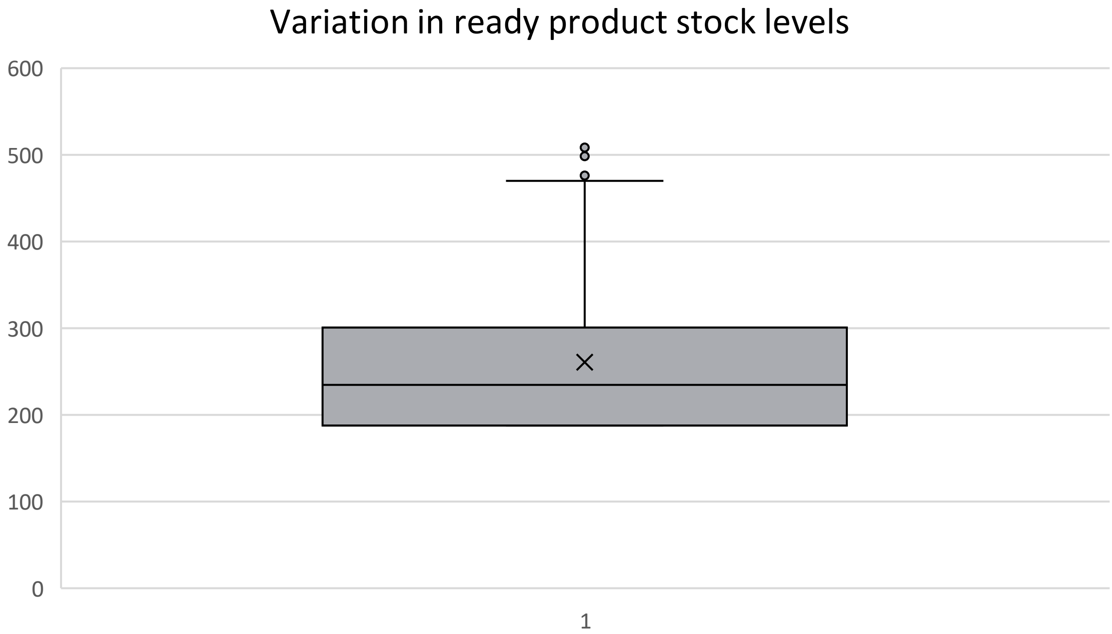

Figure 12. Variation in ready product stock levels.

While the Figure 12 suggest stable inventory levels with moderate fluctuations, the analysis of mean and standard deviations reveals that the inventory levels can still vary significantly. The standard deviation is 34% of the mean, indicating significant variation. A standard deviation at 34% of the mean suggests that inventory levels are somewhat volatile. These fluctuations, while not extreme, may still lead to challenges such as occasional overstocking or stockouts, particularly during periods of high demand or supply chain disruptions. A high standard deviation implies that inventory levels are spread far from the mean, indicating that stock levels may often be much higher or lower than expected. This can lead to:

- Stockouts: If the inventory falls below the lower threshold (in this case, 171 units), it could result in insufficient stock to meet customer demand, leading to potential lost sales or production disruptions.

- Overstocking: On the other hand, stock levels could also exceed the upper threshold (351 units), leading to excess inventory that ties up working capital and increases storage costs.

Managing these fluctuations requires robust forecasting models and dynamic safety stock levels to ensure that the company can continue meeting demand without excessive risk of either stockouts or overstocking.

The analysis of ready product stock emphasizes the importance of adjusting safety stock levels to account for variability. Given that the standard deviation is relatively large, safety stock calculations should factor in potential fluctuations in demand and supply. Safety stock is typically calculated based on the standard deviation and a desired service level. For instance, to maintain a high service level (95%), companies need to hold higher safety stock in case of unexpected demand spikes or supply delays.

In cases where the standard deviation is large, as observed in this analysis, the safety stock required to meet higher service levels also increases. For instance, in the case of a 95% service level, safety stock would need to account for at least two standard deviations ($\mu \pm 2\sigma$), which would result in a range of 81 to 441 units. This highlights the need for careful balance between holding enough stock to meet demand and avoiding excess inventory that leads to higher holding costs.

Since exceptionally large call-off variances were excluded from the calculations, the results of the analysis are based only on parts where the variation was more reasonable and predictable. This ensured that the calculated mean and standard deviation realistically reflect the potential behaviour of the inventory without excessive uncertainty that could be caused by exceptionally large variances.

4.5 Analysis of KPIs for component inventory

Effective management of component stock is a critical aspect of supply chain and production efficiency. Components are the foundation for manufacturing finished products and fluctuations in their inventory levels can directly impact production capacity, delivery schedules and costs. These calculations provide an estimate of the likely range of component inventory levels and allows for an analysis of how well the stock can meet the demands of production and supply chain requirements.

Component stock variability was calculated using two different approaches to better understand the factors contributing to stock fluctuations.

(3) The variable is examined for each part number individually

$$A = \sqrt{\sigma_{pp}{}^2 + \sigma_s{}^2}, \qquad (3)$$

where [σ_{pp} = standard deviation of the customer´s call-off variance, σ_s = standard deviation of the consumption in own production] (M. Savolainen, personal communication, October 31, 2024).

The second mathematical calculation (3) combined customer call-off variance (pp) and consumption variance (s) under the square root. This method emphasizes the variability caused by the demand side (customer requirements) and internal production consumption.

(4) The variable is examined for each part number individually

$$A = \sqrt{\sigma_p{}^2 + \sigma_s{}^2}, \qquad (4)$$

where [σ_p = standard deviation of the supplier´s call-off variance, σ_s = standard deviation of the consumption in own production] (M. Savolainen, personal communication, October 31, 2024).

The third mathematical calculation (4) combined supplier call-off variance (p) with consumption variance under the square root (s), focusing on the variability introduced by supplier reliability and internal production consumption.

4.5.1 Variance in supplier call-offs and material consumption

This calculation considers the variability caused by supplier demand (supplier call-off variance) alongside production consumption. By integrating these factors, the calculation highlights how fluctuations in supplier requirements and production processes impact component stock. Large variability here may indicate challenges in predicting supplier performance or maintaining consistent production schedules.

A normal distribution (Figure 13) was constructed from the dataset to assess the statistical characteristics of stock variability, including its mean (μ) and standard deviation (σ). While the mean stock level appears sufficient to support operational needs, the standard deviation—a measure of variability—revealed significant fluctuations, amounting to 68% of the mean. This high level of variability poses challenges to consistent inventory management, despite the dataset adhering to a normal distribution.

The high standard deviation indicates substantial unpredictability in component stock levels, even when the mean remains stable. Such variability suggests that stock levels can frequently deviate far above or below the average. While some fluctuation is expected in any inventory system, this degree of inconsistency may lead to operational inefficiencies.

On one hand, periods of understocking can result in critical issues, such as production stoppages or delays in fulfilling orders due to a lack of necessary components. On the other hand, overstocking during low-demand periods increases holding costs, ties up working capital and risks obsolescence, particularly in industries with rapid product lifecycles. Both scenarios highlight the importance of managing variability effectively to maintain a balance between supply and demand.

Normal distribution (Figure 13) allow for statistical modelling, which can be used to predict the likelihood of specific stock levels. For instance, approximately 68% of stock values fall within one standard deviation (±σ) of the mean. One standard deviation (μ ±

σ) covers a range that includes moderate fluctuations. In this analysis, these values may still pose challenges in aligning supply and demand. Two or three standard deviations ($\mu \pm 2\sigma$, $\mu \pm 3\sigma$) represent extreme scenarios, which, while less frequent, could lead to stockouts or excess inventory. These cases warrant further investigation to understand their root causes and potential prevention strategies.

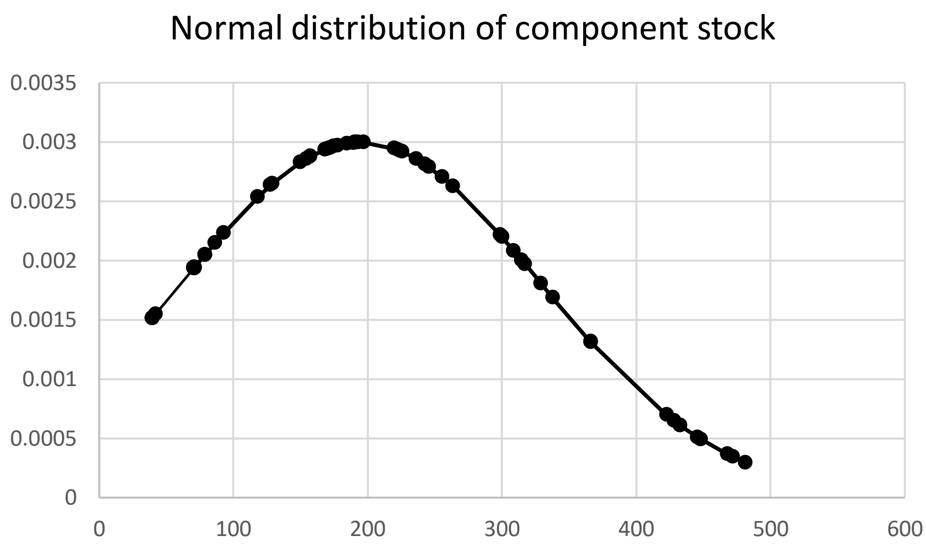

Figure 13. Normal distribution of mathematical equation 3.

The interpretation of the box plot (Figure 14) reveals a relatively stable system, but certain characteristics suggest opportunities for optimization. The median, located slightly below the centre of the box, indicates a minor skew toward smaller inventory levels. While this skewness is minimal, it highlights a tendency for inventory levels to cluster more closely toward lower values. The interquartile range (IQR), representing the middle 50% of data, is moderately wide. This suggests that inventory levels exhibit a reasonable amount of fluctuation, although not excessively large. Such variability could reflect dynamic supply and demand, necessitating proactive strategies to maintain balance.

The whiskers of the box plot (Figure 14) provide additional information on the spread of the data. The shorter lower whisker indicates stability in the smaller inventory levels, showing that these values do not deviate significantly from the lower quartile (Q1). On the other hand, the upper whisker, extending slightly beyond the box's height, suggests a somewhat greater dispersion in higher inventory levels. While not extreme, this variability at the upper end could signal occasional surges or inefficiencies in inventory management.

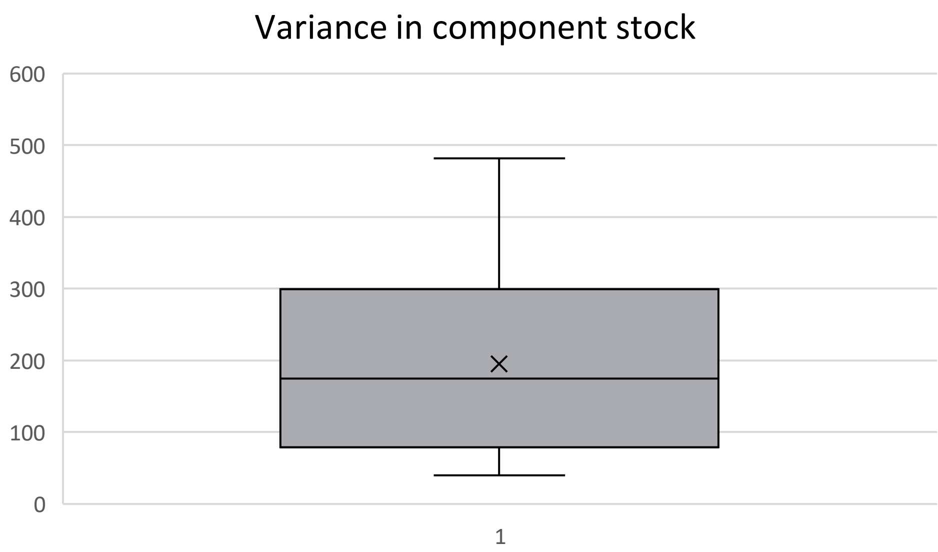

Figure 14. Box plot of mathematical equation 3.

A particularly positive observation is the absence of outliers in the dataset. This lack of extreme values indicates a well-controlled inventory system with consistent patterns. The predictability of inventory levels enhances operational reliability and reduces risks associated with sudden fluctuations, such as stockouts or overstocking.

From a symmetry perspective, the box is nearly balanced, with the median positioned close to the center. The slight skewness observed is not significant enough to disrupt overall stability but reflects a mild concentration of values toward the lower range. Such distributions often indicate that lower inventory levels are more frequent, while higher levels are less common but occur occasionally.

4.5.2 Variance in customer call-offs and material consumption

This calculation considers the variability caused by customer demand variance (customer call-off variance) alongside production consumption variance. By integrating these two factors, the analysis sheds light on how fluctuations in customer requirements and production processes impact component stock. Significant variability here may indicate challenges in accurately predicting customer demand or maintaining consistent production schedules.

A normal distribution (Figure 15) was constructed from the dataset to assess the statistical characteristics of stock variability, including its mean (μ) and standard deviation (σ). The analysis of component stock variability, based on the normal distribution shown in Figure 15 reveals key insights into the behaviour of inventory levels. The distribution is right-skewed, meaning that most data points are concentrated on the left side of the distribution, with the right tail extending further out. This indicates that most of the stock levels are relatively lower, while larger values are less frequent but still present in significant amounts. Coupled with a standard deviation of 31% of the mean, this distribution suggests considerable variability in component stock, which warrants further investigation.

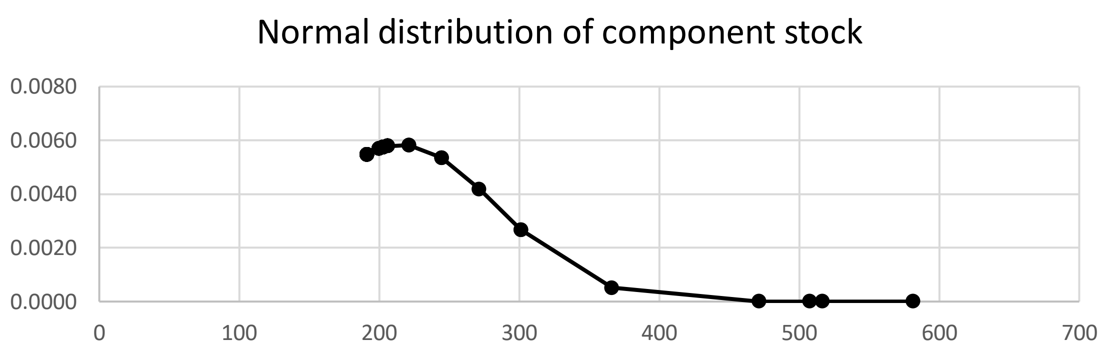

Figure 15. Normal distribution of mathematical equation 2.

The relatively low standard deviation suggests that the component stock is less prone to large deviations from the mean. Such stability in stock levels implies that demand forecasting and production schedules are more aligned. However, some fluctuations are still present and must be monitored. This variability can reflect shifts in customer demand or minor disruptions in the production process. While the system seems relatively stable, it still requires proactive management to maintain the desired balance.

Given the moderate level of variability, periods of understocking are less likely to occur compared to systems with higher variability. However, even with a 31% variability, there is still a chance of overstocking if the demand is overestimated, or production processes are not well-synchronized with actual needs. Excess inventory can lead to increased holding costs, wasted resources and potential obsolescence, particularly for products with short life cycles or fluctuating demand.

The left skew of the distribution implies that most component stock values are clustered around the lower to mid-range levels. This suggests that, in typical scenarios, component stock is generally stable and fluctuations are relatively modest. A mean that reflects the most common stock levels reinforces this observation, indicating that inventory is generally maintained within predictable and manageable boundaries. The right skew shows that there is a risk of larger-than-usual deviations from the expected levels, which can be problematic for effective stock management.

The 31% standard deviation further illustrates the scale of this variability. A standard deviation of 31% means that the component stock levels can fluctuate by up to 31% above or below the mean in a typical scenario. This is a significant level of variability and suggests that while stock levels are generally controlled, there is still a notable risk of fluctuations that can lead to challenges in managing inventory efficiently.

The rightward skew of the normal distribution (Figure 15) suggests that while stock levels tend to remain within a certain range, there are occasional instances of larger inventory surpluses. These outliers can stem from various causes, such as unexpected spikes in production, supplier delays or misalignments between demand forecasting and actual customer needs. Given that stock levels are more likely to remain low or average, the distribution also hints at the possibility of stockouts, where demand might exceed supply, particularly during periods of higher-than-expected demand.

This kind of distribution poses several operational challenges. A significant tail on the right means that, while most of the time stock levels are relatively stable, there can be rare instances of excess inventory. These excesses may lead to overstocking, which ties up working capital, incurs additional storage costs, and, in extreme cases, risks obsolescence. On the flip side, the 31% variability in stock levels implies that shortages are also a real risk. Even with this relatively stable distribution, sudden surges in demand or unexpected delays from suppliers may lead to stockouts, which could disrupt production or delay order fulfilment.

Understanding inventory stability is essential for effective supply chain management. One of the most insightful ways to assess inventory behavior is through a box plot, a powerful statistical tool that visually represents the distribution, variability and central tendencies of data.

In the analysis of Figure 16, the median is positioned close to the centre of the box, indicating a symmetric distribution of inventory levels. This symmetry suggests that the inventory is generally stable, with no strong skew toward unusually high or low values. A well-balanced distribution reduces the likelihood of unexpected stock shortages or excesses, offering reassurance in inventory management.

The interquartile range (IQR), or the width of the box, provides further insight into the stability of inventory. In Figure 16, the box is very narrow, signifying a small IQR. A narrow IQR indicates that inventory levels tend to cluster closely around the median, with little fluctuation. This suggests a stable inventory system, where inventory levels remain relatively constant, reducing the potential for unpredictable changes that could disrupt supply chain operations.

The whiskers of the box plot, extending from the box itself, illustrate the spread of values outside the central range. In this case, the upper whisker in Figure 16 is very short, and there is no lower whisker at all. This pattern further reinforces the stability of inventory, as it shows that inventory levels do not deviate significantly from the central range. Short whiskers suggest that inventory levels are predictable and that extreme fluctuations are unlikely.

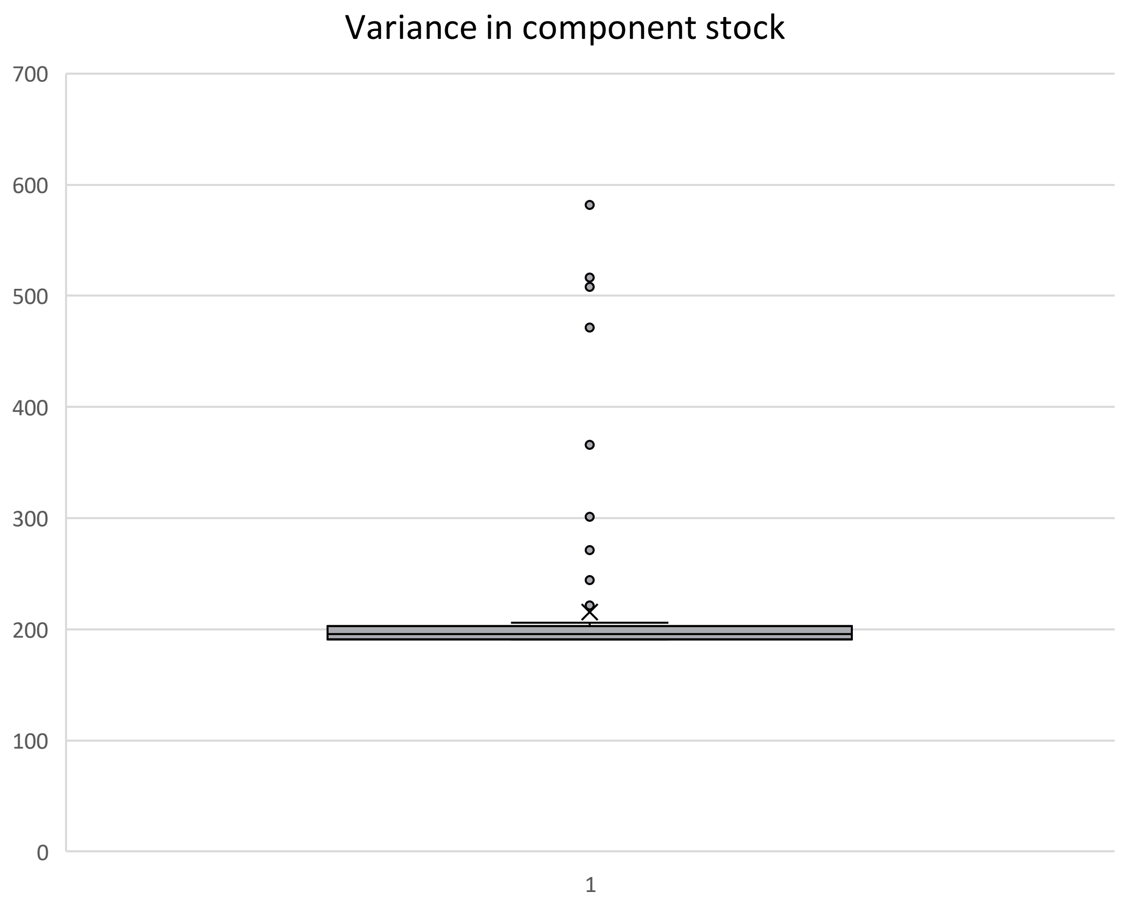

Figure 16. Box plot of mathematical equation 2.

Despite the overall stability indicated by the box plot, outliers—points that fall far outside the main distribution—are present. In Figure 16, these outliers appear above the upper whisker, indicating occasional spikes in inventory levels. Although these outliers are rare, they signal that, in some instances, inventory levels may temporarily exceed the usual range. These spikes could be due to unforeseen factors such as sudden changes in demand or delays in supply. Though infrequent, such outliers should be monitored and considered when refining forecasting models and inventory replenishment strategies.

The symmetry of the box plot also reveals that the distribution of inventory levels is balanced, with no significant skew towards either high or low values. This symmetrical distribution further suggests that inventory management practices are effective, as the inventory is evenly distributed and does not heavily Favor excess or shortage.

Figure 16 highlights that the inventory levels are stable, with minimal fluctuations. The symmetrical distribution, narrow IQR and short whiskers suggest a well-controlled system with predictable inventory levels. However, the presence of occasional outliers calls for attention. These outliers, though rare, could indicate unexpected shifts in inventory that might require adjustment in supply chain management strategies. Monitoring these occasional spikes and fine-tuning forecasting and inventory management practices help to ensure continued stability and efficiency in managing inventory.

5 Process optimization proposal

This section presents a comprehensive proposal for optimizing key processes within the supply chain. The objective is to improve efficiency, reduce costs and enhance overall performance by addressing areas with significant potential for improvement. The proposed optimizations focuses on reducing variability, streamlining workflows and leveraging data-driven decision-making to drive continuous improvement. Through targeted actions and the application of best practices, the goal is to create a more agile, resilien, and cost-effective supply chain that aligns with organizational objectives.

5.1 Key findings and conclusions

The empirical analysis of Ioncor Oy’s logistics and delivery processes highlights key factors impacting the efficiency of its supply chain and provides a detailed look at its order-to-delivery (OTD) challenges and performance metrics. Ioncor's logistics and production processes are complex, involving coordinated efforts across production planning, material management, transportation and internal logistics. The company’s approach centers on meeting high demand while maintaining inventory levels that balance the needs of diverse industries.

Ioncor's structured logistics process, supported by tools such as ERP, demonstrates a well-organized approach to managing production and inventory needs. However, analysis identified several bottlenecks that disrupt the OTD process, including delays in materials management, production scheduling and transportation. These bottlenecks are compounded by supplier reliability issues and inconsistencies in warehouse operations.

The analysis uncovered specific causes of delays in the OTD process, categorized into six main areas: materials management, production planning, communication, transportation, warehousing, and IT systems. Each of these areas presents unique risks, such as supplier downtimes, inefficient communication and transportation delays, which collectively hinder timely delivery and require coordinated solutions to improve reliability.

One additional factor that warrants attention is the internal logistics delay between picking processes and the final product's readiness for delivery. While specific tracking data for these delays was not available, they represent a potential systemic source of variability that affects inventory levels. If unmanaged, these delays could create discrepancies in stock balances, further complicating inventory planning and increasing the risk of stockouts or overstocking.

The analysis of ready product stock reveals that, with a mean of 261 units and a standard deviation of 90 units, inventory levels can vary between 171–351 units (68% probability) and 81–441 units (95% probability). This variability indicates potential risks of stockouts (if inventory falls below 171 units) and overstocking (if inventory exceeds 351 units), which can lead to production disruptions and increased costs. The box plot (Figure 11) further illustrates stable inventory levels with occasional fluctuations, though the standard deviation of 34% suggests that stock levels can still deviate significantly from the mean.

This variability underscores the need for robust inventory management strategies, especially in ready product stock, where fluctuations can directly affect production and order fulfillment. Adjusting safety stock levels is critical to handle demand and supply fluctuations effectively. For a 95% service level, safety stock should account for at least two standard deviations, resulting in a range of 81 to 441 units. Proper safety stock management helps balance the need for sufficient inventory to meet demand while avoiding the costs of overstocking.

Stock variability significantly impacts component management and supply chain efficiency. By examining both supplier and customer demand fluctuations alongside production consumption variability, it became evident how these factors influence inventory stability. Notably, a high standard deviation—68% of the mean for supplier variability and 31% for customer variability—reveals substantial uncertainty in inventory management. Large fluctuations pose risks such as understocking, which can lead to production disruptions, and overstocking, which increases storage costs and risks obsolescence.

Using normal distribution analysis (Figures 12 and 14), the behaviour of stock levels was modelled. Supplier variability showed that most fluctuations occur within one standard deviation of the mean, but risks increase significantly in extreme cases involving two or three standard deviations. Customer variability, on the other hand, displayed a right-skewed distribution, indicating that inventory levels typically cluster at lower values, with occasional instances of large inventory surpluses. These outliers increase the risk of both excess inventory and stockouts during periods of heightened demand.

The box plot analysis (Figures 13 and 15) supports the observation of relatively stable inventory systems, albeit with some variability. For supplier variability, the interquartile range (IQR) is moderately wide, reflecting dynamic supply-demand conditions. In customer variability, the IQR is narrow, and whiskers are short, indicating high stability. However, rare outliers, such as excessive stock levels, suggest occasional inefficiencies that warrant closer examination.

The analysis underscores the critical importance of managing variability effectively to ensure successful inventory control. While the systems display signs of stability, the high variability observed, particularly in supplier dynamics, presents significant operational risks. Understocking can result in critical production interruptions, while overstocking ties up working capital, increases storage costs, and risks product obsolescence. Additionally, the outliers observed in customer stock levels point to inefficiencies that require refined forecasting and inventory adjustment strategies.

Continuous monitoring of variability trends, analysis of the root causes of outliers and refinement of predictive models are essential for optimizing inventory management. These actions can help reduce costs, improve supply chain predictability, and ensure that stock levels align efficiently with supply and demand requirements.

5.2 Process improvement proposal and optimization opportunities

In today’s competitive manufacturing environment, companies are under increasing pressure to reduce costs, enhance efficiency and ensure the reliability of their supply chains. One of the most critical factors in achieving these goals is minimizing variability, particularly in inventory management. Variability in supply chains—such as fluctuations in supplier deliveries—can create significant disruptions, leading to either excess stock or stockouts, both of which add unnecessary costs and inefficiencies.

At this stage, the most significant source of variability in many manufacturing operations stems from unpredictable supplier performance. Late deliveries, inconsistent quality and unreliable lead times can all contribute to this variability, making it challenging to align inventory levels with actual demand. To address these issues, we propose the implementation of a Plan for Every Part (PFEP).

PFEP is a comprehensive system that integrates critical data on every part within a facility, including supplier performance, lead times, and usage trends. By centralizing this information, PFEP offers a clear overview of supply chain dynamics, which facilitates informed decision-making. This enhanced visibility helps reduce variability in supplier deliveries by providing accurate data that can be used to adjust inventory levels and production schedules accordingly. As a result, PFEP supports the alignment of supply and demand, eliminating the need for excess inventory buffers and reducing inefficiencies tied to unpredictable supply fluctuations. It transforms inventory management from a reactive to a proactive model, improving supply chain reliability and cost-effectiveness.

The introduction of PFEP addresses several key inefficiencies commonly found in supply chains. Many facilities are forced to overstock as a safeguard against supplier inconsistencies, leading to unnecessary holding costs and waste. Additionally, fragmented information across multiple systems makes it difficult to take a unified approach to optimize processes. Supplier variability—whether in the form of delayed shipments, variable product quality, or unreliable logistics—often exacerbates these issues. Without a structured system to monitor and manage this variability, organizations struggle with operational disruptions, inflated costs, and diminished customer satisfaction. PFEP offers the necessary framework to address these challenges by organizing data, enabling proactive management, and reducing the negative impacts of supply chain variability.

By introducing PFEP and focusing on supplier development as part of a broader process improvement initiative, companies can take a data-driven approach to reducing variability, streamlining material flows and creating a more reliable and efficient supply chain. PFEP not only standardizes inventory management but also serves as a platform for identifying root causes of supplier-related issues and implementing targeted corrective actions. This approach ensures that the company's inventory levels are aligned with actual demand, buffers are optimized to balance waste and reliability and supplier relationships are strengthened through collaborative improvement efforts.

In the company's current operations, several issues related to supplier variability and inventory management contribute to inefficiencies. A significant challenge is the unpredictability of supplier deliveries, where inconsistencies in delivery timing, quality and transportation reliability lead to fluctuating inventory levels. This results in both excess stock to safeguard against potential shortages and frequent stockouts when supply disruptions occur. These supply chain inconsistencies cause production delays, impact customer satisfaction and incur unnecessary costs, such as higher storage and handling expenses.

Currently, the facility relies on large safety stock buffers to mitigate the risk of supply disruptions. These are leading to overstocking in certain areas while other parts face shortages. This reliance on excess stock as a safeguard against supplier uncertainties is a reactive rather than a proactive approach to supply chain management, resulting in inefficiencies and waste.

PFEP offers a comprehensive solution to these challenges by enabling the company to determine the optimal inventory levels for each part. By incorporating data on supplier performance, lead times, quality metrics and delivery reliability, PFEP helps the company move away from blanket overstocking strategies and shift toward a more calculated, demand-driven inventory management model. The system allows for the identification of parts that require larger buffers due to high supplier variability, while also recognizing opportunities to reduce inventory for parts with reliable suppliers or predictable demand patterns.

PFEP allows for the integration of level scheduling—a practice that aligns production schedules with supplier deliveries to create a more predictable demand signal. By working closely with suppliers to synchronize delivery schedules with production needs, the company can reduce the frequency of emergency orders and last-minute rush deliveries, which contribute to supply chain volatility. This not only reduces variability but also helps in the gradual reduction of safety stock buffers that were previously used to compensate for supply uncertainty.

Through these improvements, PFEP helps the company reduce excess inventory while maintaining sufficient stock for reliability, thus balancing cost savings with operational resilience. By using PFEP to optimize inventory levels based on real-time supplier performance and demand forecasting, the company can ensure that inventory management becomes more efficient, reducing waste, lowering carrying costs and ensuring a smoother flow of materials through the production process.

The most significant variability in the facility often stems from inconsistent supplier performance. This inconsistency can manifest in late deliveries, inaccurate shipment quantities or quality issues, all of which disrupt production and inflate inventory costs.

One of the most immediate advantages of PFEP is the reduction in supplier variability. By enabling the company to track and analyze key supplier performance metrics—such as on-time delivery, product quality, and transportation reliability—PFEP provides the company with the tools to identify and address areas where suppliers may be underperforming. Over time, this data allows the company to work more closely with suppliers, improving communication and ensuring that production schedules align with supplier capabilities. As a result, variability in deliveries is minimized, reducing the need for large safety stock buffers and enabling a smoother, more predictable production process. This shift from reactive stockpiling to a more proactive, data-driven inventory approach helps the company avoid the risks of overstocking while ensuring that critical parts are available when needed.

The reduction of variability directly contributes to lower inventory costs. With the ability to right-size buffers and optimize replenishment policies, the company can eliminate excess stock and reduce carrying costs. PFEP enables the company to maintain only the inventory needed to support operations, cutting down on the costly waste associated with overstocking. Additionally, by integrating supplier performance data into inventory decisions, PFEP helps ensure that suppliers are not only meeting demand but doing so in a consistent and reliable manner. This prevents costly stockouts or production halts due to unexpected shortages, ultimately resulting in more efficient use of resources and a leaner inventory.

Another critical benefit of PFEP is the enhanced visibility it provides across the entire supply chain. PFEP consolidates data on inventory levels, supplier performance and replenishment schedules into a centralized system, offering real-time insights into the state of the supply chain. This transparency allows for better coordination across different departments and stakeholders, from procurement to production to logistics. By having access to up-to-date information, decision-makers can react more quickly to changes in demand, identify potential supply disruptions early and take preventive action. Improved visibility also strengthens the company’s ability to forecast demand more accurately, ensuring that inventory levels are maintained at optimal levels and reducing the likelihood of overproduction or shortages.

Reducing variability and optimizing inventory levels has a direct impact on the company’s ability to meet customer expectations. With more reliable suppliers and more accurate demand forecasting, the company can improve on-time delivery (OTD) rates for finished goods, ensuring that customers receive their products when promised. By improving the consistency and reliability of supply chain operations, PFEP enhances customer trust and satisfaction. Higher OTD rates also improve the company’s reputation in the market, fostering greater customer loyalty and long-term relationships. Satisfied customers are more likely to return for future business, which in turn drives growth and profitability.

In addition to improving operational efficiency, PFEP also helps build stronger, more collaborative relationships with suppliers. By focusing on shared goals and mutual improvement, the company can work alongside suppliers to address performance gaps and optimize processes. This collaboration fosters trust and transparency, leading to long-term partnerships. Suppliers that are engaged in this development process are more likely to prioritize the company’s needs, offer better terms, and be more flexible in responding to changes in demand. A stronger supplier network contributes to a more resilient and agile supply chain, capable of adapting to changes in market conditions or unexpected disruptions.

The implementation of PFEP to reduce variability in supplier deliveries offers significant benefits across multiple areas of the business. From reducing inventory costs and enhancing supply chain visibility to improving customer satisfaction and strengthening supplier relationships, PFEP provides a holistic approach to supply chain optimization.

By addressing supplier variability and aligning inventory levels with actual demand, PFEP not only reduces operational inefficiencies but also enhances the company’s ability to deliver value to customers and remain competitive in a dynamic market. By focusing on data-driven decision-making and continuous improvement, PFEP helps build a leaner, more efficient and more resilient supply chain for the future.

5.3 Next steps and recommendation for the company

The practical application of the integrated supply chain improvement plan developed based on this research involves systematic actions aimed at enhancing inventory management, supplier relationships and overall supply chain performance. At the core of the plan is the implementation of PFEP (Plan for Every Part), ensuring that each part has clearly defined inventory parameters such as reorder points, safety stock levels and order quantities. In addition, comprehensive data analytics is employed to monitor and improve supplier performance. This approach creates a solid foundation for supply chain optimization and continuous improvement. The key goal is to reduce variance in supplier orders.

PFEP is a key tool in supply chain management as it allows for the development of a tailored inventory system for each part. Through PFEP, inventory parameters such as reorder points, safety stock, order quantities and supplier-specific replenishment schedules are defined. This plan is not only based on historical demand data but also considers the supplier’s performance and reliability. In practice, PFEP integration takes place by synchronizing inventory replenishment with suppliers’ delivery capacities and timelines. This synchronization ensures that orders are placed at the right time and in the right quantities, minimizing inventory costs while improving delivery reliability.

Supplier segmentation based on performance is another key component of the plan. Suppliers are categorized into three tiers: Tier 1 (low variance), Tier 2 (moderate variance) and Tier 3 (high variance). This segmentation is primarily based on supplier delivery reliability, lead time fluctuations and order fill rates. Through this segmentation, actions can be tailored to the specific needs of each supplier group:

1. Tier 1 (Low Variance): These suppliers are reliable and offer consistent lead times. They can be managed with more flexible inventory policies, where inventory is replenished automatically based on need. This allows for optimized inventory levels and ensures that parts are available without excess stock.
2. Tier 2 (Moderate Variance): For suppliers with occasional delivery deviations, slightly higher safety stock levels and optimized replenishment schedules can be implemented. Closer collaboration with these suppliers can also be fostered through root cause analysis and process improvements.
3. Tier 3 (High Variance): For suppliers with lower reliability and significant lead time variability, more comprehensive development programs are required. Additionally, tighter monitoring and predictive tracking may be necessary to improve the supply chain process.

Continuous performance monitoring and data collection are crucial in translating the improvement plan into practice. Suppliers can integrate Electronic Data Interchange (EDI) systems into the supply chain, providing real-time updates on order confirmations, Advanced Shipping Notices (ASNs), and delivery status. This enables automatic tracking of order accuracy, lead time variations and fill rates, allowing for immediate corrective actions when discrepancies are detected.

By developing and leveraging performance monitoring tools such as Power BI, visual dashboards can be created to display supplier performance across different metrics, including lead time fluctuations, order accuracy and deviations from planned orders. This enables early identification of potential issues and faster responses to maintain optimal performance across the supply chain. Furthermore, the analytics provide insights into when inventory policies and replenishment schedules should be adjusted based on changing supplier performance.

Supplier development is a central aspect of implementing the plan in practice. Improving supplier performance goes beyond measurement; it also involves concrete initiatives and programs that support suppliers in enhancing their processes and operations. For Tier 2 and Tier 3 suppliers, collaborative programs can be created to focus on process improvements and increasing delivery reliability. These may include joint development sessions, root cause analyses and performance metrics development. The goal is to ensure suppliers meet the performance targets set by the organization and to foster long-term partnerships.

The application of lean principles and Just-In-Time (JIT) methodologies is key to supply chain optimization. Tier 1 suppliers can be integrated with lean techniques such as continuous flow and process streamlining, which help reduce inventory costs and improve inventory turnover. This enables a more agile response to demand fluctuations and ensures that parts are always available for production without overstocking.

This also involves providing ongoing support to suppliers, such as training and performance monitoring, to ensure that they can improve their processes and better align with organizational needs. Strengthening collaboration and applying lean thinking helps to achieve long-term benefits, such as reduced inventory costs, improved delivery reliability and overall supply chain development.

The practical application of the results occurs through a multi-step, systematic process where PFEP, supplier segmentation, continuous data monitoring, supplier development, and lean thinking form the basis for optimizing the supply chain. This approach enables inventory management improvement, enhanced delivery reliability, and overall supply chain capacity growth, which in turn supports long-term competitiveness and sustainable performance improvements for the organization.

6 Conclusion

This study has provided valuable insights into the variability and forecasting of inventory levels within supply chains. By utilizing statistical models, particularly normal distribution, we were able to assess the factors influencing stock fluctuations and their impact on operational efficiency. The findings underscore the importance of robust inventory management strategies and the need for continuous adaptation to demand and supply uncertainties.

6.1 Summary of the research results

This study examined the key factors impacting lead times in Ioncor Oy's On-Time Delivery (OTD) process, assessed its current state and proposed strategies for improvement. The findings reveal that while the OTD process is well-structured and supported by tools like ERP for production planning, it faces several critical logistical and operational challenges. Addressing these challenges is essential to enhance supply chain reliability, reduce lead times and improve overall customer satisfaction. The research was guided by three main questions:

1. What are the key logistics-related factors that impact lead times in Ioncor Oy's OTD process?
2. What is the current state of Ioncor Oy's OTD process in terms of efficiency and operational effectiveness?
3. What strategies can be implemented to optimize lead times and improve supply chain performance?

The key logistics-related factors impacting lead times in Ioncor Oy's OTD process include supplier variability, inefficiencies in inventory and warehouse management, production planning inaccuracies, transportation delays and IT and communication gaps. Supplier variability, including delays and quality issues, often disrupts the flow of materials, leading to production delays. In addition, misaligned inventory practices and errors during goods receipt or dispatch create interruptions in material flow, further extending lead times. Inefficient production planning, coupled with tight transportation schedules and challenges in reverse logistics, also contributes to the unpredictability of lead times. Additionally, IT system downtimes and poor communication across departments hinder decision-making and coordination, exacerbating delays in the OTD process.

Ioncor Oy's OTD process is well-structured, with clearly defined workflows that integrate production planning, material management, logistics and warehouse operations. Despite this solid foundation, the current process faces significant operational bottlenecks. Supplier-related issues, such as variability in delivery times and quality, frequently disrupt production. When production planning is inefficient it leads to inefficiencies such as overproduction or underproduction. Transportation delays and inefficiencies in reverse logistics, along with errors in warehouse operations, also contribute to delays in delivery. Poor communication between departments remain persistent challenges, undermining effective coordination and prolonging lead times. While Ioncor Oy has adopted sustainable practices, like reverse logistics for packaging reuse, which contribute to cost efficiency, the operational bottlenecks highlight the need for further optimization.

Several strategies can be implemented to optimize lead times and improve supply chain performance. First, the implementation of a Plan for Every Part (PFEP) framework would centralize inventory and supplier performance data, enabling better proactive inventory management and reducing lead time variability. By aligning inventory levels with actual demand, this approach would minimize waste and carrying costs. Additionally, improving supplier collaboration by segmenting suppliers based on their reliability and implementing tailored improvement programs for high-variance suppliers can help mitigate delays. Synchronizing supplier deliveries with production schedules using methodologies such as JIT and level scheduling would reduce material flow disruptions and enhance supply chain efficiency. Proactive inventory management, supported by real-time data and analytics, would allow Ioncor Oy to dynamically adjust safety stock levels and replenishment policies, optimizing inventory while maintaining reliable supply levels. Strengthening IT systems and fostering better interdepartmental communication would also be crucial to reduce delays and improve coordination. Finally, continuous improvement initiatives, including regular performance monitoring and collaborative supplier development programs, would ensure sustained progress in optimizing lead times and enhancing overall supply chain reliability.

Despite these challenges, Ioncor Oy's OTD process demonstrates strengths (Figure 17), including a clearly defined workflow that integrates production planning, material management, logistics and warehouse operations. The company has also adopted sustainable practices, such as reverse logistics for packaging reuse, which contribute to environmental and cost efficiencies. However, these strengths are undermined by significant weaknesses across various stages of the supply chain. For example, supplier-related variability frequently disrupts operations, while production planning often lacks the flexibility required to respond effectively to fluctuating customer demands. Transportation delays and inefficiencies in reverse logistics, coupled with warehouse-related errors, further exacerbate delivery delays. IT system failures and poor communication remain persistent challenges, hindering coordination and decision-making across departments.

SWOT analysis (Figure 17) identifies these strengths and weaknesses and clearly demonstrates that optimizing the OTD process requires a comprehensive approach that accounts for both external and internal variability. A key recommendation is the implementation of the Plan for Every Part (PFEP) framework, which centralizes inventory and supplier performance data, enabling more proactive and data-driven inventory management. This framework would help reduce variability in lead times and ensure alignment between inventory levels and actual demand. By shifting from reactive stocking to proactive practices, Ioncor Oy can minimize waste and inventory costs while improving overall efficiency.

To address supplier variability, the study emphasizes the importance of segmenting suppliers based on reliability and implementing tailored improvement programs for high-variance suppliers. Synchronizing supplier deliveries with production schedules through methods such as Just-In-Time (JIT) and level scheduling can further improve material flow and reduce variability within the supply chain. Proactive inventory management, supported by real-time data and analytics, allows the company to dynamically adjust safety stock levels and replenishment practices, ensuring that operational efficiency improves without compromising delivery reliability. Additionally, strengthening IT systems and improving communication across departments are critical actions to reduce inefficiencies and delays. Continuous improvement initiatives, including regular performance monitoring and collaborative supplier development programs, will ensure sustained progress in optimizing lead times and enhancing supply chain reliability.

Strenghts	**Weaknesses**
• Well structured workflows • Utililization of advanced tools such as ERP for monitoring and planning. • Sustainable practices, reverse logistics for packaging reuse.	• Significant supplier variability causing frequent disruptions. • Inflexible production planning leading to inefficiencies. • Transportation and warehouse-related inefficiencies. • Persistent IT system downtimes and poor communication across departments.
Opportunities	**Threats**
• Implementing a PFEP to centralize inventory and supplier performance data for better decision making. • Strengthening supplier collaboration through tailored improvement programs and methods like JIT. • Leveraging real-time data and analytics to enhance inventory management and reduce variability. • Addressing IT and communication gaps to improve cross-departmental coordination.	• Continued reliance on unreliable suppliers, increasing the risk of material shortages and delays • Escalting costs due to inefficiencies in logistics, inventory management and transportation. • Risks of customer dissatisfaction due to delays and inconsistencies in delivery performance. • Potential vulnerabilities arising from economic fluctuations or supply chain disruptions.

Figure 17. SWOT analysis of OTD process.

In conclusion, the research answered the three main research questions as follows. The key logistics-related factors impacting lead times include supplier variability, inefficiencies in inventory and warehouse management, production planning inaccuracies, and IT and communication gaps. The current state of Ioncor Oy’s OTD process reflects a structured system with notable strengths, such as clear workflows and sustainable practices, but significant operational bottlenecks that hinder performance. Optimizing lead times requires implementing a PFEP framework, improving supplier collaboration, adopting dynamic inventory management strategies, and addressing IT and communication weaknesses. By systematically tackling these challenges, Ioncor Oy can strengthen its supply chain resilience, reduce costs, and enhance customer satisfaction.

6.2 Study limitations

This study provides valuable insights into the factors influencing lead times in Ioncor Oy’s On-Time Delivery (OTD) process, but it is not without limitations. First, the analysis was constrained to a specific timeframe and focused on a single case company. As a result, the findings may not fully capture seasonal or long-term variability in supply chain performance. Additionally, the study primarily relied on data from existing operational systems and interviews, which could introduce biases or limit the depth of analysis in areas not thoroughly documented or discussed.

Another limitation lies in the methodological scope. While the study utilized statistical tools, such as normal distribution models, to analyze inventory variability, it did not incorporate advanced predictive analytics or simulation methods that might provide more comprehensive insights into dynamic supply chain behaviors. Moreover, external factors, such as market volatility, geopolitical risks or sudden economic disruptions, were not fully explored, despite their potential impact on supplier reliability and inventory management.

The study's recommendations were based on theoretical and statistical analyses without the opportunity for real-world testing or piloting within Ioncor Oy’s operations. This lack of practical application means that the proposed solutions, while theoretically sound, require further validation to confirm their effectiveness in a live operational environment.

6.3 Academic contribution

This research makes a significant contribution to the field of operations management, specifically in the optimization of Order-to-Delivery (OTD) processes within contract manufacturing companies. Current literature tends to concentrate on optimizing individual elements and there is lack of comprehensive understanding of the integration of these processes and their combined impact on OTD performance. By filling this gap, the study provides new empirical insights that contribute to both the theoretical understanding of process optimization and the practical application of these strategies in contract manufacturing companies.

By employing a mixed-methods approach, this research advances the understanding of how process optimization and coordinating logistics processes in dynamic operational environments affects the efficiency of the OTD process and cost optimization. It challenges existing models of lean manufacturing by highlighting the unique factors that influence process efficiency in industries with rapidly changing customer demands.

Methodologically, this research contributes to the field by combining qualitative semi-structured interviews with process flow analysis and quantitative data collected from the case company. This mixed-methods approach provides a comprehensive and multi-dimensional view of the operational challenges. This innovative combination of qualitative and quantitative methods delivers a holistic perspective that extends beyond the scope of previous studies, enabling more precise and actionable conclusions.

In addition to its theoretical and methodological contributions, this research provides valuable insights for practitioners, offering actionable recommendations for improving OTD efficiency and ensuring faster response times to customer needs.

6.4 Managerial implications

The findings of this study offer important guidance for managers looking to improve their On-Time Delivery (OTD) processes. By addressing key challenges like supplier variability, inventory mismanagement and production planning inflexibility, managers can implement strategies to optimize their operations. Improving supplier collaboration by segmenting suppliers based on reliability will reduce delays and improve material flow. Additionally, adopting a Plan for Every Part (PFEP) framework will enable managers to better align inventory with actual demand, minimizing waste and carrying costs.

Finally, fostering a culture of continuous improvement through regular performance monitoring will ensure that the OTD process remains efficient and adaptable to changing business conditions. By implementing these strategies, managers can significantly reduce lead times, lower costs and improve customer satisfaction.

6.5 Study contributions

This study provides valuable contributions to both academic and practical knowledge on optimizing OTD processes. It identifies key logistics-related factors affecting lead times, such as supplier variability, production planning inefficiencies and IT-related challenges, offering actionable insights for practitioners to improve their operational processes. The study also highlights the importance of implementing frameworks like PFEP for proactive inventory management, along with strategies like JIT to reduce lead time variability. Additionally, the research emphasizes the significance of strengthening communication and IT infrastructure to streamline coordination across departments.

By addressing these issues, the study contributes to a deeper understanding of the complexities within OTD processes and provides managers with evidence-based recommendations for improving supply chain performance. Moreover, the findings can serve as a foundation for future research exploring the broader implications of OTD optimization in various industries.

6.6 Further studies

This study provides valuable insights into the factors affecting lead times in Ioncor Oy's OTD processes. However, future research could explore several concrete areas emerging from these findings. First, a deeper analysis of internal logistics delays, particularly the time lag between order picking and the final product delivery, could uncover systemic inefficiencies not comprehensively addressed in this study. Examining how these delays impact inventory levels and lead times would offer actionable insights into minimizing disruptions and improving material flow at the inventory level.

Second, the effects of supplier variability on OTD performance could be studied in greater detail. This could include monitoring key performance indicators (KPIs) such as delivery accuracy, defect rates, and variability's influence on inventory levels. Focusing on these metrics would enable companies to develop targeted strategies for mitigating supplier-induced disruptions and improving supply chain reliability.

A third potential research avenue could investigate the use of predictive technologies, such as artificial intelligence and machine learning, in supply chain management. These technologies could facilitate the development of models that identify early warning signs of delivery delays, material shortages, or capacity constraints. Such tools could support decision-making, for example, in optimizing inventory levels or forecasting delivery times. Additionally, research could examine how these technologies can be integrated into existing systems, such as ERP platforms, to streamline processes and reduce manual effort in routine tasks.

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