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Understanding material shortage in Engineering-To-Order context: A case study

Master's thesis in Quality & Operations Managment

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Causes and prevention of material shortage in engineering to order
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Abstract

Material shortages are the leading cause of delivery delays in Engineering-To-Order (ETO) production at the studied Swedish automation company, affecting over 50% of late deliveries. This thesis identifies key internal factors, namely, unclear lead time ownership, poor coordination, inaccurate forecasting, and fragmented ERP data as the main contributors.

To address this, a structured analysis model based on Fault Tree Analysis (FTA) is proposed. The model enables systematic root cause evaluation, helping distinguish between internal and external responsibility for shortages. It is intended to support proactive shortage prevention and foster a culture of accountability over reactive blame. The study is based on an abductive research approach, combining qualitative interviews (n=14) and quantitative analysis of ERP data from 2022–2025. Findings highlight the need for improved process visibility, clearer roles, and reliable data to support effective material planning in complex, customer-specific production environments.

Keywords: Engineering-To-Order (ETO), Material Shortage, Root Cause Analysis, Fault Tree Analysis, Supply Chain Management, ERP Systems.

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List of Acronyms

Below is the list of acronyms used throughout this thesis sorted in alphabetical order.

ATP	Available to promise (calculation of what a company can deliver)
CMB	Chamber
CODP	Customer Order Decoupling Point
ERP	Enterprise Resource Planning
ETO	Engineering-to-order
FTA	Fault Tree Analysis
LVHV	Low Variety High Volume
MPP	Master Production Plan
MS01	Code for Material shortage
MTO	Make-to-order
MTS	Make-to-stock
OEE	Overall Equipment Effectiveness
OPA	Order Planning Administration
OTIF	On Time and In Full
OtD	Order-to-Delivery
PDSL	Promise Date Service Level; Measures the company's ability to deliver on the originally promised customer delivery date.
Promise Date	Committed Ship Date
Purchase order	Order sent to supplier
RCA	Root Cause Analysis
Request Date	The date the customer wants the product shipped or delivered.
Sales order	Order from customer
Status 5 Article	Article that does not have predetermined suppliers

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1 Introduction

1.1 Problem formulation

Delivering the right product at the right time and in the right configuration is one of the most pressing challenges in today's industrial manufacturing landscape, particularly for companies operating in Engineer-to-Order (ETO) environments. Unlike mass production systems, ETO companies design and build products after receiving customer orders, often with highly specific requirements. This makes their supply chains complex, lead times longer, and the risk of delays significantly higher. The material shortage is among the most critical threats to on-time delivery in ETO settings, a persistent and costly issue that often emerges too late in the production process to be corrected without disruption.

This study investigates the problem through the lens of a real-world case involving a medium-sized company in western Sweden operating in the automation industry. Among the company's product offerings, one product stands out, not because it is the only solution, but because it is typically more customizable than the others. The company often tailors its system solutions to meet customer-specific requirements and unique needs. This high degree of configurability makes the product a key offering in the company's efforts to grow within an industry where flexibility and responsiveness are essential.

As the case company expands in this segment, delivery reliability has become a critical competitive factor and a growing concern. The company's delivery precision currently stands at around 82%, and of the 18% of orders delivered late, over half (52%) are delayed due to material unavailability. This makes material shortage the most significant contributor to late deliveries, placing disproportionate pressure on the supply chain function to resolve the issue.

The urgency lies not only in how frequently material shortages occur, but also in how the organization responds to them. Shortages are typically discovered late in the process, leaving little time for effective mitigation. Although the case company uses a special delay code in its ERP system to log delivery delays, there is no structured method for tracing, analyzing, or learning from these events. As a result, delays are recorded but rarely examined in depth. This leads to a system that focuses more on documenting symptoms than identifying root causes, reinforcing a cycle of reactive problem-solving rather than proactive prevention.

Internal issues compound the challenges: fragmented visibility into inventory, unclear ownership of lead time data, and poor coordination between overlapping orders. These problems are especially pronounced in the production of the specific product this thesis is focusing on, where configuration complexity and customer-specific requirements create additional strain.

1.2 Purpose of the Study

The purpose of the study is to identify the underlying causes of material shortages in an ETO manufacturing environment and to propose a more proactive approach in managing them. Currently, material shortages at the case comapany are primarily addressed reactively. When a delivery is delayed, the immediate response is often to blame the supplier, typically based on assumptions rather than objective analysis.

This study will propose a reference or a structured model to evaluate each case of material shortage as to provide an evidance based assesement. These insights are drawn from qualitative interviews, observations, and process mapping. The study's purpose is to help the company shift from assumption-driven blame to a culture of accountability grounded in data by introducing this model.

1.3 Research questions

- What are the causes of material shortage in Engineering-to-Order manufacturing environments?
- How can the material shortage be proactively managed?

1.4 Delimitations

This study is limited in scope to ensure a focused and manageable investigation. The study is restricted to one specific product type. Other product lines offered by the company are excluded. The study focuses exclusively on material shortages as the root cause of delivery delays, specifically delays coded as MS01 in the case company's ERP system. Other potential causes of late deliveries, such as:

- Production bottlenecks (e.g., capacity constraints, machine breakdowns),
- Customer-related delays (e.g., late approvals, last-minute order changes),
- Logistics issues (e.g., transportation delays, customs clearance),
- Internal decision-making delays (e.g., prioritization conflicts),

are acknowledged but will not be analyzed in this study.

The study does not examine supplier negotiation processes or strategic agreements (e.g., pricing structures, long-term contracts, bulk commitments). These are typically handled at a higher organizational level and lie outside the operational scope of this research.

Instead, the study focuses on material availability and planning issues, specifically how procurement-related shortages impact the ability to fulfill customer orders. By setting these boundaries, the study maintains a clear and narrow focus on improving material planning performance without being sidetracked by broader organizational or contractual topics.

1.5 Disposition of thesis

This thesis is organized into six chapters. Chapter 1 introduces the study by outlining the problem formulation, purpose, and scope. Chapter 2 presents the theoretical framework and relevant literature on material shortages, ETO environments, and root cause analysis. Chapter 3 describes the research methodology, including the qualitative and quantitative data collection and analysis approaches. Chapter 4 presents the empirical findings, focusing on the identified causes of material shortages in the case company and the FTA's construction and validation. Chapter 5 discusses these results in relation to the literature, highlighting key insights and implications. Finally, Chapter 6 concludes the thesis by summarizing the main contributions, acknowledging limitations, and suggesting directions for future research.

2

Theoretical framework

2.1 Engineering-To-Order

Researchers most commonly discuss order-based manufacturing systems in the academic literature through the frameworks of Make-to-Order (MTO) and Engineer-to-Order (ETO). However, how researchers analyze these systems differs depending on their perspective, which can vary significantly. The concept of the Customer Order Decoupling Point (CODP) plays a central role in explaining how manufacturing systems differ, as explained by Olhager (2010) (See Figure 2.1).

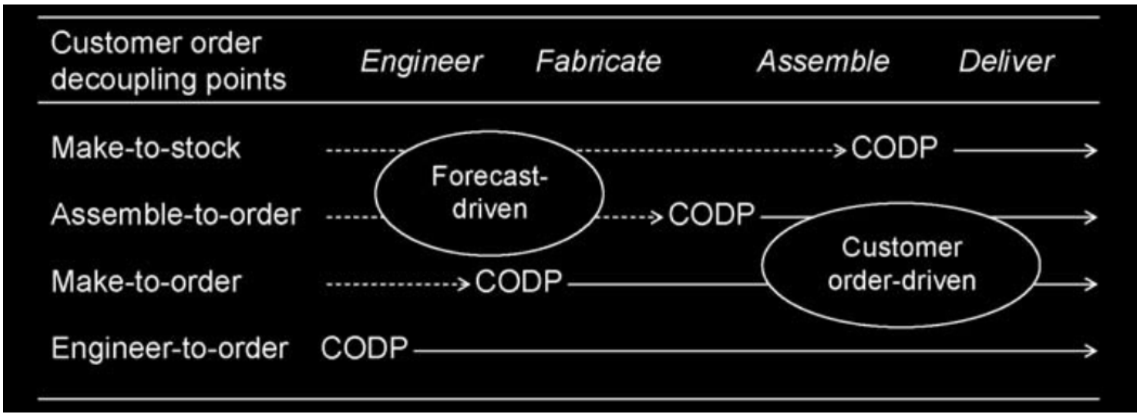

Figure 2.1: Different customer order decoupling points. [Source: Olhager (2010)]

The CODP is the point in the value chain where the flow of goods transitions from being driven by forecasts to being driven by actual customer orders. This point serves as a "strategic setting" in supply chains, determining the balance between efficiency (manufacturing in advance based on forecast) and responsiveness (producing after demand is known). This significance of CODP is emphasised by Olhager (2010) in distinguishing between manufacturing environments.

In Make-to-Stock (MTS) systems, the CODP is located upstream, closer to the manufacturer, which allows for quick delivery but increases the risk of overproduction. In contrast, in ETO manufacturing systems, the CODP is positioned further downstream, closer to the customer. This shift enables greater customization and lower inventory levels, but introduces longer lead times and higher demands on planning coordination (Willner et al., 2016). In MTO, companies start manufacturing after they receive a customer order, whereas in ETO, the customer's request also triggers the design and sourcing processes. The CODP-centered perspective highlights the strategic value of identifying the point where forecast-driven operations should be separated from customer-driven ones, enabling companies to optimize timing in scaled-up manufacturing systems.

In contrast, Amaro et al. (1999) challenges the simplicity of conventional classifications such as ETO by introducing a more detailed taxonomy. Their approach does not rely explicitly on the CODP but instead classifies companies based on three dimensions: level of customization, responsibility for design/specification/purchasing, and which operations take place after an order is received. This view offers a more granular understanding of what “order-based” really means in practice, distinguishing between different types of customization and operational responsibilities that may exist even within companies that all identify as ETO.

Together, these perspectives offer complementary insights: Olhager (2010) provides a process-oriented, planning-centered view focused on the timing of demand activation, while Amaro et al. (1999) contribute a strategic and structural lens that classifies companies based on how deeply they are involved in fulfilling unique customer needs.

In the ETO context, products must either be fully developed or adapted to customer specifications within the order fulfillment process. A large part of the delivery lead time is attributed to engineering time, meaning that engineering tasks are responsible for more than 50% of the lead time (Willner et al., 2016).

The paper Willner et al. (2016) argues that the definition of ETO products is often too narrow, as the spectrum of ETO products encompasses a broader variety in terms of both volume and the degree of order-specific engineering. Through the literature review, it was observed that there is no general consensus on a strict definition of ETO.

Variations in these definitions are especially noted in Gosling and Naim (2009). However, there is general agreement that the production of an ETO product is linked to an actual customer order, with a decoupling point in the design stage. There is, however, some confusion around the dimension of design complexity. While some scholars, such as Bertrand et al. (2000) argue that ETO involves developing a completely new product for each specific customer order, others like Willner et al. (2016) suggest that ETO refers to adapting existing products to customer specifications. According to this latter view, such products require only limited order-specific engineering and may share characteristics with Make-to-Order products.

2.2 Sales and operations planning

2.2.1 Demand Planning

Given the high level of customization in ETO environments, demand is inherently uncertain. This uncertainty complicates forecasting and material planning, often resulting in shortages. Therefore, it is essential to understand how to improve demand planning in such volatile environments. The literature suggests several ways to increase forecast reliability, including option-based forecasting and pseudo-bills of material (Bertrand et al., 2000) and collaborative planning strategies with suppliers (H. Xu et al., 2012).

Demand planning is the process through which companies translate high-level sales goals and market expectations into actionable plans for future demand. This process typically combines inputs like historical sales data, marketing strategies, and product knowledge to generate forecasts, which are refined into operational demand plans.

In ETO environments, where products are configured based on individual customer requirements, demand planning becomes especially challenging due to the wide variety of product configurations and customer preferences (Ross, 2015).

Ross (2015) goes on to say that demand forecasting in such environments is most effective at the product family level. A product family groups items that fulfill a general market need, allowing companies to aggregate sales data and detect trends across similar product variants. Forecasting at this level balances detail and accuracy, offering more precision than high-level business forecasts and a greater reliability than overly detailed item-level forecasts.

This aggregation provides a stable basis for statistical forecasting, either from the bottom-up (aggregating item-level sales) or top-down (disaggregating from product families). This method reduces forecast error by focusing on demand patterns rather than individual product combinations (Ross, 2015). In settings where configuration uncertainty is high, forecasting product family demand enables companies to anticipate total volume needs and ensure the availability of standard components across different variants, even when final specifications are unknown.

Bartezzaghi and Verganti (1995) offers a complementary but distinct approach to managing uncertainty. Instead of focusing on product families, they propose the use of order commonality, analyzing orders across customers to identify shared components used in multiple configurations. In this bottom-up approach, the focus shifts from forecasting end-products to forecasting the demand for components that appear frequently across various product variants. They argue that in highly customized ETO settings, where customer preferences lead to countless possible combinations, reducing uncertainty at the component level can buffer against misalignments between forecasted and actual demand. By concentrating planning efforts on components that are commonly needed, regardless of the final product configuration, manufacturers can reduce material shortages and avoid overstocking rarely-used parts.

Although Ross (2015) focuses on demand uncertainty at the product family level and Bartezzaghi and Verganti (1995) at the component level, both approaches share the same goal which is to enable more resilient and anticipatory supply planning in unpredictable environments.

Ross (2015) provides a the higher-level view that helps stabilize demand signals for broader planning, while Bartezzaghi and Verganti (1995) gives a more granular method to secure critical components when configuration variability is high.

Together, these perspectives underscore the need to manage demand uncertainty by identifying repeatable patterns, either in the types of products sold or the parts most frequently used to build them. This dual perspective offers a robust framework for ETO manufacturing to improve material availability and reduce the risk of shortages due to demand variability.

2.2.2 Order-to-Delivery Process

The Order-to-Delivery (OtD) process includes the complete chain of activities that begins when a customer orders a product and ends with the delivery of the final product (Croxton, 2003). In ETO manufacturing, the efficiency and smoothness of the OtD process are crucial for a company's competitiveness, especially when it comes to cost, quality, and, most importantly, delivery performance (Ebadian et al., 2009).

Additionally Croxton (2003) defines the OtD process as a core cross-functional supply chain process that requires coordinated actions across sales, production, logistics, and procurement. This process is not limited to internal operations but includes information and product flows between upstream suppliers and downstream customers (see Figure 2.2).

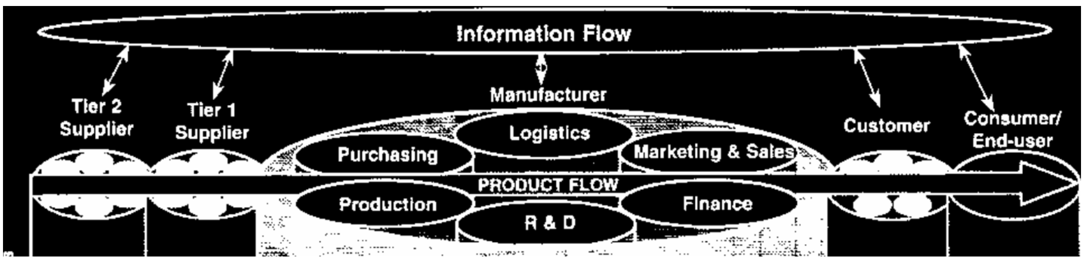

Figure 2.2: Information and product flows between upstream suppliers and downstream customers [Source: Croxton (2003)].

In this context, seamless communication and timely information sharing are essential to meeting customer expectations and reducing lead time variability. Forslund et al. (2009) further emphasizes that OtD performance should be assessed across the entire value chain, as focusing solely on individual departments may lead to sub-optimization. They propose a structured view of OtD that includes four major subprocesses: customer ordering, supplier delivery, transportation, and goods receipt (See Figure 2.3).

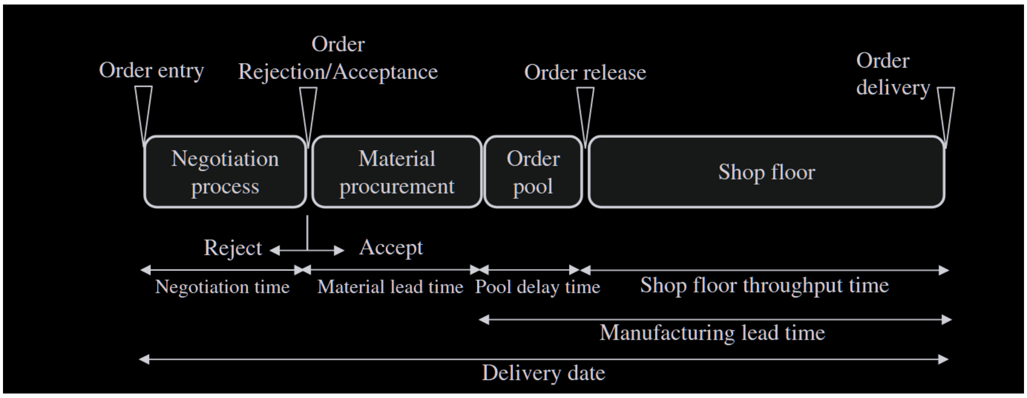

Figure 2.3: Different stages in the OtD process [Source: Ebadian et al. (2009)]

Each element contributes to the total delivery performance and must function cohesively to avoid unnecessary delays and inefficiencies.

To understand the OtD process more operationally, Ebadian et al. (2009) present a breakdown of the internal stages of fulfilling a customer order in an MTO setting. This includes key steps such as order entry and acceptance, material procurement, order pooling, shop floor execution, and final delivery. Each of these stages adds time and variability to the overall lead time. Inaccuracies in any step, particularly in procurement lead times or production scheduling, can directly affect the promised delivery date.

In ETO environments, the OtD process is especially complex because many upstream activities, such as design, material sourcing, or production planning, are triggered only after the customer order is received. Unlike MTS systems, where inventory buffers absorb variability, ETO systems rely heavily on efficient internal coordination to prevent disruptions. As such, the OtD process becomes not just an operational necessity, but a strategic capability that can differentiate companies in highly competitive and customization-driven markets.

2.2.3 Delivery Performance in Order-Based Manufacturing

In today's unforgiving global marketplace, the rules of competition have changed. Price and quality, once the twin pillars of manufacturing success, are no longer enough. These dimensions have become mere entry tickets, basic expectations in a market where customers are more demanding and competitors more agile than ever. The battleground has shifted for companies operating in MTO and ETO environments, where the ability to deliver reliably and quickly has now emerged as a source of competitive advantage.

In production settings where every product is customized and lead times are tight, delivery reliability is no longer optional, it is the deciding factor in determining whether a firm will win the next order or lose it to a competitor. As Shang and Liu (2011) emphasizes, in time-based competition, delivery speed and reliability have evolved from being performance indicators to becoming the core strategic positioning in high-mix, low-volume industries.

As noted in Fawcett et al. (1997), the delivery capability is not just a supply chain metric, but a strategic weapon. Firms that consistently meet promised delivery dates build trust, loyalty, and repeat business. Those that cannot, risk losing customers in an instant.

Although Sarmiento et al. (2007) argued decades ago that delivery reliability could be a game-changer, today, it has evolved from a differentiator to a survival requirement. Without it, even the best-engineered products may never reach the customer.

Empirical studies further emphasizes this point, highlighting that late deliveries can erode customer confidence, disrupt operational planning, and lead to switching behavior. In industries driven by short lead times and complex customization, reliability is often the only way to stay in the game, let alone win it (Mundt & Lödding, 2024).

Delivery performance is no longer a back-end operational concern. It is a frontline competitive dimension, especially in low-volume, high-mix production where every order matters.

As Mundt and Lödding (2024) emphasize, the ability to deliver on time and in full (OTIF) is not just a key customer metric, it is increasingly viewed as the currency of trust in order-based manufacturing.

2.3 Material Shortage

2.3.1 Material Shortage as a Critical Bottleneck

Material shortages in a manufacturing environment refer to the unavailability or insufficient supply of essential materials and components required for production. These shortages can arise from various causes, including supply chain disruptions, surges in demand, or logistical challenges (Melnychuk et al., 2022). The impact of material shortages on manufacturing performance is significant, particularly in terms of on-time delivery and overall delivery reliability. Lack of available materials delays production schedules, resulting in late customer deliveries. Having materials at the right place at the right time is especially critical since on-time delivery is a key factor in market competitiveness and customer satisfaction (McLean, 2017).

Poor management of raw material availability can lead to rescheduling and delivery delays, undermining production efficiency and planning (Chiu et al., 2020). In addition to delays, material shortages can cause production line stoppages, which drive production costs and reduce operational performance. For example, in the aerospace industry, shortages often result in unexpected design changes and the need for obsolescence management, both of which increase overall program costs and extend schedules (Nadarajan, 2019).

Material shortages can be particularly disruptive in low-volume, high-mix manufacturing environments such as ETO. As noted by McLean (2017), when critical components are missing, production halts, lead times increase, and meeting customer deadlines becomes more difficult. As highlighted by Willner et al. (2016) in ETO environments, shortages occurring early in a project can create a domino effect, delaying subsequent stages and pushing back entire project timelines.

Moreover, uncertainty surrounding material availability makes it difficult to provide reliable delivery estimates, often leaving customers uncertain about when they will receive their orders (Melnychuk et al., 2022). These delays can lead to increased operational costs due to expedited shipments, rushed production, and unplanned downtime. Ultimately, late delivery not only inconveniences customers but can also damage a company's reputation and erode long-term business relationships (Mundt & Lödding, 2024).

2.3.2 Causes To Material Shortages

This section examines the most commonly cited causes of material shortages in ETO production environments, as identified in the literature. By exploring key factors such as late engineering changes, order interdependencies, lack of coordination between functions, inaccurate demand forecasting, ineffective procurement and supplier management, and unrealistic lead times, the aim is to provide a structured understanding of the systemic challenges that impact material availability in customized manufacturing contexts.

2.3.2.1 Lack Of Coordination Between Functions

Material shortages in an ETO manufacturing environment can often be traced to several key factors and one such factor as noted in the literature is the lack of coordination and integration across different functions (McLean, 2017).

Research by Mello et al. (2017) highlights that in both ETO and MTO supply chains, engineering, procurement, and production are deeply interconnected. Without real-time insights into production needs, procurement may struggle to order the right materials at the right time.

As noted by Cigolini et al. (2022), when multiple suppliers are involved, poor communication can further disrupt material flow, leading to shortages. The complexity of ETO environments, coupled with a high demand for customization, makes it difficult to balance supply and demand. To manage this, companies rely on tactical planning, which requires effective cross-functional communication between departments. When this integration is lacking, material availability is negatively impacted (Cigolini et al., 2022). To manage customization and address the imbalance between supply and demand, companies tackle these challenges within the tactical planning horizon, which requires highly efficient cross-functional communication between departments. According to Cigolini et al. (2022) if this integration is lacking, it will affect material availability.

Similarly, Naim and Towill (1994) argue that poor integration between core functions, particularly production planning, purchasing, and engineering, is a fundamental cause of material shortages in complex manufacturing environments. Material planners often work under high levels of uncertainty, relying on incomplete or delayed information regarding engineering requirements and future demand. As a result, procurement decisions may be mistimed or misaligned, leading to either excess inventory or critical shortages.

These issues, according to Naim and Towill (1994) are not technical but rather organizational, rooted in siloed functions and fragmented communication. For example, when engineering changes are not effectively shared with procurement or when production schedules are not aligned with material planning, availability declines.

Naim and Towill (1994) further explain how poor internal information distorts demand signals, resulting in overreaction and inefficient material flows. When each function acts independently, it adds safety stock or places reactive orders, further amplifying supply chain variability. They note that while simulation tools and ERP systems are commonly used to support planning, they often fail to account for the real-world complexity and interdependencies within and between departments. Therefore, they advocate for a more holistic and integrated approach to materials logistics where departments collaborate in real time and share a unified understanding of demand and resource constraints. Without such alignment, they argue, firms will continue to experience material shortages that directly undermine delivery performance (Naim & Towill, 1994).

2.3.2.2 Inaccurate Demand Forecasting

Another contributing factor to material shortage is inaccurate demand forecasting (Bertrand et al., 2000). Since the ETO supply chain operates with a decoupling point at the design stage, as noted in Olhager (2010), every customer order affects the product's design. This high level of customization makes it difficult to predict material needs precisely, increasing the risk of shortages.

Over the past decades, the order-based manufacturing industry has experienced a steady increase in product variety, often referred to as a proliferation of products alongside intensified competition in customer markets (ElMaraghy et al., 2013). These shifts have forced companies to adapt by offering a wider range of highly customized products. Such volatile market conditions have introduced several operational challenges, particularly in forecasting, as traditional methods struggle to handle the growing complexity and unpredictability of high variety, customer-driven demand (Bertrand et al., 2000).

Bertrand et al. (2000) emphasizes that demand uncertainty is a key cause of material shortage. In order-based industries, customers rarely specify technical product types directly. Instead, they describe functional requirements, such as "I want a fast machine," "I want it in blue," or "I want high accuracy". The manufacturer is responsible for translating these functional requirements into technical product configurations. Each customer choice, such as speed or color, corresponds to a feature, and each feature(e.g. color or speed) includes several options, and the manufacturer combines these into unique configurations for each customer order.

The problem arises because each option may require different components, making it difficult for the manufacturer to anticipate which combinations customers will choose (Bertrand et al., 2000). The number of possible combinations can grow significantly, making component-level forecasting extremely difficult. Because companies cannot accurately predict which product variants customers will order, they also struggle to determine which parts and quantities they need, and as a result, some components may be missing when orders arrive, which leads to material shortages, while others may be overstocked due to low usage frequency, leading to waste (Bertrand et al., 2000).

Furthermore, when companies share components across multiple options and product configurations that are difficult to forecast, they increase the risk of running out of critical parts. This may delay production or prevent it from starting at all, ultimately leading to delivery delays (Bertrand et al., 2000).

This view is supported by Aykin (2003), highlighting the increasing difficulty of material management in order-based manufacturing. The view from this author aligns with the view of Bertrand et al. (2000), who contrasts the predicability of fixed bills of materials, where component needs are known and manageable using traditional methods like MRP, with the challenges of managing customer specific orders. In more complex scenarios where products are built according to customer-specific orders, managing production and material availability becomes significantly more challenging. In such cases, the quantity and type of components may vary from one order to another, making forecasting and material planning far more uncertain and error-prone. This variability supports the argument that in environments with higher degree of customization and product variety, traditional planning methods can be error prone, and the risk of material shortages can potentially increase when demand is difficult to predict.

2.3.2.3 Ineffective Procurement and Supplier Management

Another contributing factor to material shortages, as highlighted in the literature, is ineffective procurement and poor supplier management. Mello et al. (2017) argue that ETO companies often maintain one-sided relationships with suppliers, which results in weak commitments and communication gaps. This point is further emphasised by Cigolini et al. (2022) where the importance of strong supplier collaboration is underscored, especially when components are engineered to order and frequently subject to design changes. Without robust supplier relationships, material availability becomes increasingly unpredictable.

As noted in McLean (2017) companies often attribute material shortages to suppliers, but the root causes are often internal. In a study conducted at major manufacturer of complex, high-tech products facing over 100 material shortages daily, approximately 90% of those shortages were traced back to internal process failures, with only 10% resulting from supplier issues (McLean, 2017).

2.3.2.4 Unrealistic or Long Lead Times

Another factor contributing to material shortages is the use of unrealistic or inaccurate lead times for supplier-sourced components. When lead times recorded in the planning system do not reflect the supplier's capabilities or constraints, a disconnect arises between what the company expects and what the supplier can deliver. This mismatch can often lead to missed deliveries and production delays (Graves, 2022).

In H. Xu et al. (2012), they emphasize that lead time is a major contributor to the bullwhip effect, where small fluctuations in customer demand lead to increasingly severe distortions further down the supply chain. Longer or more variable lead times make it harder to share reliable information, reducing visibility and increasing the risk of shortages when materials do not arrive as expected.

Myrelid (2017) also highlights that inaccurate lead time data disrupt production planning. Poor input from the manufacturing company forces suppliers to react to changing schedules, which drains safety stocks, creating capacity imbalances, and ultimately delaying component availability.

This point is reinforced in the study Lanning and Eng (n.d.), showing that misaligned or poorly communicated lead times limit the ability of a supplier to respond to changes in demand, especially in environments of limited capacity. Together, these studies show that unrealistic lead time assumptions are not just planning errors, they represent deeper structural issues that directly impact material availability and delivery performance.

2.3.2.5 Engineering changes

Engineering changes, particularly those made late in the product development or production cycle, can have an impact on material availability within manufacturing systems. As highlighted by ElMaraghy et al. (2021), late product changes are among the most challenging aspects to manage in a production environment.

This is due to their unpredictable and wide-reaching consequences across both the external supply chain and the internal manufacturing system. In ETO supply chains where products are custom-designed and manufactured to meet specific customer requirements, these changes are especially disruptive. The effects are magnified when design modifications occur after production has commenced or once the design has been set, leading to considerable disruptions in lead times, inventory management, and overall supply chain efficiency (Mello et al., 2017).

When changes are made after materials have already been ordered or received, the supply chain must react swiftly, often requiring last-minute procurement. This reactive behavior introduces delays and increases the likelihood of ordering errors or shortages. Furthermore, such abrupt changes can propagate upstream in the supply chain, triggering the bullwhip effect, a phenomenon where small changes in demand at the customer level cause progressively larger fluctuations in upstream orders (Wang & Disney, 2016). This not only disrupts material flow but also adds inefficiencies and waste throughout the supply network.

Additionally engineering changes can also strain supplier relationships and jeopardize their ability to meet previously agreed-upon delivery schedules.

Mello et al. (2017) points out that late detection of material-related problems is another critical factor for late changes. If issues with materials such as incorrect specifications, poor quality, or incompatibility with other components are not identified until later in the process, the time required to rectify them becomes much longer. When material problems are not communicated promptly across the supply chain, they can create a cascading effect, where multiple stages of production and material handling are disrupted, which creates delays.

As noted in Mello et al. (2017), the impact of these changes is often underestimated. Engineers may perceive the changes as minor technical adjustments or quick fixes, yet the downstream coordination required across the value chain is frequently overlooked. This misalignment is further emphasized in ElMaraghy et al. (2021) where the complexity of integrating changes across interconnected production and supply chain processes is highlighted as a great challenge.

2.3.2.6 Order interdependencies

In ETO environments, it's common for different production orders to share some of the same components (Gosling & Naim, 2009). This creates order interdependencies, which can make it harder to ensure all the needed materials are available on time. In standardized or repetitive production, this is usually easier to manage because products and processes are more predictable. But in ETO, where every product is custom-built and configurations often change, it becomes much more difficult. As L. Xu and Chen (2021) explain, this is because the full product setup isn't usually finalized until production is about to begin. Only then, shared components across different orders becomes visible, often too late, leading to conflicts over materials and increasing the risk of shortages.

This issue is further emphasized by McLean (2017), who highlights the operational risks associated with unclear order interdependencies. When the component requirements for each order are not clearly defined early, production planning becomes uncertain and exposed to risk. McLean (2017) goes on to argue that because production performance is often measured by output metrics such as units produced per shift there is an operational tendency to advance production on any available order to maintain efficiency. However, this practice can lead to the premature use of shared components, causing later orders to cannibalize materials intended for earlier ones. This behavior disrupts the intended production sequence and compromises material availability for other jobs.

Moreover L. Xu and Chen (2021) also discusses how such cannibalization undermines the reliability of ATP calculations. These calculations, which are a part of the S&OP process, become invalid when materials are reallocated in real time due to unforeseen interdependencies, regardless of the original intentions behind such changes. As a result, even well-planned ATP commitments can fail, creating further inefficiencies and eroding trust in the planning process.

To get an overview of what each literature says about the causes of material shortage, a table has been created (See Table 2.1)

2.3.3 Summary Table of Literature

Table 2.1: Summary of Literature on the Causes of Material Shortage.

Literature	Lack of coordination	Forecasting inaccuracy	Engineering changes	Order interdependencies	Poor procurement supplier mgmt.	Unrealistic lead times
N&T (1994)	X					
B. (2000)		X				
Ayk (2003)		X				
H et al. (2003)				X		X
G&LR (2009)	X	X	X		X	
M (2017)	X	X	X	X		
L (2017)						X
C (2020)	X	X	X		X	

N&T (1994) = Naim and Towill (1994)
B. (2000) = Bertrand et al. (2000)
Ayk(2003) = Aykin (2003)
H et al.(2003) = Huang et al. (2003)
G&LR (2009) = Gosling and Naim (2009)
M(2017) = Mello et al. (2017)
L (2017) = Lanning and Eng (n.d.)
C (2020) = Chiu et al. (2020)

2.4 Root cause analysis

Root Cause Analysis (RCA) is a problem-solving method used to understand the underlying reasons behind problems and prevent them from happening again (Bhamu & Singh Sangwan, 2014). It helps identify the root causes, the most fundamental, essential reasons that explain why a disturbance or issue occurred in the first place (Rooney & Heuvel, n.d.).

RCA is commonly used in manufacturing, but the approach can be applied in any field where there is a need to improve systems and solve recurring problems. RCA is often carried out by people with diverse backgrounds who may use one or several tools, such as Five Whys, Fishbone Diagrams, or Fault Tree Analysis, to investigate failures systematically (Rooney & Heuvel, n.d.).

Ito et al. (2022) explain how to conduct an effective and efficient root cause analysis, in manufacturing context. They describe some enablers and challenges related to conducting an efficient and effective root cause analysis. An effective RCA process allows manufacturing companies to enhance their ability to learn from past disturbances and leads to the design and development of a more resilient production system (Ito et al., 2022).

According to Ito et al. (2022), challenges refer to the difficulties that practitioners encounter when performing root cause analysis, and enablers refer to activities or tools that practitioners can use to facilitate the same process. This distinction is important because, in practice, manufacturing companies often struggle to be effective and efficient when conducting root cause analysis of their production disturbances due to the time-consuming process of root cause analysis, which takes time to collect information, analyse the data, and draw conclusions (Ito et al., 2022).

A key requirement as mentioned by Ito et al. (2022) for effective RCA is access to high-quality and complete data. This view is shared by Kozjek et al. (2017), where the author categorises different types of data needed for RCA into the following categories:

- Process-specific data
- Fault-specific data
- Other types of data

Process-specific data refers to the data directly connected to the production process, fault-specific data refers to alarms and disturbance data, and other data includes information from subsystems such as maintenance, quality, and logistics.

While process-specific data is often available, its may not be as available for for fault-specific data, even though this type of data is critical to understanding the causes of disturbances (Ito et al., 2022). This can happen for several reasons, including that it may not be part of a company's culture to report and collect data about disturbances, or that employees may not have enough time to perform those activities (mainly when focused on firefighting the disturbances) (Ito et al., 2022).

Another issue noted by Kozjek et al. (2017) is that data is available, but not at the proper level of quality. The author points out that many manufacturing companies still rely on manual data collection, which can be time-consuming and, because the process is more error-prone, the data quality tends to be lower (compared to an automatic process).

This is especially an issue for fault-related data, which tends to be much scarcer than process-related and “other types of data”.

Although tools and frameworks for RCA are well established, their effectiveness ultimately depends on availability, completeness, and quality. Without this foundation, even the best-structured RCA processes will fail to uncover the real causes of failures. This insight will be further explored in the discussion chapter.

2.4.1 Fault tree analysis

Fault Tree Analysis (FTA) is a structured, top-down approach for root cause analysis. It diagnoses and traces system-level failures to their underlying causes by modelling the logical relationships between component-level events and the undesired system state. The method provides a diagrammatic representation of the failure logic, making it easier to visualize and analyze how combinations of faults can lead to a critical event (Kabir, 2017). FTA is beneficial for understanding both single-point failures and combinations of interacting causes. It utilizes standard logic gates, such as AND, OR, and inhibit gates, to represent how different basic events (e.g., component or subsystem failures) contribute to an intermediate or top-level system fault (Peeters et al., 2018).

FTA supports root cause identification by enabling analysts to systematically examine how individual or combined factors might trigger an undesired condition. This makes FTA especially valuable in complex systems, where multiple elements interact and obscure the origin of problems (Kabir, 2017).

In building decision-support models, FTA offers a logical foundation for constructing rule-based structures that can classify or diagnose the root causes of observed failures. Its structured nature aligns well with efforts to automate or formalize analysis procedures, especially when integrating empirical observations and expert knowledge.

One key limitation of FTA, as Bertsche (2008) highlighted, is that its effectiveness heavily depends on the completeness of the system knowledge and the scope defined by the user. Although analysts design FTA to systematically identify all possible causes of failure through its deductive structure, they can only achieve thorough results if they have complete information and make accurate assumptions during the analysis. If specific failure modes, human factors, or common-mode failures are not known, not considered, or inaccurately defined by the analyst, those causes may be entirely missed. This presents a significant challenge in practical applications, especially in complex or dynamic systems, where full knowledge of all interactions is rarely available. This limitation means that building an accurate and reliable fault structure requires strong technical data and deep tacit knowledge from experienced stakeholders, making validation and collaboration crucial parts of the process (Peeters et al., 2018).

Researchers have extensively used FTA to identify design and operational weaknesses in product development and process safety assessments. Although researchers commonly apply FTA to explore external risks or technical system failures as noted by Bertsche (2008), this method has not been used to evaluate system reliability in internal OtD processes, particularly in ETO contexts. The closest application relates to the research by Sherwin et al. (2020) which applies FTA to a broader supply chain context.

Some researchers have used FTA to model supply chain risks, but these applications have focused mainly on external causes, such as supplier delivery failures (Sherwin et al., 2020). There appears to be a gap in how FTA has been constructed to evaluate internal process-related failures from a company's perspective, failures that may lead to an undesired outcome, such as material shortages or delayed deliveries.

Sherwin (n.d.) proposed using a fault tree structure to represent a supply chain network, beginning with a product's bill of materials (BOM). The BOM comprises assemblies, subassemblies, subcomponents, raw materials, and the services required to manufacture the item. Analysts model suppliers that produce goods and services as basic events within the fault tree in this approach. They represent the overall delivery reliability of the supply chain as the top event, which encompasses the final assembly of all procured products and services. Thus, the supplier network and its configuration can be structured logically as a fault tree.

A fault tree is applied to determine the unreliability of a system, defined as the probability that a failure to deliver on time occurs within a specified time interval (Sherwin et al., 2020).

In Sherwin et al. (2020) the author uses a simplified example: a firm seeks to evaluate the likelihood that an undesired event (delivery failure) will occur during the manufacture of Product 1. The product's BOM consists of three subassemblies supplied by four suppliers: A, B, C, and D. Suppliers A and B provide critical materials. If either supplier A or B delivers on time, the supply chain succeeds; however, if both are late, the chain fails. Suppliers C and D supply non-critical subassemblies and contribute to the structure, but not to the top event, with the same weight.

Analysts model this relationship using logic gates, which form the backbone of any fault tree structure(Bertsche, 2008).

As illustrated in Figure 2.4, a basic fault tree is composed of the following hierarchical levels:

- Top Undesired Event (e.g., delivery failure),
- Intermediate Events (e.g., subassembly delays or planning errors),
- Basic Events (e.g., raw component delays, system input errors),
- Logic Gates (such as OR or AND gates).

Each event in the tree is connected via logic gates to reflect causal relationships. The OR gate indicates that the top event occurs if at least one of the inputs occurs. The AND gate models scenarios where all input events must co-occur to trigger the output event. In the supply chain example, if either Supplier A or B is late, an OR gate would suffice to propagate that delay to the top event. If both must fail for the delay, an AND gate would be more appropriate.

Additionally, fault trees include concepts like minimal cut sets (MCS), which refer to the smallest combinations of basic events that can independently cause the top undesired event (Sherwin et al., 2020).

As the number of events increases and systems become more complex, manually identifying these cut sets becomes inefficient, and algorithms are typically used to identify and prioritize critical combinations that threaten system reliability (Sherwin et al., 2020).

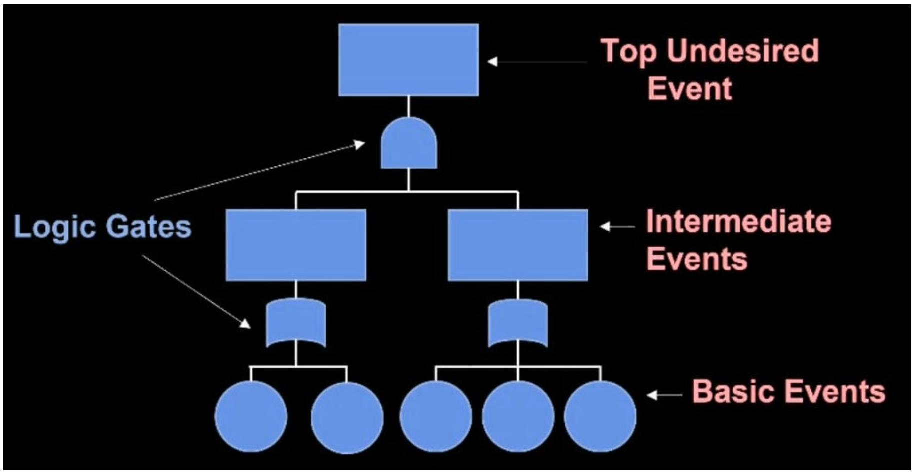

Figure 2.4: Basic diagram of a fault tree structure [Source: Aina et al. (2023)]

Symbols	***Functions***
Rectangle	Fault which is extracted from fault evidence via logic gates
Diamond	Event with insufficient information
OR gate	Output happens if one of the branch occurs

Figure 2.5: Symbols used in a fault tree structure [Source: Aina et al. (2023)]

3
Methods

This chapter describes the methods used in this thesis and analyses the quality criteria and ethical aspects of the work.

3.1 Research Design

The study focuses on analyzing and identifying improvement opportunities specifically related to how the supply function can better support the company's OtD process. This topic has not been previously examined within the organization, and there is currently no shared or cohesive understanding of the underlying problem

This thesis will have an exploratory outlook for researching this topic and the aim of explanatory research is to find out what is happening, seek new insights and assess phenomona in new light (Saunders et al., 2019).

This study adopts an abductive research approach, which combines elements of both inductive and deductive reasoning. Rather than starting with a fixed hypothesis (as in deductive research) or purely building theory from scratch (as in inductive research), abductive reasoning allows the researcher to move iteratively between data and theory. This iterative process enables the research to remain flexible and adaptive throughout the project (Creswell & Creswell, n.d.)

The study began with initial exploratory interviews and internal documentation reviews, which helped identify key patterns and raised questions regarding the frequent use of the material shortage delay code within the case company's OtD process. These early findings did not point directly to a single theory but instead uncovered gaps in existing processes, such as unclear lead time ownership and planning disconnects. Based on these insights, further data collection was directed toward refining emerging themes, particularly by investigating the impact of ERP system transitions, planning roles, and procurement practices.

3.2 Research methods

3.2.1 Literature review

The literature review process did not begin with a structured screening. At the start of the project, the nature of the problem at the company was not fully defined, and the theoretical relevance of the issue was unclear. Instead, we began by immersing ourselves in the organizational context, engaging with employees. This early phase was driven by the need to grasp the complexity of the problem before attempting to frame it theoretically. While there were some initial assumptions, it was difficult to identify a clear academic topic or research domain based solely on early assumptions.
As the researchers understanding of the problem developed, they were gradually able to identify emerging themes and key terms, which in turn enabled them to formulate a more targeted and focused literature review. The literature review was conducted iteratively, guided by emerging insights from interviews and system observations, rather than starting with a fixed theoretical model. This allowed the problem context to direct the exploration for relevant academic discussions (see Figure 3.1).

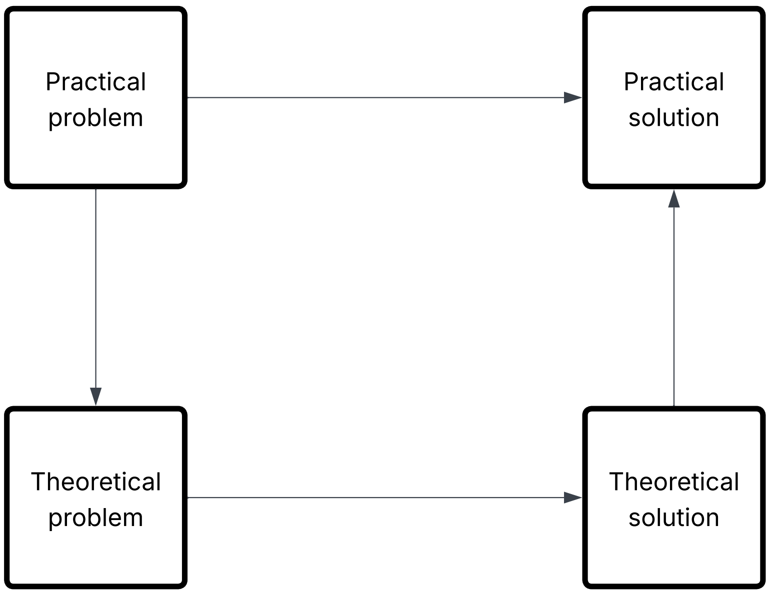

Figure 3.1: Literature review process

This approach ensured that the reviewed literature was grounded in the real-world challenges faced by the case company, and not merely selected based on abstract assumptions as well as identify related fields.

The process began with a practical problem that needs to be understood and translated into a theoretical problem. While the symptoms of the problem at the case company were easier to observe, such as recurring material shortages, the underlying causes and connections to relevant literature framework were less apparent. To gain deeper insight into the issue, the researchers conducted interviews, reviewed internal documents, and observed planning processes to understand the ecosystem around the problem. Subsequently, as the immersion process began, they performed a structured literature review (see Figure 3.2) on various topics related to the problem. Journal databases such as Web of science, Taylor and Francis and Emerald were used. The first screening was conducted using the keywords “material shortage in ETO” and “material planning in ETO,” which resulted in identifying several papers addressing material shortage issues primarily in ETO environments. After excluding papers unrelated to the topic, approximately 60 articles remained. The second screening involved evaluating the relevance of these papers by reviewing their abstracts and applying predefined exclusion criteria, including a journal impact factor above 1 and the exclusion of articles focused on privacy or ethics. In the third stage, additional relevant articles were identified through snowballing Saunders et al. (2019), with the final selection based on the researchers’ judgment which included reading through the abstract and discussion with eachother.

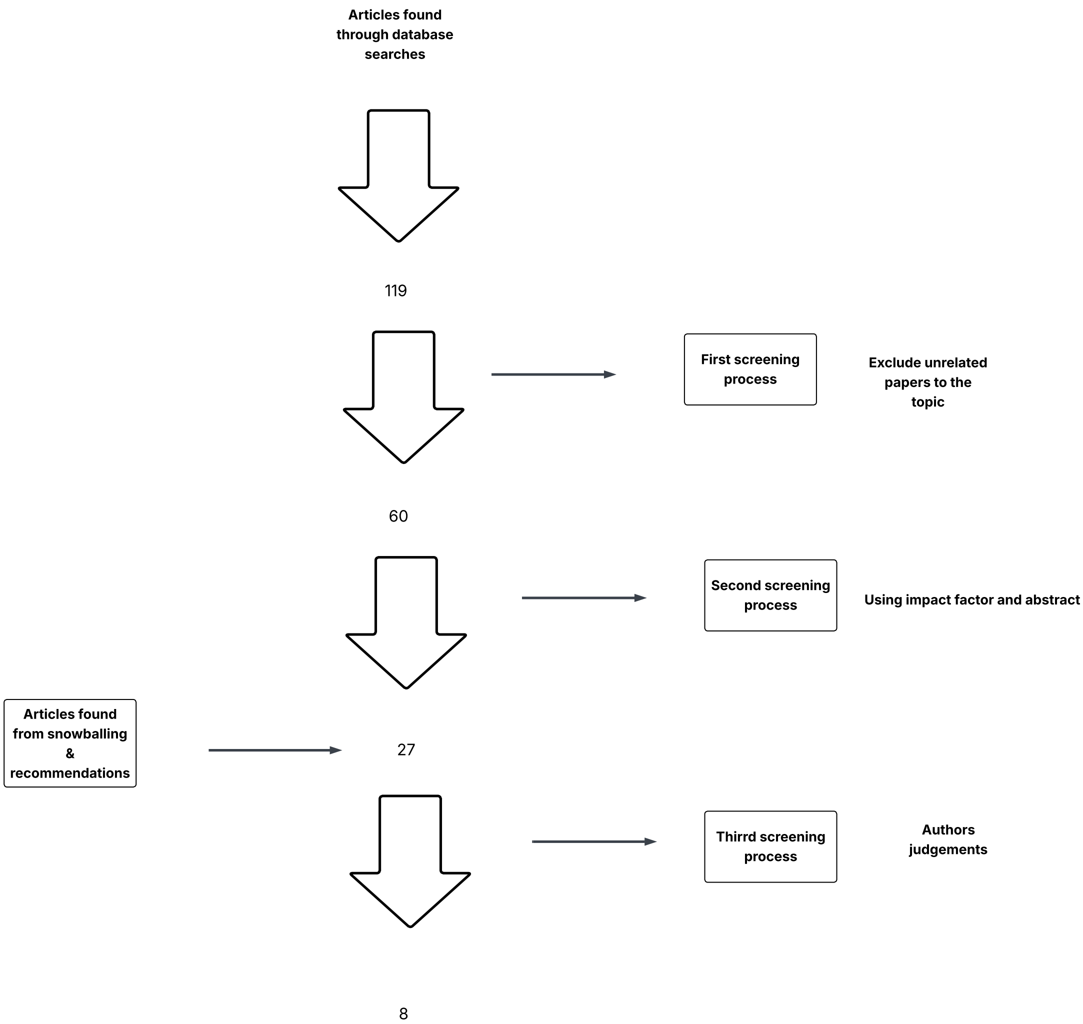

Figure 3.2: Literature review process

3.2.2 Qualitative

The qualitative component of this thesis consisted primarily of semi-structured interviews with key stakeholders at the case company, including personnel from order planning, operative procurement, production planning, and strategic purchasing. The purpose of these interviews was to deepen the understanding of the OtD process and identify the underlying causes behind recurring material shortage related delivery delays.
Rather than starting with predefined hypotheses, the interviews were used to iteratively explore and define the problem, in line with the abductive research strategy employed. Insights gathered during early interviews helped inform the direction of subsequent interviews, as well as guide the focus of internal document reviews and system analyses.
This iterative process allowed for continuous refinement of emerging themes and categories, as findings from one data point were compared with others in a process of constant sensemaking (Saunders et al., 2019).
Although not strictly following a grounded theory methodology, the study adopted a similar logic of coding and comparison, where qualitative data was broken into components and analyzed to uncover patterns related to process inefficiencies, system limitations, and coordination gaps.
The interviews were particularly valuable for capturing subjective experiences and operational insights that were not visible in formal documentation or ERP system outputs. These qualitative insights provided the foundation for the empirical findings presented in Chapter 4 and served as a lens for understanding how organizational practices and system design contribute to material shortages and delivery delays.

3.2.2.1 Data collection

The qualitative data were gathered by doing semi-structured interviews, this facilitated the immersion of the studied problem and seeing the problem from the people who are working in the organisation and getting a deeper insight on the problem. The purpose of the interviews was to gain a deeper understanding of the problem and connect this to a relevant topic in the literature, it was also used as a means to identify and map out the order to delivery process and potential improvement areas.
In total 14 interviews were done with the employees at the company. To collect relevant qualitative data, purposive sampling was used (Saunders et al., 2019), which is a type of sampling where the selection of units (e.g. people, departments etc) which direct reference to the research question. The notion is that the research question should guide the researchers towards what units or functions need to be sampled. The research questions guide the researchers to what categories of employees that were the focus of the study and therefore sampled.

Snow ball sampling was also used, this is another sampling approach, in which researchers make initial contact with a small group of employees who are deemed relevant to the research topic and then use these to establish contacts with others (Saunders et al., 2019). The sampled participants propose other participants who

have had the experience/knowledge relevant to the research.
The choice of which functions in the organization to interview was based on mainly on the recommendation from the supervisor at the company, but also on internal document at the organization detailing the OtD process and from the researchers own judgement.

The interviews were held in Swedish and were in person. Both researchers were present during the interviews. One researcher was keeping track of the voice recording device, which was later used for analysis, as well as keeping track of the time.The other researcher were conducting the interview questions. The interviews were guided by a prepared interview guide, with additional questions asked when relevant opportunities arose during the conversation. The average length of the interviews were around 50 minutes and took place at the case company's site in western Sweden.

Interview ID	Role	Function	Date
OPC1	Production planner	Production	5/2/2025
OPA1	Order planner	Order planning	18/2/2025
SO1	Operative procurer	Supply chain	20/2/2025
PP2	Strategic purchaser	Supply chain	26/2/2025
SP1	Strategic purchaser	Supply chain	2/3/2025
PS1	Product specialist	Product development	17/3/2025
S02	Operative procurer	Supply chain	17/3/2025
P1	Production	Production	17/3/2025
PP1	Project procurer	Project	24/4/2025
SO2	Operative procurer	Supply chain	28/4/2025
SQE	Supplier Quality Engineer	Supply chain	28/4/2025
SP1	Strategic purchaser	Supply chain	30/4/2025
OPA2	Order planner	Order planning	30/4/2025
OPC2	Production planner	Production	5/5/2025
S02	Operative procurer	Supply chain	5/5/2025

3.2.2.2 Data analysis

The data collected during the interviews was processed by listening to the recordings and transcribing them. Most of the interviews were conducted in Swedish, and since this thesis is written in English, the transcriptions were carefully translated from Swedish to English. A.I. tools such as ChatGPT were used to support the translation process, ensuring that no important meaning or message was lost.
When analyzing the gathered data, open coding was applied. This is a process that involves breaking down, examining, comparing, conceptualizing, and categorizing data. Through this process, initial concepts are generated, which are then grouped into themes and further refined into categories (Saunders et al., 2019).
Codes, or memos as they are referred to in Saunders et al. (2019), are notes that researchers write for themselves to serve as reminders of the meaning behind the terms being read. They act as building blocks for reflection and are useful for summarizing ideas, helping the researcher avoid losing track of their own thinking.
Coding facilitated a continuous analysis of the gathered data. The interview notes were imported into a qualitative data analysis tool called ATLAS.ti. The interview transcripts were read within the software, and using the research questions as a guide, relevant concepts and ideas were assigned appropriate codes. These tags were later analyzed and compiled into an Excel file containing key points from all the interviews.
The statements in the transcripts were then grouped into similar themes, which made it easier to identify common patterns and recurring topics. This analysis enabled the researcher to identify concepts and insights that served both as a foundation for locating relevant literature and for highlighting the underlying causes of material shortages in ETO environments.

3.2.2.3 Trustworthiness

Trustwortiness is made up of four criteras which are creditability, transferability, dependability and conformability (Saunders et al., 2019). To ensure credibility in this thesis, the concept of triangulation has been used, this involves using multiple theoretical perspectives, using different sort of data (Saunders et al., 2019)
In this thesis triangulation was achieved through using different interviews by different employees at the company as well as cross checking the data with other employees. Additionally some quantitative data were used to get a broader understanding of the distribution of material shortage along a certain period of time.
To ensure dependability, the researchers maintained a complete and transparent record of all phases of the research process. This included documentation of the problem formulation, selection of research participants, fieldwork notes, interview transcripts, and decisions made during data analysis, all stored in an accessible manner.
Confirmability was also a key aim in this thesis. This concept refers to ensuring that the researchers did not impose personal values or theoretical biases that could influence the conduct of the study or its findings (Saunders et al., 2019). To support confirmability, the researchers held regular meetings with their university supervisor, where ideas and interpretations were discussed in order to gain alternative

perspectives and reduce individual bias.

3.2.3 Quantative

The quantitative methods used in this thesis included data analysis and data visualization with data provided by the case company. Data were analyzed using excel and the statistical analysis tool JMP, which is a statistical software that makes it possible to visualize your data and perform a number of different statistical analyzes. Data analysis allowed a broad view of data on material shortages, particularly for a specific product group.

3.2.3.1 Data collection

The data that was used for analysing the material shortages for product 1 was retrieved from the companys database and subsequently arranged in Excel files. The data logs included information such as :

- Order ID
- Order row number
- Item number
- Business area
- Order type
- Project code
- Reference name(employee)
- Actual delivery date(from factory)
- Original promise date
- Delay code
- Comment

The data log includes all the orders of the product 1, between the year 2022 to 2025. Initially the raw data included all the orders for all products not only product 1, but the researchers filtered out these non product 1 using Power query in excel.

3.2.3.2 Data processing

The data analysis phase aims to support answering the research questions. To achieve this, the researchers intend to understand, in broad terms, how material shortages for product 1 have developed over time and to identify any patterns that can be explored further. The overarching goal of the method is process discovery, with a focus on visualizing how material shortages occur and how they are recorded within the organization.

The first step will be to carefully prepare the dataset for analysis. The researchers will organize the raw data into a format that makes it suitable for analysis, with the purpose of ensuring that the data is analyzable. To make the dataset more analyzable, inconsistencies, errors, and missing values must be minimized (Kotronoulas et al., 2023). Based on an initial review, some of the most common issues in the raw dataset relate to inconsistent data entry. For example, in the variable “comments,” some values lack standardized input, which makes it difficult to trace them to a specific cause. These values may create problems during interpretation.

According to Kotronoulas et al. (2023), several techniques exist to address missing or incorrect values in a dataset. The standard methods include deletion, substitution, and imputation. In this thesis, the substitution method will be used. Specifically, the researchers will assign a different code to every value in the "comment" column that cannot be traced to an article or a purchase order. A new column will be created where all untraceable values are replaced with a new value label.

Once the data has been cleaned and structured, a series of descriptive analyses will be performed to support the qualitative findings and to better understand the extent and nature of material shortages at the case company. These analyses are not intended to test hypotheses or make inferential claims, but rather to explore the structure and patterns of delays linked to material shortage codes and data quality limitations (Kotronoulas et al., 2023).

Three primary descriptive analyses are planned:

- First, the researchers will examine how late customer orders were delivered by calculating the difference between the promise date and the actual delivery date (i.e., factory shipment date). This time difference will be categorized into four lateness intervals (1–7 days, 7–14 days, 15–30 days, and 30+ days) and visualized using a Pareto chart. This will help illustrate how lateness is distributed across orders and whether a majority of delays fall within specific ranges.
- Second, the researchers will assess the traceability of MS01-coded delays. This analysis is motivated by a recurring observation from interviews: many material shortage cases cannot be traced back to a specific article number or purchase order. The researchers aim to determine the proportion of MS01 entries that can be matched to a valid article number or purchase order reference, compared to those that remain unidentifiable. Frequencies and relative percentages of identified vs. unidentified entries will be calculated to evaluate the data integrity of the material shortage records.
- Third, the researchers will investigate how the traceability issue has evolved over time by analyzing data from 2022 to 2025. A year-by-year distribution of identifiable versus unidentifiable MS01 entries will be created to determine whether coding practices have improved or deteriorated. This trend analysis will be visualized using basic charts to observe patterns across years.

Although no formal statistical testing will be conducted, the descriptive approach is intended to reveal patterns, highlight inconsistencies, and guide managerial attention toward areas requiring systemic improvement. As discussed by Kotronoulas et al. (2023), descriptive statistics play an important role in summarizing what is typical or problematic within a dataset. In this thesis, quantitative data will be used in this way to support exploration and understanding rather than to draw generalizable conclusions.

3.2.3.3 Validity & reliability

Validity refers to the extent to which the conclusions drawn from a piece of research are credible and trustworthy and it is commonly assessed across three dimensions which are measurement validity, internal validity, and external validity (Saunders et al., 2019). Measurement validity concerns whether the data truly reflects the concept or phenomenon it intends to measure (Saunders et al., 2019).
In this study, the phenomenon of interest was the cause of material shortages. However, the data retrieved from company's internal ERP systems was partially incomplete, approximately 14% of material shortage cases could not be traced back to a specific article number or purchase order. This limitation directly affects the ability to capture the full scope of the issue, thereby weakening the measurement validity of the dataset.

External validity refers to whether the findings of the study can be generalized beyond the immediate research context (Saunders et al., 2019). The context of this research is highly specific to the case company, particularly during a transitional phase between two ERP systems (Jeeves and Oracle). This shift influenced processes, data structures, and reporting accuracy, making the case environment relatively unique. As such, the findings may have limited generalizability to other companies or industries not experiencing a similar systems transition.
Internal validity is concerned with the credibility of causal inferences, whether observed relationships between variables can be confidently interpreted as causal (Saunders et al., 2019).

Due to the exploratory nature of this study and the limited availability of comprehensive and consistent data, it was not possible to isolate or control for all possible influencing variables. While patterns and plausible causes were identified, the conclusions do not establish definitive causal relationships. Addressing this limitation would require more detailed data access and extended research time, which were beyond the scope of this thesis.
Reliability refers to the repeatability of a study, specifically, whether other researchers following the same methods would arrive at similar results (Saunders et al., 2019). To assess the reliability of this thesis, two key aspects were considered: data source consistency and the repeatability of the analysis process.

First, data source consistency examines whether the same data could be retrieved using the same filters and procedures. In this study, the material shortage data was extracted from companys's internal ERP systems. However, during the course of the thesis, the organization transitioned from one ERP system (Jeeves) to another (Oracle), which affected the structure and accessibility of the data. As a result, the data retrieval process was not fully consistent over time, reducing the overall reliability of the quantitative component.

Secondly, the repeatability of the data analysis process refers to whether the steps taken to analyze the data were clearly defined and could be replicated by another researcher (Saunders et al., 2019).

In this study, the analysis procedures, such as the categorization of order lateness, the traceability assessment, and the historical trend evaluation, were documented and followed a structured logic. This improves the reliability of the analysis method itself.

However, because the underlying data source changed during the project, affecting what data could be retrieved and how it was classified, the overall reliability of the study is limited, particularly in the quantitative analysis.

3.2.4 FTA model building

In addition to the descriptive data analysis, this study will also develop a model based on the principles of FTA to categorize and structure the potential causes of material shortages. The model aims to provide a systematic framework for identifying root causes by breaking down contributing factors into logical layers. The fault tree model was developed by first defining the top-level event,material shortage, and then working systematically backward to map the underlying causes. These causes were identified through a combination of literature information and empirical findings gathered from qualitative interviews. The model illustrates how these contributing events are logically connected, highlighting how internal and external factors interact and cascade to result in shortages. From this structure, a selection of specific material shortage cases will be made based on their complexity and relevance. These selected cases will then be run through the model to evaluate how the identified causes interact and contribute to the shortages, thereby offering a structured and repeatable approach for diagnosing similar problems in the future.

3.2.5 Ethics

According to Saunders et al. (2019), there are four key ethical principles that researchers should consider when conducting research: avoiding harm to participants, obtaining informed consent, respecting privacy, and avoiding deception.

These principles were particularly important in the qualitative component of this thesis. To protect participant privacy and minimize potential harm, all interview transcripts were anonymized using coded identifiers, ensuring that individual opinions could not be traced back to specific individuals. This step was taken to safeguard participants from any negative consequences that might result from sharing candid insights about internal processes. Efforts were made to include representation from both sexes in the interviews; however, the sex of each interviewee has been anonymized in this report, as disclosing it could increase the risk of identifying individual participants.

Additionally, participants were informed in advance that their interviews would be recorded, and explicit verbal consent was obtained before beginning each session. These steps ensured transparency and adherence to ethical standards throughout the data collection process.

3.2.6 The use of artificial intelligence in this thesis

During this thesis, artificial intelligence tools like ChatGPT have been used to construct sentences and wording in a more concise and understandable way. Artificial intelligence was also used to create some of the figures included in the report as well as to provide suggestions on formatting and layout.

4

Empirical Findings

This chapter presents the key empirical findings from a study conducted at the case company. The findings are based on a combination of qualitative data, including semi-structured interviews, workplace observations, process walkthroughs, and quantitative data extracted from internal systems and documents.
This chapter is organized to provide an overview of the OtD process, explaining how the company manages a sales order from when it is received until the final product is shipped to the customer. It outlines how the organization receives and processes a requested delivery date, generates a promise date, and executes the order to meet customer expectations. The chapter then introduces the key functions involved in this process, such as order planning, purchasing and production, describing their responsibilities, the inputs they rely on, and the outputs they deliver to other departments.
Next, the chapter examines the planning parameters that influence the performance of the OtD process, including lead times, forecasts, inventory levels, and order integrity. It investigates how these parameters affect material availability and planning reliability. Additionally, the chapter reviews the recent ERP system transition. It highlights how the new system aims to improve parameter handling by reducing manual work, increasing consistency, and supporting more accurate planning.
Lastly, the chapter explains how deviations from delivery performance are currently documented, with specific emphasis on cases where the cause is reported as material unavailability. In addition, the chapter explores how the company could work more proactively with material shortages. This includes an investigation of how the documentation process supports or limits preventive action, as well as an early stage evaluation of a model based on fault tree analysis that may serve as a structured tool for future root cause identification and proactive shortage management.

4.1 Order-to-Delivery Process

The OtD process at the case company (see Figure 4.1) begins when an order is received, either from an external customer or internally from the engineering department. The order first reaches the Order Planning Administration (OPA), where an order planner establishes a realistic promise date to communicate to the customer. To calculate this promise date they use several planning parameters like sales forecasts, inventory status, available production capacity, and planned lead times for materials that are not currently in stock or are in transit.

Using these inputs, the order planner determines the delivery promise and creates the Master Production Plan (MPP). The MPP outlines what should be produced and when, serving as the foundation for the downstream production. The order planner essentially acts as the “spider in the web,” integrating planning information from sales, capacity, and procurement while generating two key outputs: the promise date and the MPP.

Once the MPP is established, the plan is transferred to the production planner. This role breaks down the high-level plan into a more detailed short-term production schedule, typically spanning a 7 to 10-day horizon. The production planner ensures that materials are available, that capacity constraints are respected, and that operations are sequenced efficiently to maximize Overall Equipment Effectiveness (OEE). If needed, they rearrange tasks to create a continuous and balanced flow on the shop floor.

Meanwhile, operative procurement part of the supply function, secures the materials required to fulfill the plan. This team primarily works from the sales forecast and current inventory levels, but also incorporates updates from the MPP to fine-tune order quantities and delivery timings. Operative procurement is responsible for daily communication with suppliers, placing purchase orders to suppliers, and adjusting planned lead times based on real-world supplier performance.

Strategic purchasing supports operative procurement. This function manages supplier relationships and sets the planned lead times for each supplier and part category. Strategic purchasing involves sourcing new suppliers for development projects, replacing under-performing vendors, and optimising cost or risk profiles. Order planners use the lead time variables they establish directly when calculating the customer promise date.

Once materials are ordered, the actual lead time begins. If inventory or safety stock already covers the needs of the MPP, production can begin without delay. If not, the production schedule must wait for incoming materials. After the manufacturing process is completed, the finished product is prepared for delivery. This step sometimes includes a customer-specific release process, requiring the customer’s confirmation before shipment.

The final step involves delivery and billing. If the delivery occurs after the committed promise date, the order is flagged as delayed. A delay code must then be recorded in the system, typically by the production planner, order planner, or production team. MS01 is the most frequently used code and is applied when the delay is due to material unavailability.

4.2 Key Functions in the Order-to-Delivery process

To better understand the OtD process, the roles of various departments are summarized below:

- **Order Planning:** Oversees the OtD process. Determines promise dates and constructs the master production plan based on forecasts, inventory, and lead times.
- **Production Planning:** Converts the master plan into detailed production schedules and ensures material and capacity readiness.
- **Operative Procurement (Supply Function):** Secures materials required for production. Adjusts orders based on inventory levels and feedback from planning.
- **Strategic Purchasing:** Defines planned lead times and manages long-term supplier relationships.
- **Operational Procurement :** Issues purchase orders based on both forecast and confirmed requirements. Maintains dialogue with suppliers to track actual performance.

These functions operate interdependently, but gaps in communication, data accuracy, and system integration still hinder overall performance. The upcoming sections further explore how these gaps contribute to MS01 delays and what changes have been introduced to address them (see Table 4.1).

Table 4.1: Functions, Customers, and Inputs in the case company's Order-to-Delivery Process

Function	Responsibilities	Customers	Inputs (Suppliers)
Operative Procurement	Procures materials to ensure timely availability for production.	Order-to-delivery process, material stocking process	Order planners, system forecasts, procurement requests
Order Planning	Manages the full order-to-delivery process, aligning demand with production and supply.	Operative procurement, production planning	Sales offices, distribution centers, project departments
Production Planning	Determines when to manufacture specific orders to meet demand and minimize disruptions.	Manufacturing teams, material handlers, order administrators	Order planners, project departments, S&OP, operative procurement
Strategic Purchasing	Conducting strategic negotiations with suppliers, determining lead times, and setting the framework for the lead times that operational procurement maintains.	Operational procurement team and the order planner.	The primary inputs to this function come from operational procurement and the order planner.

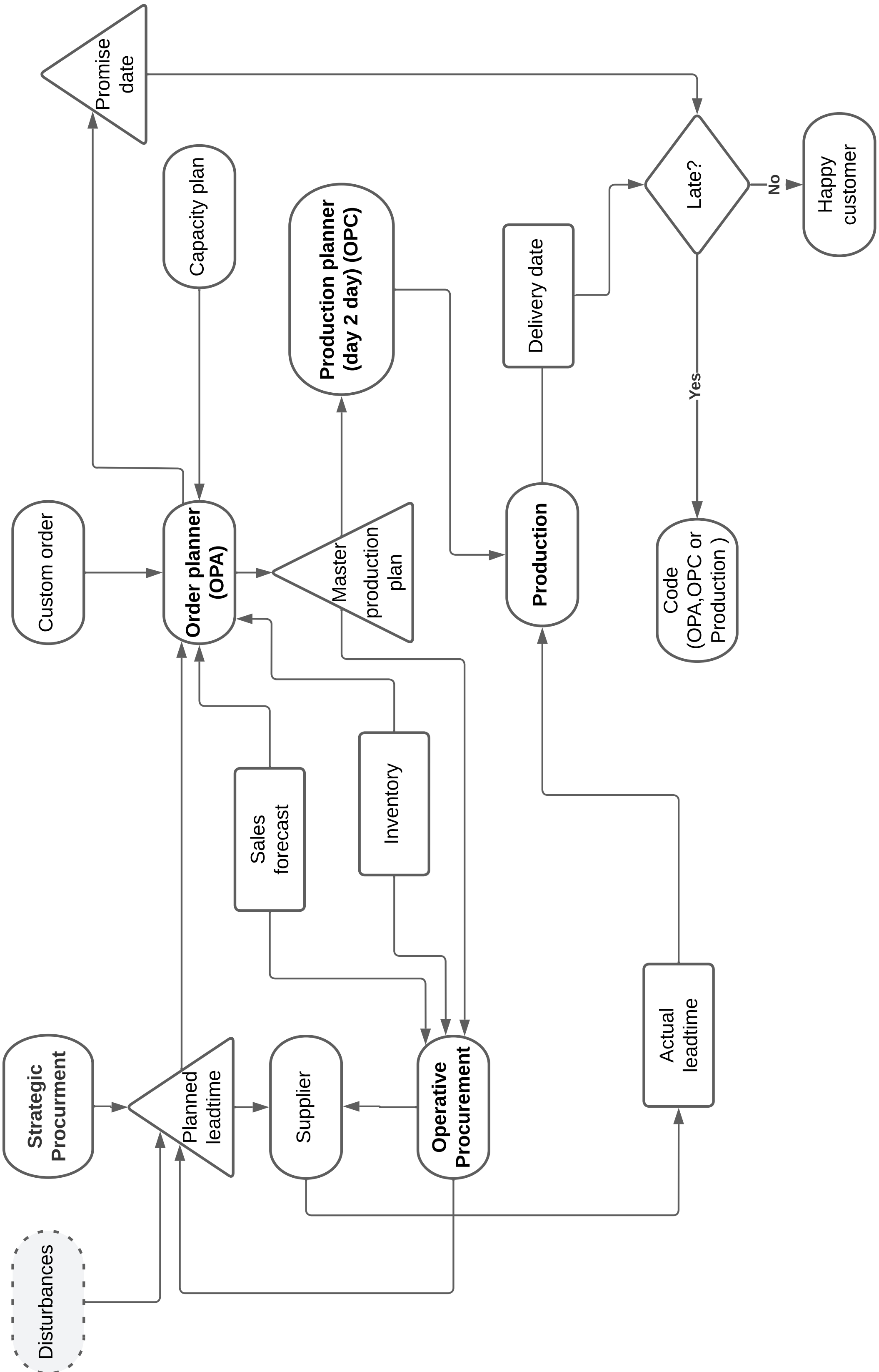

Figure 4.1: Relationship between functional departments in the order-to-delivery process at the case company

4.3 Parameters affecting the Order-to-Delivery process

Despite the defined roles and structured handoffs, several challenges persist. One challenge causing late deliveries in the OtD process is related to what was described as "sensitive parameters" in the system. These parameters include lead times, forecast accuracy, inventory, and order integrity.

4.3.1 Lead times

One recurring issue identified during the interviews is the questionable reliability of planned lead times. Rather than being based on actual supplier input or negotiations, lead times are often influenced by internal targets. Additionally, there is a lack of clear ownership over lead time data, allowing multiple actors to make changes without proper oversight. This results in inconsistencies that undermine production and delivery planning.

As one purchaser explained:

> *"The question of who determines lead times depends on several factors... Strategic purchasing originally determined them after detailed talks with suppliers... But when outsourced actors manually enter data, they 'contaminate' what was agreed. Ownership becomes unclear. Strategic purchasing raised this issue, but the answer they got was that the company's site in western Sweden owns it, yet they can't stop others from influencing it... Changes are made by planning groups without informing strategic purchasing or suppliers, which makes the data unreliable."*

This quote illustrates the fragmentation of responsibility, where different functions (e.g. strategic purchasing, planning, and outsourcing teams) all interact with the same data, often without communication or coordination. These conflicting inputs reduce confidence in the data and contribute to what was internally referred to as "disturbances."

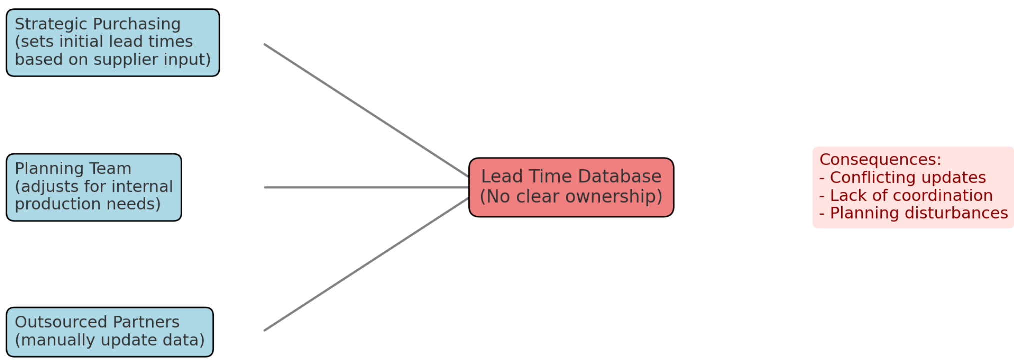

Figure 4.2: Lack of lead time management and its consequences.

Another observed issue is the inconsistent maintenance and updating of lead times. Instead of using systematically updated figures, planning relies on approximate values, often tracked manually in an Excel sheet. These values are sometimes outdated or estimated, offering a distorted view of supply capabilities. As a result, the planning process becomes unstable and vulnerable to errors and misalignment. This concern was clearly voiced by purchasers at the company that explained:

> *"Under unrealistic lead times, staggered lead times can also be a contributing factor. For example, the lead time for a quantity of 5 might be 6 days, but if we receive a mega order, the lead time becomes misleading"*

A similar issue were also raised by purchasers, who reflected on training and system limitations.

> *"At the Oracle training, they say 'the lead times in the system must be correct'. That's easy to say, but let's say it's a large order (e.g., 20,000 units of a refinery product to be built) and the order has a strange option this could, for example, happen during the summer. We don't currently have system support for this dilemma. We in procurement have requested something called "staggered lead times." We asked for this because we didn't have it in Jeeves, and it seems that we won't get it in Oracle either."*

This concern was mentioned by several interviewees involved in the supply chain side of the planning process and was perceived by many as a recurring issue. Additionally, an order planner pointed out that, in the ERP system(previous on), planning often relied on outdated lead time data:

> *"We (OPA) are responsible, or rather, we were responsible, for many of the tools used to plan orders. In Jeeves, we didn't have much system support for order promising, but we do in Oracle now. Previously, we worked with many static tools to be able to promise orders."*

When asked to clarify what was meant by "static tools," the order planner explained:

> *For example, we used to promise orders based on an Excel file where we had all the options available for each model. We tried to identify which options drove which materials and set lead times for them... In reality, it was updated quarterly... It wasn't exactly live data.*

4.3.2 Forecast

The forecast is another parameter that could potentially affect the performance of the OtD process. The findings indicate that it plays an important role in planning future purchases, and several interviewees emphasized the pressure for forecasts to be accurate, as inaccuracies may contribute to material shortages and delayed deliveries.

> *"We have a forecast, which is the best guess. At a high level (product level, e.g. 1408, 3408), it's relatively accurate and deviates by maybe ±10%. But when it comes to the detailed level (for example, which specific flange the product should have), we see very large deviations from the forecast."*

One strategic purchaser emphasised the inherent limitations in the forecasting process that underpins material planning. The forecast shared with suppliers is based on a rolling sales forecast generated by the company's global sales offices. The planners break down these forecasts through multiple levels, from regional sales expectations to product configurations, and finally to forecasted components.

As one strategic purchaser pointed out, each step introduces uncertainty, making it difficult to predict precisely what customers will buy.

> *"The forecast is entirely based on sales figures from the sales offices, how many units we think will be sold in the US, in Europe, and so on. These figures are broken down into options, products, and forecasted articles. Of course, there are many possible sources of error along the way. In the end, it's a kind of crystal ball."*

This highlights that forecast-driven planning has structural weaknesses, especially in ETO environments like the case company's, where customers' specific options can vary widely and unpredictably.

Another observation regarding the forecast is that the company sends forecasted article volumes to its suppliers and, in addition, asks them to be prepared to supply at least 25% more than the forecasted quantity. This expectation serves as a buffer, giving suppliers a heads-up to reserve additional capacity in case actual demand exceeds projections. Data provided by one of the purchasers indicated that, in a random sample of articles for the year 2025, the actual deviation reached an alarming 133%. This figure substantially exceeds the communicated buffer of 25% set forth for suppliers.

One purchasers also noted the following :

> *We usually say that the supplier should be able to meet our forecast plus 25% over a three-month period, but we don't specify when this three-month period occurs, and we don't communicate about it either.*

4.3.3 Inventory

The company aims to keep minimal inventory levels and applies an ABC classification system to manage storage priorities. Through interviews and process analysis, it became evident that inventory levels and safety stock settings might influence material availability and delivery precision. From an inventory optimization perspective, the company places a strong emphasis on minimizing inventory levels as part of its broader cash management philosophy.

As described by one purchaser:
"the company largely operates using other people's money, without its own capital". This underscores the company's incentive to reduce capital tied up in stock.

This financial strategy creates a trade off, while higher inventory levels could buffer against material shortages and improve delivery performance, the company's internal priorities favor minimizing inventory, even if this increases the risk of stock shortages.

As on respondent noted:

> *It (Safety stock) should really be based on the ABC code and annual consumption, but you can often see that when they're building an LG vessel, for example, they always need 12 of a particular item. But the safety stock is set at 8 and if the withdrawal is always 12, then we might disregard the rest and just set the safety stock to 12 instead*

This statement illustrates the disconnect between actual usage patterns and formal inventory policy. Even when consumption is predictable and recurring, safety stock levels are often conservatively set, potentially due to overarching cash flow targets rather than operational needs. As a result, material shortages may occur not because of supplier issues, but due to systemic understocking, which in turn compromises delivery reliability.

4.3.4 Order integrity

In addition to lead times, forecast accuracy, and inventory levels, the stability of customer orders after they have been confirmed and entered into the planning flow emerged as a critical factor affecting delivery precision. Interviews revealed that late changes to order configurations, especially in complex customer projects, can significantly disrupt the book-build-ship process.

In addition to lead times, forecast accuracy, and inventory levels, the integrity of sales and purchase orders emerged as a potential parameter that may influence the precision of delivery in the OtD process. Interview data suggests that late changes in sales orders, particularly in complex customer projects, can disrupt the OtD process. These changes often occur after orders have been confirmed and entered the planning flow, creating uncertainty for downstream activities. Moreover, several purchasers described how engineers within the organization occasionally modify technical drawings or specifications after purchase orders have already been initiated. When these changes are not communicated promptly or structured, purchasers may unintentionally send outdated documentation to suppliers. This lack of purchase order integrity can lead to confusion, rework, and delays in material delivery. Sales and purchase order integrity disruptions contribute to planning instability and increased risk of material shortages.

As described by one representative from the order planning office:

> *"Some of the challenges we face in order planning include an unstable input from customers. They place an order and then come back and make changes. The problem is that we have already accepted the order, planned it, started pulling materials, started purchasing and then they realize this was not what they wanted. In the worst case, we have already started building the product and then have to backtrack. Late changes from customers are a major pain point. Large customer projects are particularly problematic. product 1 are often part of those. If changes are made to these large projects,which consume a lot of materials and are hard to plan, it becomes very challenging. In some cases, we've already purchased materials, reserved capacity, and then they decide, sometimes just a week before the build, that it needs to be redone. We might have already postponed other orders to reserve capacity for this project, and then suddenly we're expected to push it out by a month. For the entire book-build-ship chain, this is one of the biggest problems."*

This statement illustrates the operational impact of order instability, especially in large customer projects where changes can invalidate already-purchased materials, waste production capacity, and force rescheduling of other orders. From a planning perspective, unstable order input undermines the reliability of all downstream processes, making even accurate lead times and sufficient safety stock ineffective in ensuring delivery precision. Order configuration stability should therefore be recognized as a key parameter within the OtD process. Its absence introduces risk, inefficiency, and contributes directly to material shortages and missed delivery commitments.

Another dimension of order configuration stability involves internal factors that affect the completeness and correctness of order documentation. For example, several interviews pointed out that missing or outdated drawings, incorrect revision levels, or orders placed on articles still in engineering status often lead to delays in supplier processing.

One purchaser noted:

> *"Sometimes a delay is caused by missing documents. For example, if operative purchasing places an order, the supplier might respond, 'This is the wrong revision, you requested AB, but we have AA in our system, can you check?' Then it turns out an engineer internally changed a dimension, and the update never made it through the system."*

These internal misalignments reduce the reliability of the order information that is sent to suppliers, which in turn undermines the effectiveness of the planning process. As such, order integrity must also account for the internal coordination and accuracy of technical and engineering data, not just changes made by the customer.

4.3.5 Order interdependencies

How components are shared among different projects creates an interdependency between them. This interdependency becomes especially problematic because the ERP system does not reserve materials for a specific order until production officially begins. As a result, the ATP check for individual orders can be misleading or inaccurate. This issue is reflected in the interviews:

> *"When I do six ATP checks a day, I can see things like 'ah, this item, for example, a housing I've already checked, so I know its lead time.' But then, if the first project is supposed to have a 10-day lead time, and second one should also have 10, even though they don't take each other into account. So I have to manage that manually to avoid overlaps. We also don't have coordination meetings for every project, only for the largest ones. So it happens quite often that a project gets planned based on what's currently on hand, and then another project gets scheduled without knowing that we're actually supposed to consider the first one."*

Because components are shared across orders, changing the production schedule for one project can disrupt the material availability for others. This dynamic is also highlighted in the interviews.

> *"It also often happens that a project is scheduled, and it has to be pushed further out because a flange (component) is arriving late. Then, it's quite common that someone else schedules a project earlier, thinking, 'Well, up until, say, May 5th, we have 100 of this component in stock so I'll just use those.' But when May 5th comes around, those 100 flanges that I needed are gone, and we end up with a material shortage. Then no one understands what happened, and I get blamed because they think I didn't order the material on time."*

4.3.6 Impact of ERP system transition on the handling of parameters in the Order-to-Delivery Process

With the transition to the Oracle ERP system(see Figure 4.3), the core parameters that influence delivery precision, such as lead times, forecast accuracy, inventory levels, and order stability, will remain fundamentally the same as in the previous system (Jeeves), the only is in how these parameters will be managed.

Interviews highlighted several key differences between the previous ERP system (Jeeves) and Oracle, particularly regarding how lead times are handled and how the system relies on accurate parameter maintenance.

In Oracle, the system places much greater emphasis on having correct and up-to-date lead times, unlike Jeeves, which was more forgiving and allowed manual adjustments further along the process. Oracle depends on accurate input from the beginning in order to function as intended. According to one purchaser:

> *"Lead times are also meant to become dynamic. For example, if we receive an order confirmation from the supplier and they say, 'the lead times are getting longer because we have a material shortage,' then we in operative procurement should update the lead times in the system. Then, when the supplier's lead times begin returning to normal, we should adjust accordingly. Lead times should always move in line with what the suppliers are reporting. We will have documentation where we track this, like, 'okay, we changed the lead time for this article, so we should follow up on it weekly until the lead time returns to normal, and then we can remove it.' Nothing should be left to chance, everything should be up to date at all times. "*

Because Oracle's planning logic relies heavily on accurate parameters, particularly lead times, maintaining these parameters has become significantly more important. If lead times are outdated or inaccurate, it directly affects ATP calculations and overall planning accuracy, often leading to misaligned schedules and costly rescheduling.

One production planner noted :

> *"Maintenance of parameters and article lead times, for example, routing (how long it takes to build things), will become more important going forward, because the entire planning process depends on them. As it stands today (with the Jeeves system), we don't update lead times; purchasing sticks to their five days, even if it actually takes two months to receive the item, and they just place the orders further ahead in time. But if these updates aren't made in Oracle, the ATP will be incorrect, and as a result, so will the planning and order confirmations, which will then require us to replan."*

A central improvement in Oracle is the implementation of system-driven ATP and capacity-to-promise functionality. Based on available inventory and production capacity (assuming the data is accurate), the system automatically calculates the best possible promise date. This is expected to improve the reliability of the first promise date given to customers, in contrast to Jeeves, where such planning often relied on manual estimation and workarounds.

As one order planner underscored:

"When we switch to Oracle, one advantage is that we will have a system-driven Available-to-Promise and Capacity-to-Promise. This means that the system, based on available material and available capacity (assuming it is correctly set), will provide the best possible lead time. The goal is that we will get it more accurate from the start when using Oracle."

However, some limitations remain despite the new ERP system. One such limitation is the continued absence of volume-sensitive or "tiered" lead times. In Oracle, the system assumes that lead time is the same regardless of order quantity, whether ordering 1 unit or 100 units. In practice, suppliers may require longer lead times for larger orders, which means that ATP calculations can still be misleading when it comes to large-volume requests.

This is reflected in the following statement made by a purchaser :

"In the Oracle training, they say, 'the lead times in the system must be correct.' That's easy to say, but let's say there's a large order (e.g., 20,000 units of a product to be built), and that order includes a special option, this can, for example, happen during the summer. We currently have no system support for this kind of dilemma. We in procurement have requested something called 'tiered lead times.' We asked for this because we didn't have it in Jeeves, and it seems we won't get it in Oracle either."

An explanation for the lack of tiered lead times even in the new system Oracle was given to the searchers, and it was due to the difficulty in implementing volume-based lead times, as explained by a Supplier Quality Performance Engineer, which is primarily related to the complexity of the system itself.

They noted that:

"The calculation model underlying the system is already so complex, and if you add another layer where lead times vary based on order quantity per article, then the system simply can't compute it in a reasonable time. It becomes difficult to make it work."

Additionally, D-class articles (those purchased infrequently) continue to present challenges. Although the system default aims for a five-day lead time, this is often unrealistic, especially when the supplier is not local. In some cases, default lead times are set as high as 150 days under placeholder statuses like "consult factory," requiring manual follow-up to determine the actual lead time. If the system defaults to a five-day lead time for a D-article that actually takes 20 days to procure, planning will be inaccurate from the outset.

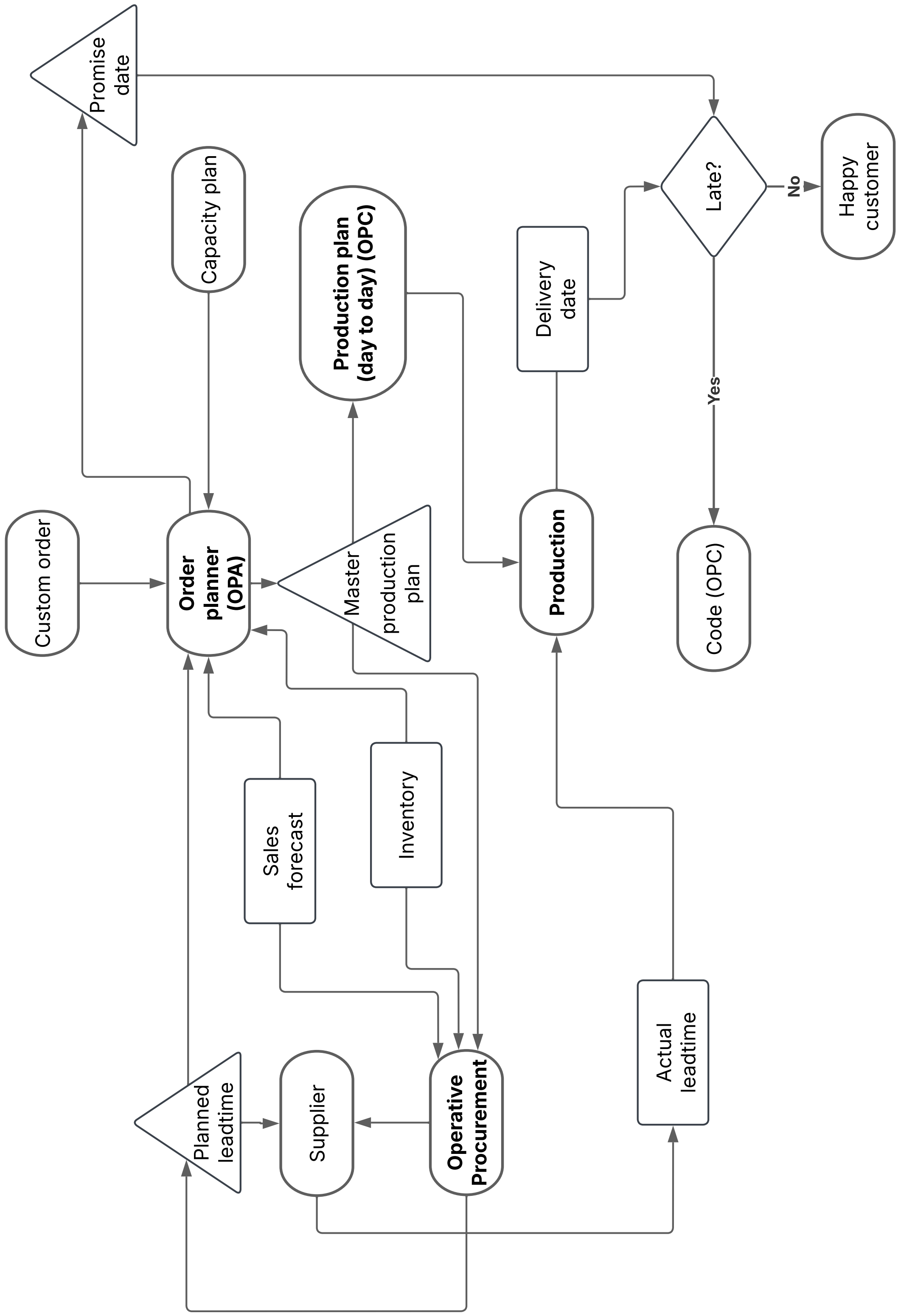

Figure 4.3: Relationship between functional departments in the order-to-delivery process after ERP system transition to Orcle

4.4 Overview of Material Shortage Reporting Process

The company uses an internal delivery performance metric called PDSL, which measures the company's ability to deliver customer orders on the original promised delivery date. As one order planner described it :

> *"Promised Date Service Level is a metric, an outcome. For example, if we're supposed to deliver an order to a customer on February 10, that becomes the original promise date. But if we then realize we're missing a part and have to reschedule the delivery to February 12, we get a 'hit' on that order, a PDSL hit. We then code the reason for the hit in the system. That means our overall PDSL percentage drops because we failed to meet the original promise date given to the customer."*

This metric is central to measuring delivery reliability and serves as a foundation for identifying and categorizing the reasons behind missed deliveries.

The PDSL metric includes a specific delay code known as MS01. This code is used to classify delays related to material availability. MS01 is applied when a customer order cannot be delivered by the promised date due to unavailable materials. It identifies situations where the company cannot meet the planned delivery timeline because the necessary components were unavailable on time.

The MS01 code is significant within the case company's performance reporting system because it is the most frequently occurring delay code. According to internal performance metrics shared with the researchers during the thesis, delays categorised as MS01 account for 52% of all PDSL deviations (See Figure 4.4).

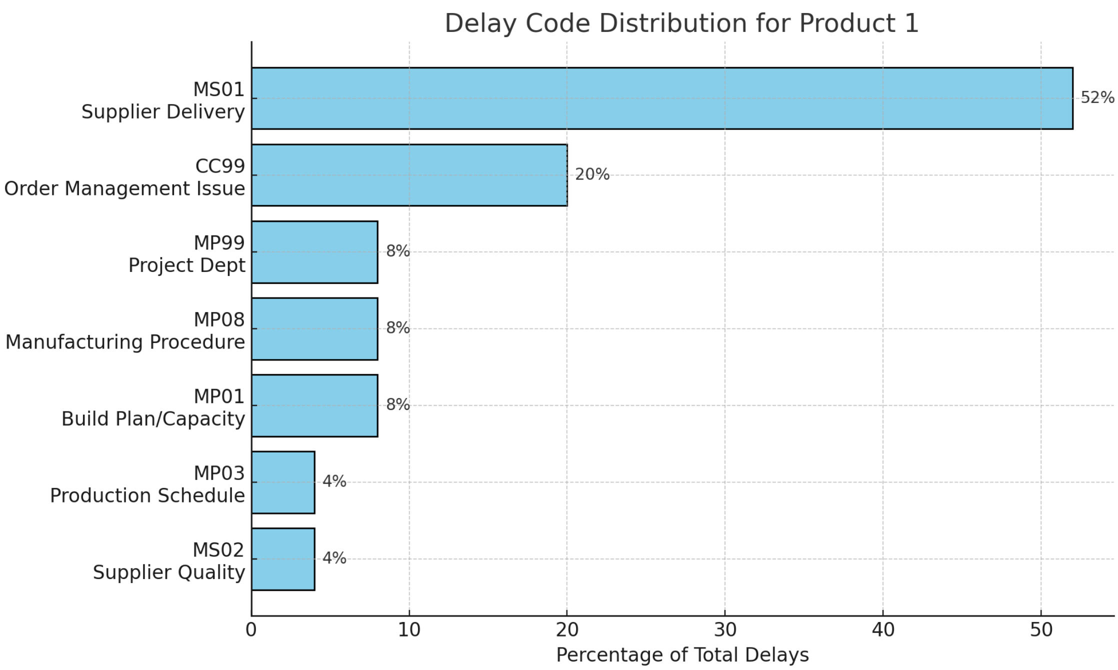

Figure 4.4: Percentage of all the delay codes for product 1.

While there are several potential reasons for delays, such as issues with internal planning or production, MS01 indicates that the primary cause is material shortage, whether from suppliers or challenges in internal supply planning.

Notably, the MS01 only applies when an order is delayed compared to the promised date, it is not applied if production is delayed but can still meet the promised date.

> "*If the promised date is met according to the initial plan, no MS01 or any other delay code is registered. This means that even if there were internal issues or material delays along the way, no coding occurs as long as the order is delivered on time based on the original promise.*"

From the interviews, the researchers understood that PDSL is considered the most important parameter for customers after quality and safety. This means that MS01 is highly important, as it has a significant impact on the outcome of PDSL.

When asked about the importance of PDSL for the company, one supplier quality engineer said:

> *"Of course it's important, it reflects the customer's experience of their purchase. There are rare cases where PDSL doesn't matter as much, but I would say that after quality (and safety), delivery precision is the most important factor."*

Some challenges were observed with the current process for reporting and coding delivery delays. When a sales order misses its original promised delivery date, the responsible planner records the delay using a predefined set of codes. A typical sales order at the company represents a complete system, which may consist of several subsystems of multiple products, such as product 1, product 2, and product 3. Each of these subsystems is, in turn, comprised of multiple individual articles and components. If a material shortage delays just one subsystem, because a specific component required for it is unavailable, the entire sales order receives the MS01 code, regardless of whether the other subsystems were completed and ready on time (see figure 4.5). The delay is registered on the overall system level, not at the level of the specific subsystem or component that caused it. As a result, this coding practice limits visibility into which parts of the system are actually causing delivery issues. It becomes difficult to analyze trends, identify recurring bottlenecks, or implement targeted improvements, since the broad application of the MS01 code obscures the root cause.

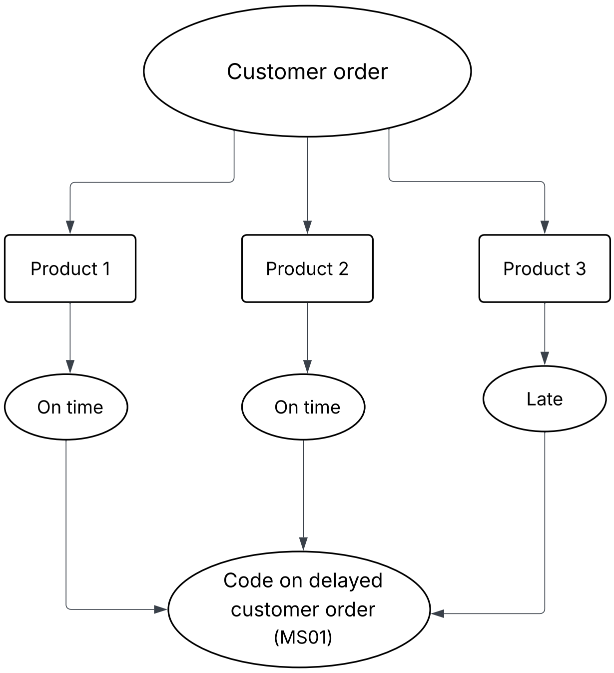

Figure 4.5: Illustration of system sales order in Jeeves

The quantitative analysis of MS01 data further supports the issue of traceability in deviation reporting. Data related to MS01 coded delays for product 1, covering the period from 2022 to 2025, were compiled, cleaned, and analyzed. Among these, only the MS01 entries that could be traced back to specific articles responsible for the delay were considered. A Pareto chart was then generated to identify the vital few articles that contributed the most to delays(See figure 4.6).

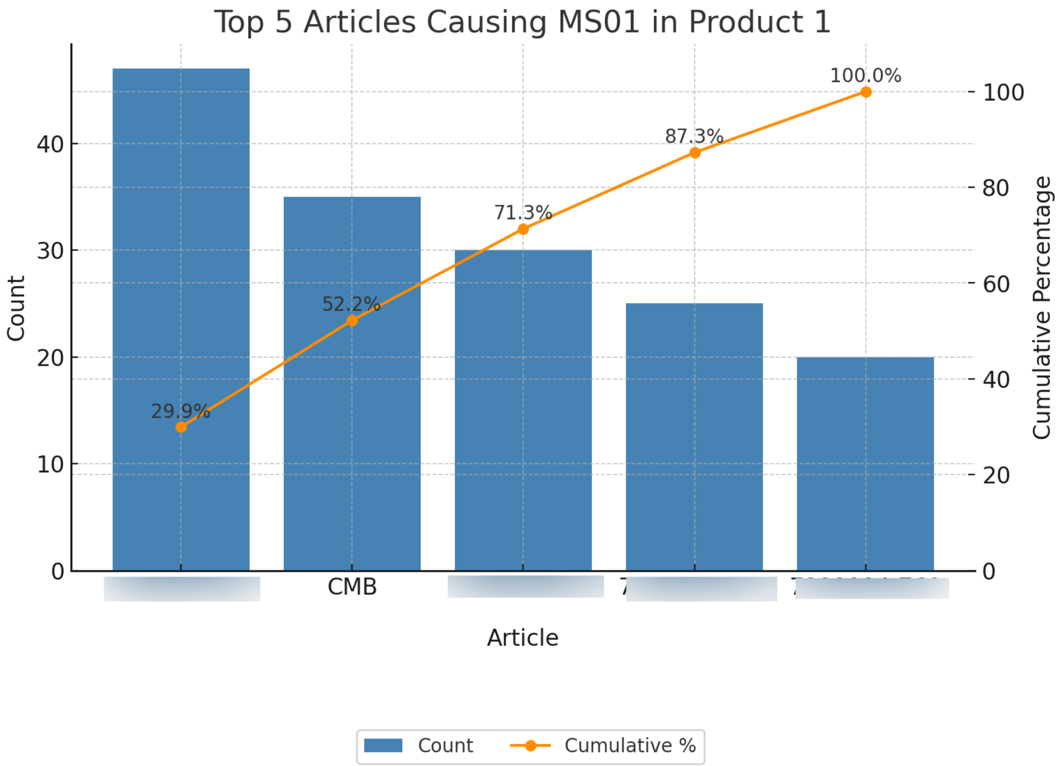

Figure 4.6: Pareto chart of articles causing MS01 in product 1

Upon closer examination, the researchers found that some of the articles recorded as causing the delays were not part of the product 1, product 1. For example, one such component was the chamber (CMB), which belongs to another subsystem but is often purchased alongside product 1 as part of a complete system, included in the same sales order.

This lack of traceability suggests that when a material shortage occurs in one subsystem, it can delay the entire sales order at the system level. In such cases, the coder applies the MS01 code to the entire sales order, regardless of which specific product or component actually caused the delay. As a result, the MS01 code may fail to offer product-specific traceability and could potentially lead to an inaccurate representation of the performance of the subsystem under investigation

The lack of granularity in this coding system makes it difficult to identify which product caused the delay and why. It also limits the company's ability to assess the performance of specific product groups over time, which is critical for making targeted improvements. For instance, if product 1 are consistently the bottleneck due to recurring material issues, that insight may be obscured because of the broad application of the MS01 code to mixed-product orders.

This reduces the company's ability to identify and address recurring material shortages correctly and obscures the trustworthy source of the problem, ultimately limiting the value of MS01 data for continuous improvement.

Through the interviewees, another issue concerning how the current reporting process assigns delay codes was observed. The coding function is accessible to multiple organisational roles, including order planning (OPA), production (OBC), and shipping. The intention is that anyone who encounters a delay should be able to register the reason by assigning a code. However, several interviewees, particularly from production planning, described this open-access approach as problematic and confusing.

One planner expressed frustration in the following way :

> *"I think it's messy when some people go in and remove codes, and it is unclear who have the mandate and ownership, which make people give up on fighting over it. Everyone have their own performance metrics and want to look good in their area. I think it would have been better if there were a dedicated function responsible for this, with some kind of validation of what gets done and not done. That way, things would be more consistent across different production lines and among different purchasers. The fewer people involved, the more consistent it becomes. For example, if someone wants to make a change"*

This problem became evident in the raw data on delivery delays provided by the case company. Many of the comments explaining the reasons for delays could not be traced to any specific cause. Some comments were not standardized, making it difficult to categorize them into a defined code group. When these uncoded delays were visualized in a pie chart, it was found that approximately 14% of the delay entries were uncoded (see figure 4.7).

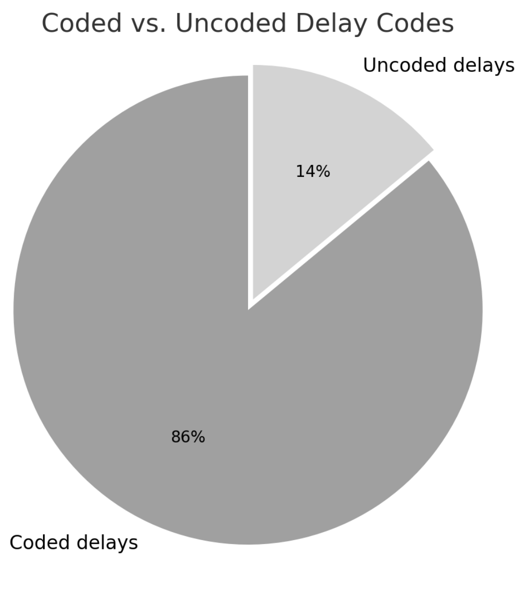

Figure 4.7: Percentage of coded and uncoded delays.

Focusing specifically on the MS01-coded delays, the analysis examined whether each delay could be traced to a specific article or purchase order. The results showed that approximately 59% of the MS01 delays could be linked to a specific article, 19% could be traced to a purchase order, and the remaining 22% could not be clearly linked to either an article or a purchase order(see figure 4.8).

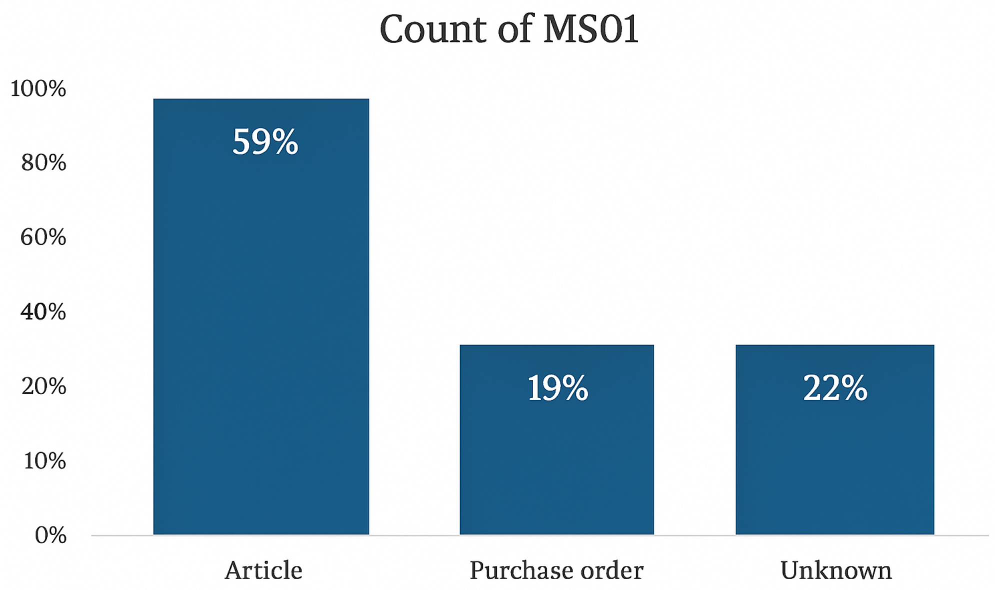

Figure 4.8: Tracability of MS01 data

These findings suggest limitations in the consistency and structure of how delivery deviations are documented in the system, which may affect the ability to perform accurate root cause analysis.

4.5 Impact of the ERP System Transition on material shortage reporting

Following the transition to the Oracle ERP system, the process for recording and categorizing delivery delays has undergone several notable changes. Previously, in the Jeeves system, delay codes, such as MS01 for material shortages, were applied at the customer order level, regardless of which specific product or component caused the delay. In Oracle, however, delays are now registered at the manufacturing order level, which is product-specific. This shift allows for greater traceability by linking the delay directly to the affected product line, making it clearer which specific item caused the issue.

Additionally, the MS01 code has been disaggregated into three distinct codes:

- 2A for general material shortages,
- F2A for Assemble-to-Order (ATO) purchased materials,
- F2B for intercompany purchased materials.

This refinement enables a clearer distinction between delays caused by external suppliers and those originating from within the company, thereby improving the quality and usefulness of delay data for root cause analysis (see Figure 4.10).

The responsibility for inputting delay codes has also changed. Under Jeeves, the system allowed any user to input a delay code directly, often without standardized controls or validation. With Oracle, the process has become more structured: only the planner is now authorized to enter delay codes. If a delay is identified by another function, such as production, they must report the issue to the planner, who then reviews the situation and determines which jobs are affected and how the delay should be classified.

As one planner described :

> *In Jeeves, it was open to everyone, allowing anyone encountering issues to directly input delay codes into the system. However, with the transition to Oracle, the process has become more structured. Now, only the planner is responsible for coding delays. If production identifies a delay, they must contact the planner, provide an explanation of the situation, and specify which jobs will be delayed or affected.*

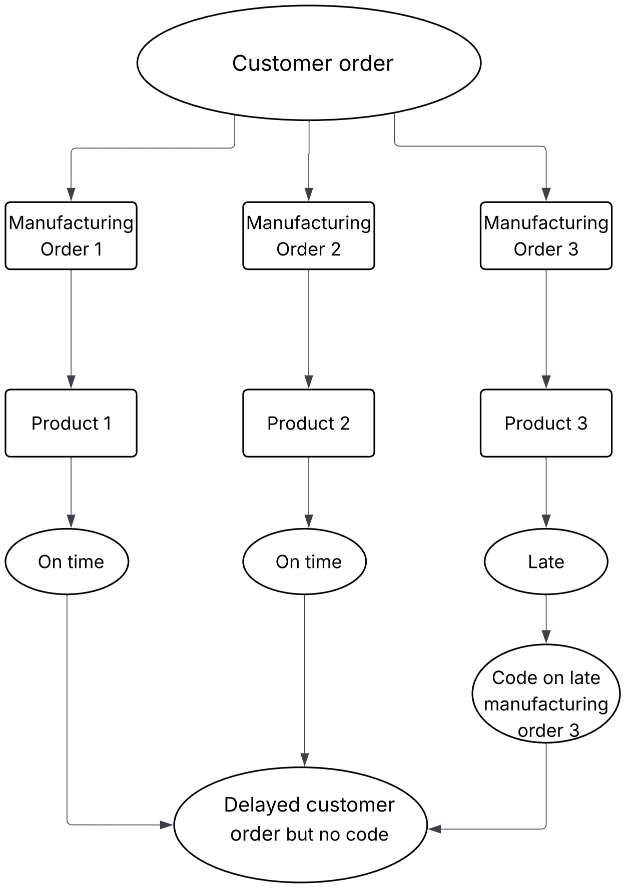

Figure 4.9: Illustration of systems order in Oracle

4.5.1 Interview tables on the causes to material shortage

Table 4.2: Summary of interview on the Causes of Material Shortage.

Functions	Lack of coordination	Forecasting inaccuracy	Engineering changes	Order interdependencies	Poor procurement supplier mgmt.	Unrealistic lead times
Operative procurer 1	X	X	X	X	X	X
Operative procurer 2	X	X			X	X
Order planner 1		X		X		X
Order planner 2	X					X
Strategic purchaser	X	X	X	X	X	X
Project procurer	X	X				X
Production planner 1	X	X			X	X
Production planner 2	X					X
Production					X	

4.6 Proposed model on how to proactively manage material shortage

The model for categorizing and proactively working with material shortages at the case company was developed using a fault tree root cause analysis approach(see figure 4.11). At the top of the model is the top event, which represents a fault or deviation in delivering a sales order on time. From this top event, the causes are divided into two intermediate events: either the supplier delivers within the agreed lead time, or the supplier exceeds the agreed lead time.

If the supplier delivers within the agreed lead time, the cause of the material shortage cannot be attributed to the supplier and is instead assumed to originate from internal planning. This intermediate event is further divided into two causes: lack of materials or a faulty promise date to the customer.

In the case of lack of materials, the shortage of planned material for an order can occur either because previously planned materials were moved to other orders, or because materials were unintentionally consumed by prioritized orders (order cannibalization).

For the intermediate event of a faulty promise date, the causes are further broken down into three basic events:

1. Planners may knowingly set shorter lead times to the customer and hope that purchasers can provide the materials in time.
2. Planners may unknowingly use incorrect planning parameters because the lead times in the system are not accurate.
3. There may be inventory discrepancies, where the system shows that items are available even though they are not physically in stock.

One reason for incorrect lead times in the system can be that updates are made to lead times, but these updates are not communicated. Another reason is the lack of system support for tiered lead times, which means that regardless of whether a small or large volume is ordered, the same static lead time is applied.

On the other side of the fault tree, if the supplier exceeds the agreed lead time, the cause can be categorized into two intermediate events: either internal lead times are long or external lead times are long.

If internal lead times are long, it may be due to:

- Long processing times for purchase orders.
- Miscommunication between departments.
- Incorrect item setup in the system.

In the case of long purchase order processing times, this can result from a wrong revision of an item or missing documents needed to place the order.

If the delay is caused by external lead times being long, the causes can include:

- The purchase order being changed while the supplier is already processing it.
- Excessive pressure on the supplier, leading to performance issues.
- Delays caused by the transport carrier.
- The supplier not being able to deliver due to their own material shortages or capacity constraints.

4.6.1 Validation of the model

To validate the applicability of the developed model, the researchers, together with a purchaser from the case company, selected three real material shortage cases and applied the fault tree structure to trace the underlying causes. The aim was to assess whether the model could be used to systematically categorize the cascading events that led to each specific material shortage. The sample of material shortages was selected using purposive sampling, where the purchaser intentionally chose challenging cases to stress-test the model.

For material shortage number one (See figure A1 in the Appendix), the top event was identified as a deviation in delivery performance due to material unavailability. By using the fault tree model, this shortage was first categorized under the branch where the agreed lead time with the supplier was exceeded(late PO). This indicated that the issue could be attributed to external rather than internal planning factors. From there, the shortage was further classified as the intermediate event of external lead time being exceeded. The analysis then pointed to a more specific cause, too high pressure on the supplier. This, in turn, was linked to the basic event that the item in question was not included in the forecast and had not been purchased from the supplier in over 10 years. As a result, the supplier had not anticipated the demand, and the lead time required to fulfill the order significantly exceeded the previously agreed time.

For the second material shortage case analyzed using the fault tree model(See figure A2), the first identifiable intermediate event was that the delivery time exceeded the agreed lead time. In practical terms, this indicated that the purchase order late.

Following the logic of the fault tree, this delay was then traced back to the intermediate event of long internal lead times. Upon further investigation, the underlying cause of the prolonged internal lead time was linked to a wrongly configured item setup in the system. This incorrect setup contributed to increased processing time when initiating the purchase order to the supplier. Because the item was not properly defined in the system, the time needed to clarify or correct the configuration before placing the order became longer than usual.

In the third material shortage case(See figure A3), the analysis using the fault tree model began with identifying that the supplier delivered within the agreed lead time, meaning the delay could not be attributed to the supplier. This pointed instead to an issue within the internal planning process of the case company. Following the fault tree structure, the next identified event was a faulty promise date given to the customer. This suggested that the order had been scheduled for delivery earlier than what the internal processes and supply capabilities could realistically support. The faulty promise date was then traced back to a basic event, where planners had consciously set a shorter lead time in the system. This was likely done in the hope that the required materials would still arrive in time to meet the promised date. However, this planning decision resulted in a misalignment between actual material availability and customer expectations, ultimately leading to the delivery deviation. This case illustrates how the model can be used to identify internal decision-making as a root cause of material shortages, particularly when supplier performance is not at fault. The structure provided by the fault tree helped clarify how specific planning behaviors can lead to inaccurate delivery commitments.

This structured tracing of the root cause using the fault tree model provided a clear visualization of how a single material shortage could evolve from multiple interacting factors, and how lack of forecasting and historical demand visibility can affect supplier performance.

This model was validated by the purchaser, who used it to assess the chosen material shortages. When the researchers asked the respondent whether the model was useful or if it required extra work, the purchaser responded in the following way:

> *The model is pretty straightforward; it does not require any extra effort from my side. It brings out what i already do in my head on paper which is good.*

5
Discussion

5.1 Key Findings

One of the most prominent empirical findings in this study concerns the existing lack of reliability and ownership surrounding lead times within the case company's OtD process. The planned lead times spanning from material need identification to supplier delivery are not always derived from empirical supplier data but instead shaped by internal assumptions, informal planning practices, and fragmented departmental inputs. Strategic purchasing, order planning, and external partners are all able to alter lead time parameters without cross-functional alignment, resulting in conflicting data and planning discrepancies. This systemic misalignment is further exacerbated by the company's continued reliance on outdated planning tools, such as manually updated Excel spreadsheets. The lack of integrated system support for staggered or volume-dependent lead times further impedes planning accuracy. Although the ongoing transition to Oracle introduces more advanced lead time management functionalities, interviewees consistently emphasized that these system capabilities are unlikely to rectify planning errors in the absence of improved process governance and cross-functional coordination.

These observations are supported by the existing literature that highlights the strategic importance of lead time accuracy for OtD performance. McLean (2017) stresses that unreliable lead times may disrupt supply chain performance, an argument which are reflected in the empirical data.

Interviewees frequently cited lead time inaccuracies as one of the root causes of material shortages, safety stock miscalculations, and inaccurate customer promise dates. This mirrors L. Xu and Chen (2021)'s concept of a "delusional planning environment," wherein lead time planning is detached from actual supplier performance, thereby compromising the reliability of downstream planning.

Most interviewees, excluding those in production, acknowledged that the lead times in the legacy Jeeves system were often outdated, as they were updated only quarterly. The lack of real-time integration led planners to rely heavily on Excel-based workarounds, which further reduced data consistency and increased uncertainty. Although Oracle introduces enhanced capabilities, the system has yet to address tiered or volume-sensitive lead times, particularly affecting Available-to-Promise (ATP) calculations for complex or large-volume orders.

Forecasting emerged as another vulnerable yet critical element within the case company's order-to-delivery (OtD) process. While forecast accuracy at the product family level remained within a ±10% deviation, forecast reliability deteriorated significantly at the component level, particularly for highly configurable products.

This challenge, described by multiple interviewees as akin to “using a crystal ball,” reflects the uncertainties introduced as global sales projections are broken down into specific article-level demand. The case company primarily employs a top-down, rolling forecast methodology. However, the lack of feedback loops from actual order data to planning models results in significant variances, with an example of 133% for a certain article. Despite a nominal forecast tolerance buffer of 25% communicated to suppliers, these expectations are often ambiguously defined and inconsistently enforced, leading to misalignments and stockouts. These findings are consistent with prior research. Bertrand et al. (2000) notes that forecast precision diminishes significantly in Engineer-to-Order (ETO) environments due to the proliferation of customer-specific configurations. Ross (2015) similarly contends that forecasting at the product family level is generally more reliable in high-variability environments. To mitigate these forecasting challenges, the application of bottom-up techniques, such as order commonality analysis (Bartezzaghi & Verganti, 1995), may offer a viable complement. Such methods identify frequently used components across configurations, reducing dependency on high-precision forecasts for individual variants. Given the component-level volatility identified in this study, a hybrid forecasting model could enhance accuracy without substantially increasing inventory levels.

Another significant finding concerns the adverse impact of uncoordinated engineering changes on order reliability. Interviewees highlighted several instances where technical drawings, component codes, or revision levels were altered without proper communication with the supply function. As a result, purchasers frequently issued orders based on outdated documentation, leading to supplier rejections or delivery delays. In other cases, clarifying discrepancies required time-intensive coordination with engineering, consuming valuable lead time and disrupting delivery schedules. This indicates a deeper systemic issue, namely, the lack of structured communication between engineering and operational functions.

Order integrity relies not only on external supplier performance but equally on robust internal alignment. The absence of synchronized workflows and version control undermines even the most accurate forecasts or lead times. This aligns with findings from ElMaraghy et al. (2021) and Mello et al. (2017), who emphasize that mismanaged engineering changes can disrupt supply reliability and unfairly transfer accountability to external suppliers.

A comparative analysis of literature and stakeholder interviews(See figure 2.1 & 4.2) shows that the literature and the empirical findings align fairly well in terms of the root cause of material shortage. However, the empirical data highlighted problem with unrealistic lead times as one of the main contributors to this problem, more then the literature did. While literature places stronger emphasis on forecasting and supply chain complexity, stakeholders within the case company placed greater emphasis on inaccurate lead times and poorly communicated engineering changes.

In the empirical findings, the problem with engineering changes was emphasized as one of the main contributors, however it was only mentioned by purchasers. This discrepancy may be due to the fact that purchasing personnel directly experience the consequences of these issues, such as expediting materials or manually resolving documentation mismatches. while other parts only experience these problems as lack of coordination or as the supply chain can not deliver.

Another root cause identified by internal stakeholders particularly those in production was inventory discrepancies. Although not explicitly addressed in the literature, this issue affected material availability and production reliability within the case company, suggesting that future research may need to address this overlooked variable.

To structure the various causes of material shortages, a Fault Tree Analysis (FTA) model was developed. Drawing on both empirical findings and literature, the FTA categorizes root causes into two main branches(See figure: 5.2 & 5.3) internally driven planning failures and externally driven supply disruptions. The top event, defined as a material shortage, is linked to intermediate events such as lead time exceedance, inaccurate forecasts, or uncoordinated engineering changes.

Although FTA is a well-established methodology in engineering reliability studies (Bertsche, 2008), its application in internal planning within ETO environments remains limited. An exception is Sherwin et al. (2020), who applied FTA to external supply risks. By adapting this logic to internal planning, the case company can better trace how internal misalignments contribute to delivery delays.

The fault tree's development was challenged by the research team's limited system knowledge. Nevertheless, the use of tacit organizational knowledge allowed the researchers to populate the tree structure. This reflects observations by Kabir (2017) and Rooney and Heuvel (n.d.), who emphasize that the effectiveness of FTA is contingent on a complete understanding of the system.

The first branch of the fault tree focuses on internal causes such as lead-time misalignments, order interdependencies, and coordination gaps. The second branch addresses externally driven issues that occur when agreed-upon supplier lead times are exceeded. These include supplier prioritization conflicts, inaccurate forecasts, and excessive pressure from the buyer. Sub-branches also distinguish delays caused by third-party carriers versus those attributable to suppliers.

For the FTA model to yield actionable insights, robust traceability in material shortage cases is essential. However, the empirical data revealed significant limitations in this area. In the legacy Jeeves system, approximately 14% of material shortage cases were uncoded, and only 60% of MS01 delay codes could be traced to specific articles. This limitation is consistent with research by Kozjek et al. (2017) and Ito et al. (2022), which emphasise the importance of standardised and fault-specific reporting to enable effective root cause analysis.

Another data integrity issue was the use of PDSL hits at the sales order level rather than at the individual product line level. This created ambiguity when trying to isolate the impact of shortages on specific subsystems or product variants. A delay in one component could distort the perceived delivery performance of unrelated components. This underscores the critical need for high-quality data granularity, as emphasized in broader literature on root cause diagnostics.

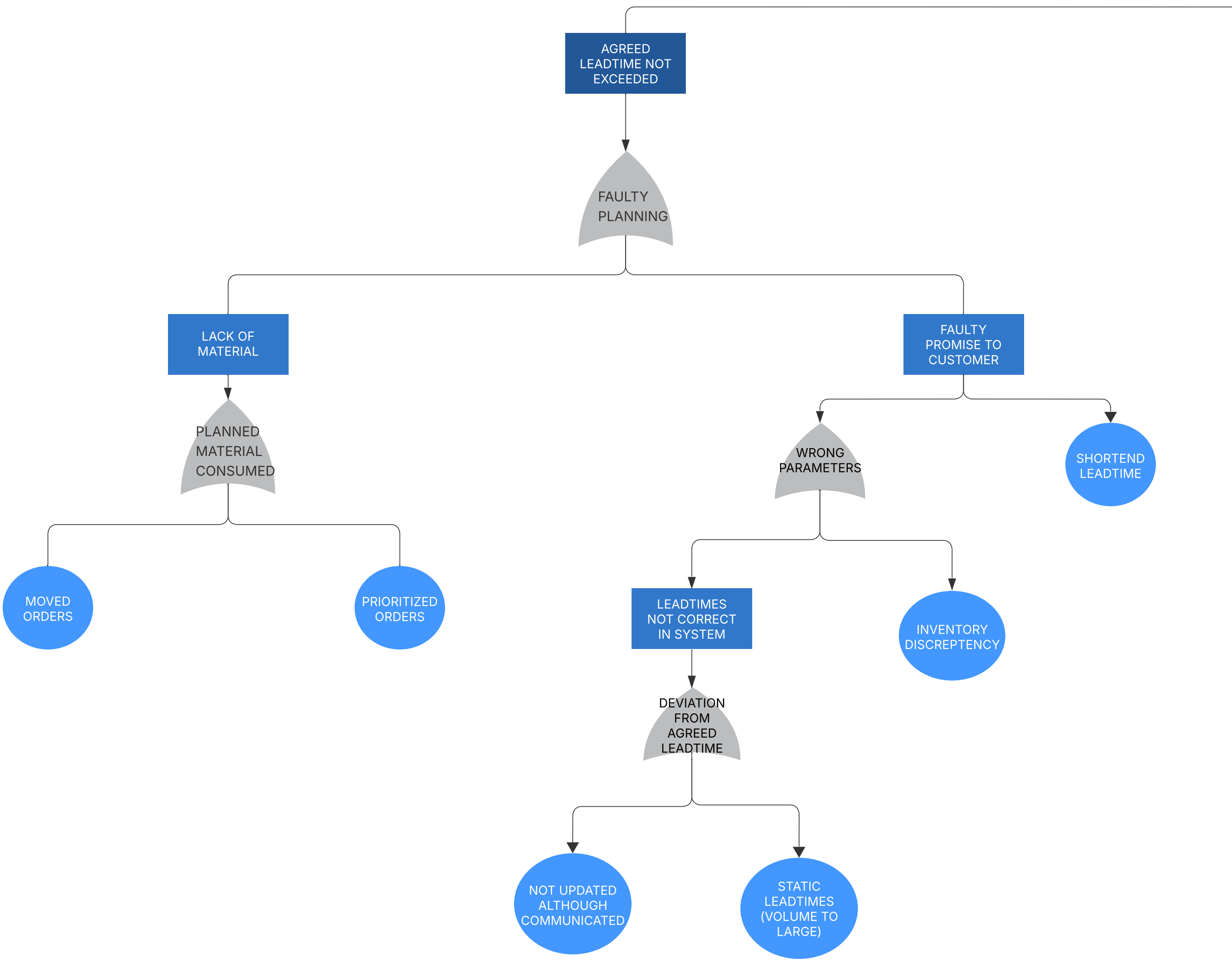

Figure 5.1: Fault tree path when agreed lead time not exceeded.

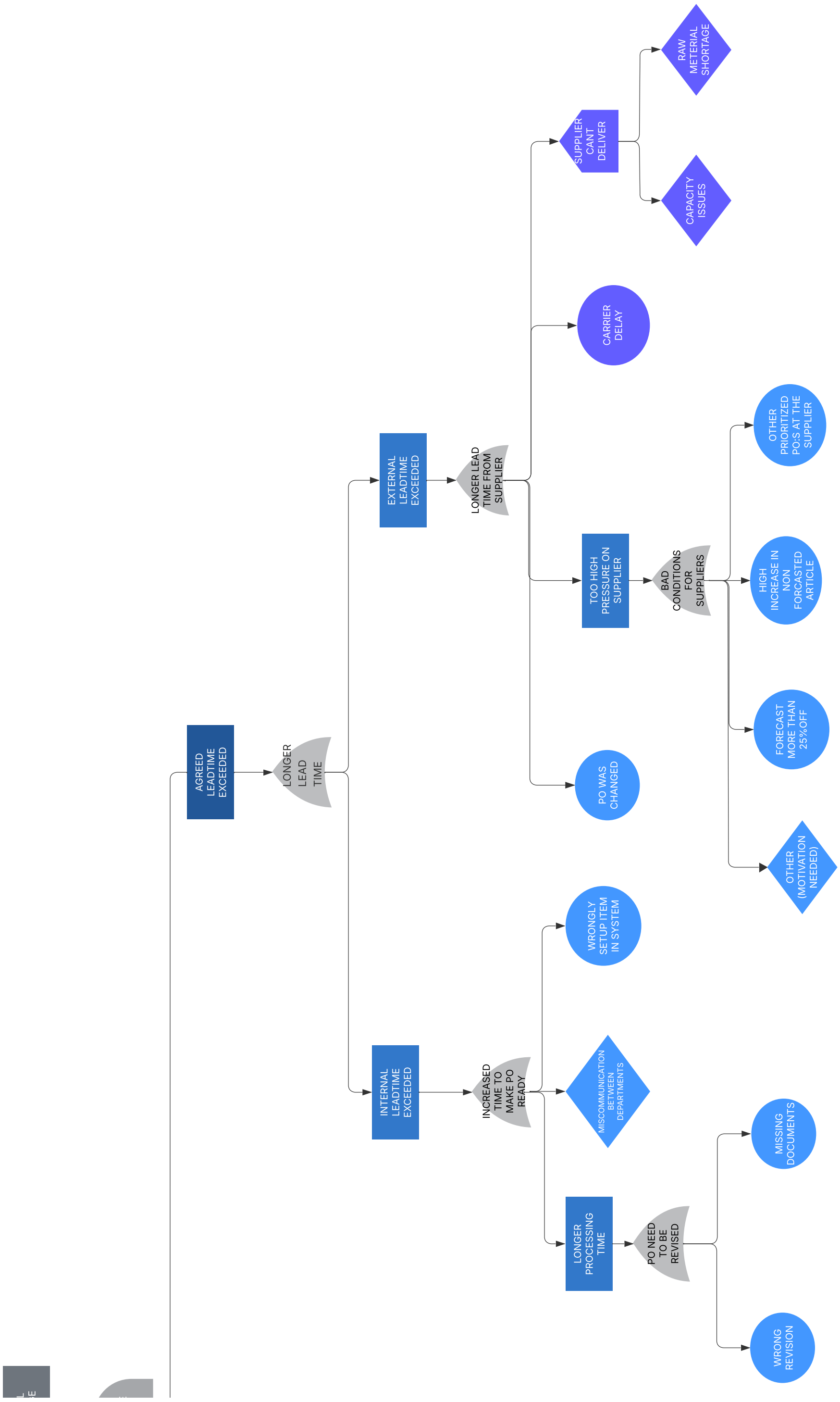

Figure 5.2: Fault tree path when agreed lead time is exceeded.

5.2 Implication

5.2.1 Practical implication

This thesis provides the case company with a tailored and scalable RCA model (Figure 5.1) that enables operational teams to distinguish between internally and externally caused material shortages.

It provides the case company with a concrete framework to pinpoint where material shortages originate. By categorizing delays as either internally or externally caused, The case company can better priorities its improvement efforts and identify underperforming suppliers based on data rather than assumptions. This enables a more targeted approach to increase delivery performance.

5.2.2 Theoretical implication

The literature review revealed that existing research, to some extent, focuses on internal sources of material shortage (see, e.g., McLean, 2017; Cigolini et al., 2020). However, there are a limited number of real-life studies done in an ETO environment, and those that are conducted are usually in construction (.e.g. Cigolini et al. (2022)) or the shipbuilding industry (e.g Ito et al. (2022)). This study offers a complementary perspective of a case study where ETO is studied in the aspect of a factory LVHV environment. It further extends FTA into internal planning processes an application largely unexplored in current literature.

Additonally it expands existing literature on internal reasons for material shortages within an ETO context by applying FTA, which is an underexplored area.

6
Conclusion

The purpose of the study was to identify the underlying causes of material shortages in an ETO environment and to propose a more proactive approach to managing them.The research addressed two core questions:

- **What causes material shortages in an ETO manufacturing environment ?**

The findings reveal that material shortages in ETO settings are rarely isolated incidents. Instead, they are often the result of several interconnected internal factors. Through a combination of interviews, document reviews, and data analysis, the study identified key contributors to these shortages: inaccurate lead time settings, difficulties in forecasting due to product complexity, and weak cross-functional coordination.

Although suppliers are often blamed for late deliveries, the study reveals that material shortages originate from internal misalignments, particularly in planning and communication. Unclear ownership of lead times, inconsistent demand signals, and siloed departmental practices increase the risk of shortages and reduce the ability to prevent them early. Moreover, the case company's current practice of logging delay codes without conducting deeper analysis has created a cycle of reactive problem-solving rather than continuous improvement.

- **How can these shortages be managed more proactively?**

To break this cycle, the causes of material shortages identified in this study were used to build an FTA structure. The factors, or intermediate events, are derived from the findings of Research Question 1, and these comprise the components of the FTA structure. These are then implemented in the FTA. This approach facilitates a more structured, data-driven method based on RCA and supported by FTA.

A practical outcome of this approach is a reference model or checklist that the case company can use to systematically evaluate each MS01 case. This will help teams distinguish whether a shortage is due to internal factors or external factors such as supplier issues, promoting a more consistent and objective assessment process. Over time, such a model could shift the organisation away from a blame-oriented culture toward one focused on learning, accountability, and process improvement.

The limitations of this study include its exclusive focus on one product line, which may reduce the generalisability of the findings to other product lines within the case company. Furthermore, the timing of the ERP system transition introduced additional uncertainty, making it more difficult to track and interpret certain data. Due to limited documentation and lack of granularity in the reported material shortages at the case company, the study relied almost entirely on qualitative investigation to identify root causes. As a result, while the identified causes are likely the main contributors to material shortages, it is not possible to determine which are the most frequent or to quantify the actual impact of each material shortage cause.

For future work it is recommended that the delay coding process be further standardized to enhance both traceability and data quality. In particular, delay codes should be linked to specific articles, enabling the company to identify all material shortages more accurately. This would ensure that input data is both sufficient and reliable for tracing the underlying causes. With improved traceability, the organization can collect and analyze data on material shortages more effectively, identify the most frequent internal contributors, and develop targeted solutions. This represents a more data-driven approach to quality work within the supply chain.

For future research, the fault tree structure could be extended by collecting additional quantitative data to gain deeper insight into the impact of each root cause. Furthermore, the proposed model could be applied and evaluated over time to measure the effectiveness of the fault tree structure in identifying and preventing material shortages.

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Appendix 1

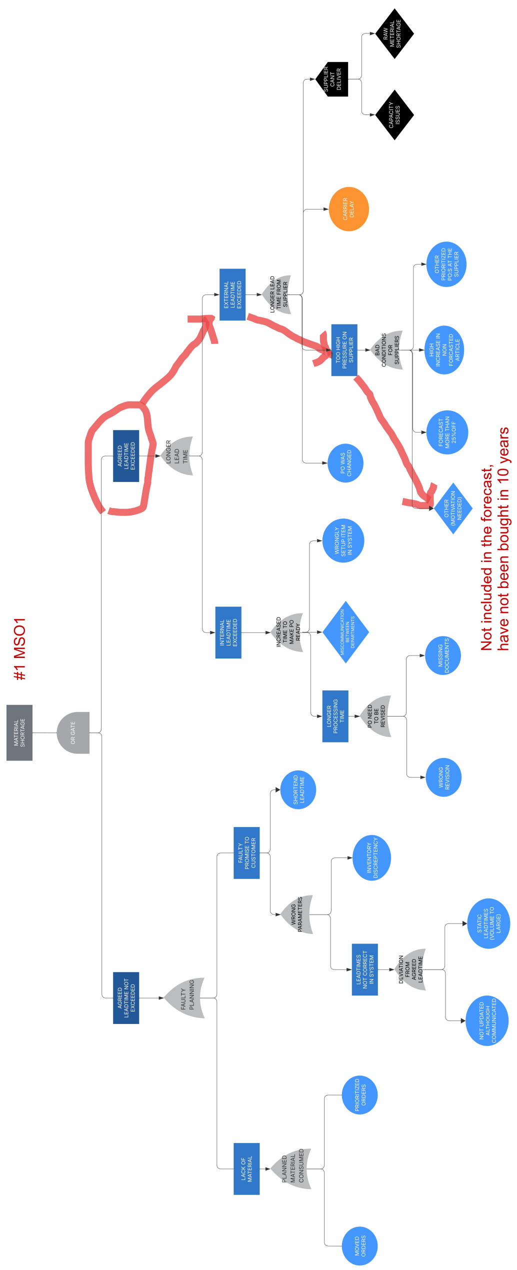

Figure A.1: Validation of model: material shortage case 1.

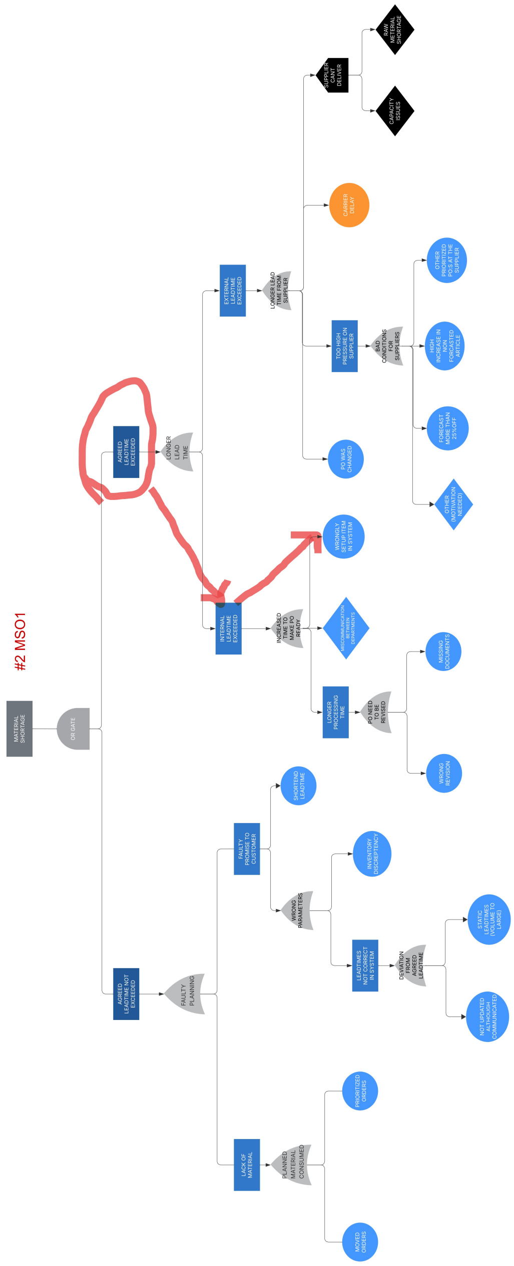

Figure A.2: Validation of model: material shortage case 2.

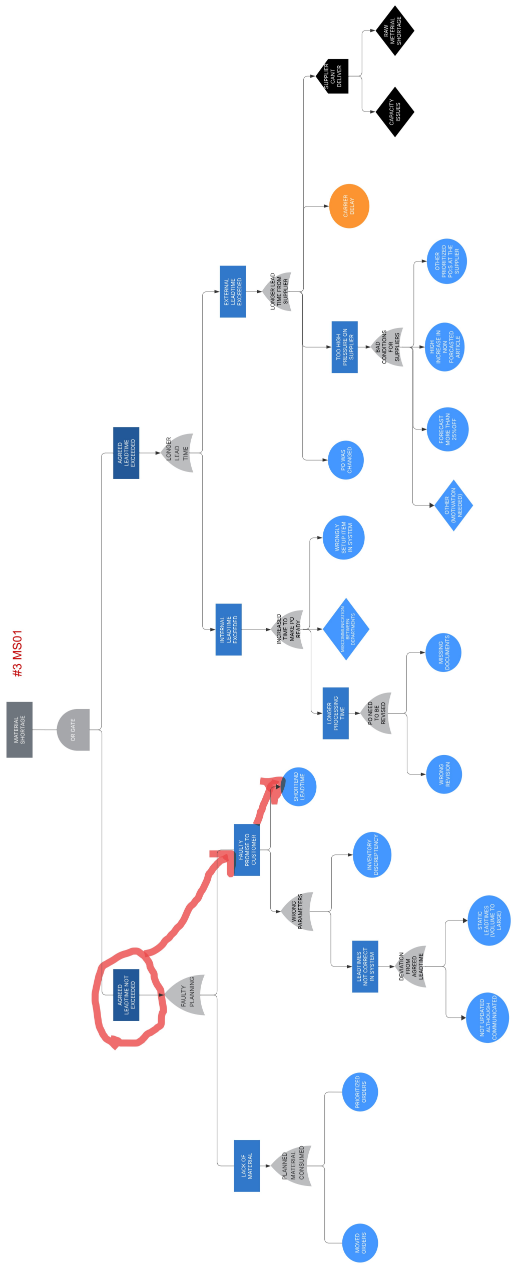

Figure A.3: Validation of model: material shortage case 3.

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