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Modelling and Analysing Scheduling Structures and Deviations in Material Flows

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ABSTRACT:

This master's thesis examines how production scheduling structures affect material flow performance in an ERP environment. The study is motivated by the need to ensure a stable and reliable material flow. The analysis indicates that material flow performance depends not only on schedule stability but also on underlying structural factors. These factors manifest as deviations between planned and actual requirement timings. The objective is to model and analyse scheduling structures, identify deviations, and assess their significance for material flow performance.

The work was conducted as a case study within operational purchasing in the manufacturing industry. The empirical analysis is based on operational data collected from ERP systems and analysed in a Power BI environment. The examination focused on schedule stability, requirement timing deviations, and their relationship to key material flow metrics, such as inventory levels, availability, and shortages.

The results indicate that material flow performance is more strongly associated with deviations between planned and actual requirement timings than with schedule instability alone. In the analysed data, these deviations were predominantly late and were linked to both material availability and inventory development. In addition, the analysis highlights a trade-off in which better availability is often achieved with higher inventory commitment, whereas inventory optimization may increase shortages. This shows that deviations serve as a key mechanism that controls material flow performance and the balance between inventory and availability.

The findings suggest that the main challenge in material flow management is not schedule instability alone, but rather how scheduling changes translate into operational deviations between planning and execution. In this context, those deviations are the primary mechanism by which scheduling structures shape material flow performance. The study offers a new perspective on the relationship between scheduling structures and material flow, providing a basis for improving synchronization between production scheduling and purchasing.

KEYWORDS: Production scheduling, scheduling structures, requirement timing deviations, material flow, ERP data analysis

VAASAN YLIOPISTO
Tekniikan ja innovaatiojohtamisen yksikkö

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TIIVISTELMÄ:

Tämä diplomityö tarkastelee tuotannon aikataulutusrakenteiden vaikutusta ostoon liittyvän materiaalivirran suorituskykyyn ERP-ympäristössä. Lähtökohtana tutkimukselle on tarve varmistaa vakaa ja luotettava materiaalivirtaus. Tarkastelu osoittaa, että tämä ei riipu ainoastaan aikataulujen vakaudesta, vaan siihen vaikuttavat myös rakenteelliset tekijät. Nämä ilmenevät suunniteltujen ja toteutuneiden materiaalitarpeiden välisinä poikkeamina. Tavoitteena on mallintaa ja analysoida aikataulurakenteita, tunnistaa poikkeamat sekä arvioida niiden merkitystä materiaalivirran toimintaan.

Työ toteutettiin tapaustutkimuksena valmistavan teollisuuden operatiivisen oston kontekstissa. Empiirinen analyysi perustuu ERP-järjestelmistä kerättyyn operatiiviseen dataan, jota analysoitiin Power BI -ympäristössä. Tarkastelu kohdistui aikataulujen vakauteen, materiaalitarvepoikkeamiin sekä niiden yhteyteen liittyviin materiaalivirran keskeisiin tunnuslukuihin, kuten varastotasoon, saatavuuteen ja puutteisiin.

Tulokset osoittavat, että materiaalivirtojen sujuvuus liittyy läheisemmin suunniteltujen ja todellisten tarveajankohtien välisiin eroihin kuin pelkästään aikataulun epävakauteen. Analysoiduissa tiedoissa nämä erot olivat pääasiassa viivästyksiä, ja ne liittyivät sekä materiaalien saatavuuteen että varastotilanteen kehitykseen. Lisäksi analyysi tuo esiin tasapainotilan, jossa parempi saatavuus saavutetaan usein korkeammalla varastositoutumisella, kun taas varaston optimointi voi lisätä puutteita. Tämä osoittaa, että poikkeamat toimivat keskeisenä mekanismina, joka ohjaa materiaalivirran suorituskyvyn ja varasto-saatavuustasapainon muodostumista.

Tulokset viittaavat siihen, että materiaalivirtojen hallinnan suurin haaste ei ole pelkästään aikataulun epävakaus, vaan myös se, miten aikataulumuutokset näkyvät suunnittelun ja toteutuksen välisinä poikkeamina. Tässä yhteydessä nämä poikkeamat toimivat pääasiallisena mekanismina, jonka kautta suunnittelurakenteet vaikuttavat materiaalivirtojen suorituskykyyn. Tutkimus tarjoaa uuden näkökulman aikataulurakenteiden ja materiaalivirran väliseen suhteeseen ja antaa lähtökohdan tuotannon aikataulutuksen ja oston paremman synkronoinnin kehittämiselle.

AVAINSANAT: Tuotannon aikataulutus, aikataulutusrakenteet, tarveajankohtien poikkeamat, materiaalivirta, ERP-analyysi

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Abbreviations

BOM = Bill of Materials

ERP = Enterprise Resource Planning

JIT = Just-in-Time

LT = Lead Time

MPS = Master Production Schedule

MRP = Material Requirements Planning

PGR = Purchasing Group

PR = Pegged Requirement

RO = Research Objective

RQ = Research Question

SoA = Start of Assembly

SCM = Supply Chain Management

1 Introduction

In the marine and energy technology industry, the case company's growing market demand underscores the importance of reliable material flow. Components must be available when needed to improve overall production performance (Chankov et al., 2018). Therefore, a stable and accurate production schedule is crucial for maintaining a continuous flow of purchasing activities (Jonsson et al., 2024). In environments with complex BOM structures and long LTs, scheduling challenges can disrupt the entire material flow (Klug, 2017). The objective of the thesis is to identify potential improvement areas to further enhance alignment between production scheduling and purchasing. As a result, this thesis focuses on modelling and analysing scheduling structures to better understand material flows and identify opportunities to improve the case company's operations.

The first main chapter of this thesis, the introduction, is divided into five sections that lay the foundation for the study. The first section (1.1) presents the research background, emphasizing its relevance and timeliness. The second section (1.2) explains the research purpose, gap, objectives, and value, clarifying why this thesis is necessary and how it aims to contribute to the case company and the academic community. The third section (1.3) outlines the RQs, indicating what the study seeks to answer. The fourth section (1.4) defines the study's overall scope by highlighting key definitions, boundaries, and limitations. Lastly, the fifth section (1.5) describes the thesis's structure from start to finish, offering a clear roadmap for the project. For confidentiality reasons, the case company, projects, and product identifiers have been anonymized while preserving the data's structure and integrity.

1.1 Background

This thesis is conducted on behalf of the case company and its production purchasing function. The function operates within the production plant in the Nordic region. The case company is a global technology company focused on marine and energy markets, with a strong emphasis on decarbonization and lifecycle solutions. Its supply chains operate worldwide, supported by extensive supplier networks and complex material flows. In this environment, the purchasing function plays a key role in ensuring a continuous and timely material flow for production and project deliveries. Therefore, this study focuses on the purchasing function at the production plant in the Nordic region to improve its operations.

As demand for the specific product line increases, consistent scheduling and reliable material flow become more crucial for staying competitive and meeting customer needs. As production demands grow and supply chain disruptions intensify, maintaining a steady, predictable flow of components is essential. This heightened uncertainty can lead to both excess inventory and material shortages, creating operational challenges. Therefore, it is important to study how scheduling structures affect purchasing-driven material flows, which form the foundation of this research.

Synchronization among manufacturing systems is essential to overall performance (Chankov et al., 2018). Therefore, aligning production scheduling with purchasing ensures that materials are available when needed. Frequent schedule changes and uncertainty can significantly disrupt material flow across the supply chain (Atadeniz & Sridharan, 2020). When scheduling and purchasing decisions are properly synchronized, stakeholders can maintain stable material flow and reduce costs (Ghasemi et al., 2023). Thus, modelling and analysing scheduling structures are valuable for improving understanding of material flows.

Nervousness and instability in scheduling structures undermine material flow across the supply chain, especially for external suppliers (Law & Gunasekaran, 2010). When material flow is unstable, the risk of shortages and excess inventory rises throughout the system. Unstable scheduling can also leave essential components unavailable when needed, leading to production delays and reduced customer satisfaction (Pujawan & Smart, 2012). Meanwhile, organizations seek to reduce uncertainty by increasing safety buffers, which can lead to excess stock and tie up resources (Chaturvedi & Martínez-de-Albéniz, 2016).

Frequent schedule changes in purchasing operations increase the workload for rescheduling and reactive decision-making (Herrera et al., 2016). In increasingly complex, data-rich manufacturing environments, understanding how scheduling structures affect material flows is both operationally and academically significant (Herrera Vidal & Coronado Hernández, 2021). This highlights the need to identify opportunities to improve the scheduling-purchasing interface to support more stable material flow and enhance material availability in the case company's operations.

1.2 Research purpose, gap, objectives, and value

In today's global supply chain networks, the stability and reliability of material flows are prioritized (Klug, 2017). This thesis examines how scheduling structures affect the flow of purchased components. By analysing these structures, the study seeks to identify opportunities for improvement through modelling and visualization. These improvements should help the case company's purchasing function ensure reliable material flow. Based on internal company data, this is especially important given the rising demand for the specific product line in the coming years. In summary, the research aims to improve operations while maintaining material availability. The findings are intended to apply to other similar product families and organizations.

Existing literature identifies planning quality, scheduling instability, and forecast accuracy as key challenges in production scheduling and SCM (Claes et al., 2015; Jonsson et al., 2024; Lingitz & Sihn, 2020). However, the literature lacks a systematic comparison of planned and actual requirement timings as drivers of material flow reliability. Only 1 of the 25 reviewed studies quantifies fluctuations between planned and actual requirement timings. It shows that production schedule reliability can drop to 25% within 3 days, while requirement timing deviations can increase by up to 75% during this period (Lingitz & Sihn, 2020). In conclusion, structural analysis of requirement timing deviations within scheduling systems remains under-researched.

The root causes of requirement timing deviations, such as inaccurate planned LTs and delivery reliability issues with external suppliers, have been identified in the existing literature (Koh et al., 2006; Mohan & Ritzman, 1998). However, these studies are typically conducted in isolated environments or simulation settings. Only 4 of the 25 reviewed studies analyse ERP transaction data. Therefore, there remains a research gap for a uniform ERP-data-based analysis of requirement timing deviations in a real, complex manufacturing environment.

Prior research shows that centralized planning, demand-driven MRP, and stability-oriented execution improve operational metrics, including material availability and fewer disruptions (Ihme, 2015; Liu et al., 2025; Moscoso et al., 2010). However, the link between scheduling stability and operational purchasing performance remains undertheorized and rarely evaluated empirically. Only 1 of the 25 reviewed studies reports that integrated planning can reduce the frequency of emergency purchasing by 42% (Kang, 2025), suggesting that scheduling stability may significantly influence purchasing operations.

This thesis addresses these research gaps by empirically analysing deviations in requirement timings in a real-world manufacturing scheduling environment using ERP data. The study systematically compares planned requirement timings with actual requirement timings, identifies patterns of deviation, and examines how scheduling instability affects material flow performance in purchasing processes. By integrating structural scheduling analysis with ERP data, the thesis aims to provide empirical evidence for the field of simulation. This study explores whether requirement timing deviations may offer stronger explanatory power for material flow performance than scheduling instability. The research gap is shown in Figure 1.

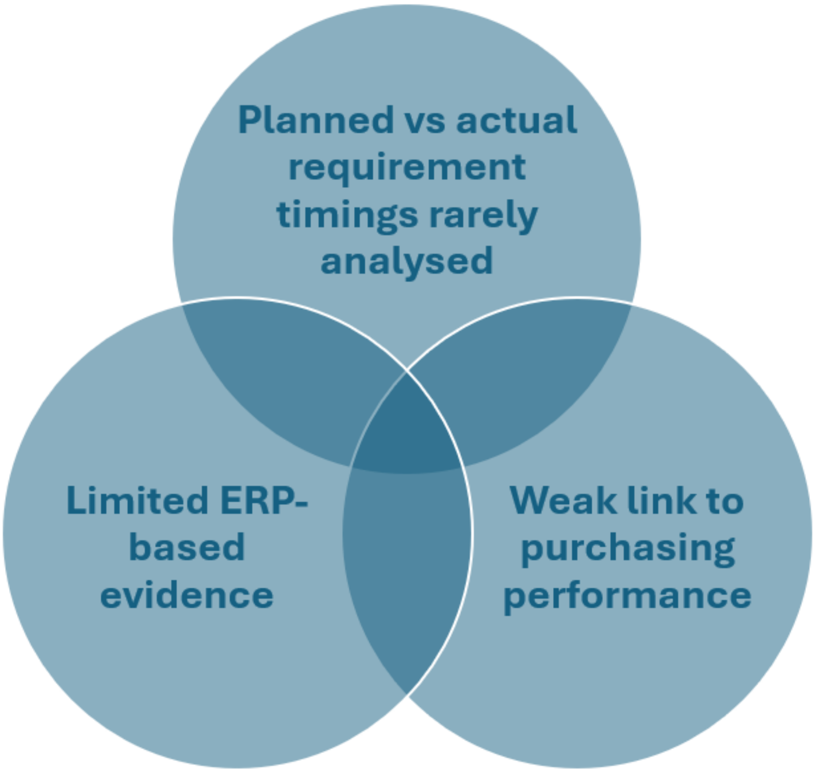

Figure 1. Identified research gap based on the literature review.

The objectives of this thesis align with the purchasing function's goal of improving understanding of scheduling structures to enhance material flows. The study outlines five specific goals, developed in collaboration with the case company. RO1 focuses on analysing scheduling stability and structures using planned requirement timings. RO2 measures deviations between planned and actual requirement timings. RO3 assesses the relationship between scheduling stability, deviations, and their impact on purchasing and material flow performance. RO4 visualizes timing, stability, and deviation patterns, and RO5 identifies improvement opportunities to enhance consistency in material flows. The following operational ROs are listed below.

RO1: To analyse scheduling structures and their stability using planned requirement timings.

RO2: To measure deviations between planned and actual requirement timings.

RO3: To assess the relationship among scheduling stability, deviations, and their impact on purchasing and material flow.

RO4: To visualize scheduling, timing, and deviation patterns.

RO5: To identify opportunities to improve material flow synchronization.

By achieving these objectives, this thesis offers practical value to the case company. The value stems from improving visibility into deviations in requirement timings and aligning scheduling with purchasing decisions. The study supports more data-driven decision-making and helps enhance material flow assurance and operational stability. From an academic perspective, the research provides empirical insights into the alignment between scheduling and purchasing. This broadens understanding of requirement timing deviations in complex manufacturing environments. It links schedule stability to purchasing performance and demonstrates how data-driven modelling applies to material flow analysis.

1.3 Research questions

The primary objective is to improve understanding of material requirements in a complex manufacturing environment. Accordingly, this thesis explores how modelling and analysing scheduling structures can enhance material flow performance. RQ1 examines how scheduling-stability structures affect material flows. RQ2 identifies the types and magnitudes of requirement-timing deviations or misalignments between planned and actual requirement timings, while RQ3 investigates potential development opportunities to improve synchronization between scheduling structures and purchasing processes, thereby enhancing material flow performance. The three research RQs are outlined below.

RQ1: How do scheduling structures influence material flows?

RQ2: What types and magnitudes of deviations occur between planned and actual requirement timings?

RQ3: What development opportunities can improve synchronization between scheduling behaviour and purchasing processes to enhance material flow performance?

1.4 Definitions, scope, and limitations

ERP is an integrated information system that manages core business processes, such as production scheduling and purchasing, on a shared platform (Wang et al., 2005). In this thesis, ERP data serve as the primary source for analysing planned and actual requirement timings. A BOM is a structured list of components required to manufacture a finished product, linking material requirements to production orders (Cinelli et al., 2017). Production scheduling determines the timing of production tasks to meet demand and operational constraints. The scheduling structure defines the logical order, timing, and release method for sequencing production activities and assigning them to resources to execute a production plan (Parente et al., 2020).

Material flow encompasses the movement, availability, and timing of materials and purchased components as they move through the production system to meet manufacturing needs (Plinta & Radwan, 2023). LT is the total duration from the start to the end of a process. In this thesis, it refers to the time between the release of a PO and the receipt of the goods (Biazon De Oliveira et al., 2021). Flow variability reflects instability in material movement, timing, or availability within the production system, driven by demand fluctuations, scheduling changes, or supply disruptions (Prabhu et al., 2024). This instability can lead to material shortages. A material shortage occurs when essential components are unavailable when needed, potentially causing delays and higher costs (Kouvelis et al., 2023).

Synchronization in a supply chain aligns production schedules with purchasing timelines, ensuring materials are available when needed and preventing shortages or excess inventory (Kouvelis et al., 2023). In a complex manufacturing environment, effective synchronization helps maintain a stable material flow and improves operational performance. Process modelling involves the structured representation and analysis of operational processes, using data and visualization tools to understand system behaviour and identify opportunities for improvement (Claes et al., 2015). In this thesis, process modelling is used to examine scheduling structures and their effects on material flows.

This thesis focuses on modelling and analysing scheduling structures and deviations from requirement timings within the purchasing function at the production plant in the Nordic region. The study examines planned versus actual requirement timings and evaluates their impact on material flows. The analysis uses data retrieved from the ERP system and applies modelling approaches to the case environment. The goal of the thesis is to analyse the scheduling and purchasing interface within the case production facility. Therefore, this research does not assess the entire supply chain network, enabling a detailed and manageable analysis within the time frame of a master's thesis.

The thesis focuses on a single company, a single production facility, and projects within a single product line, which may limit the applicability of the findings to other contexts. Because the analysis relies on ERP system data, issues with data quality, system constraints, or missing information could influence the results. Additionally, the study primarily examines deviations in requirement timings and does not consider all external factors affecting material flow. Factors such as supplier disruptions or macroeconomic conditions might also affect material flow performance. These limitations are acknowledged to keep the research manageable while maintaining a clear scope.

1.5 Thesis structure

The thesis consists of five main chapters that adhere to academic writing standards. It begins with English and Finnish abstracts, a table of contents, and a section of abbreviations. Chapter 1 introduces the thesis by covering the background, purpose, main objectives, questions, definitions, limitations, and scope of the study. Chapter 2 reviews key theories and concepts, providing a solid foundation for the remaining chapters. Chapter 3 explains the research methodology and the data used in the thesis. Chapter 4 presents a detailed analysis of the results, including modelling of the scheduling structures for the purchasing process. Chapter 5 concludes with a summary of the research findings, an exploration of their implications, and suggestions for future research topics. The references and appendices are included at the end. This structure is also shown below.

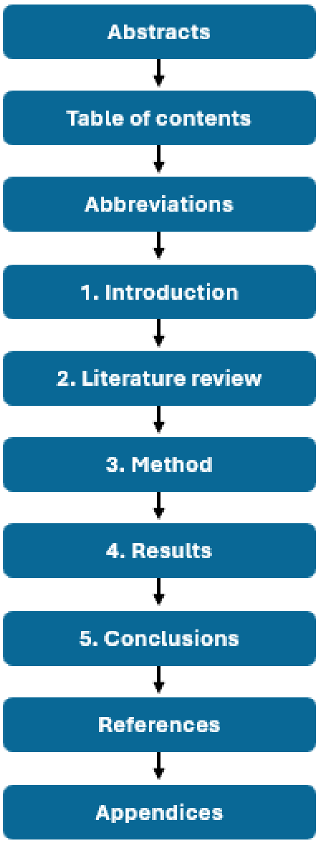

Figure 2. Structure of the thesis.

2 Literature review

In manufacturing systems, the timely availability of materials is essential for maintaining efficient, continuous operations (Chankov et al., 2018). Production scheduling, material flow management, and their synchronization constitute a unified process that directly affects delivery reliability, inventory levels, and operational performance (Stadtler, 2005). In the literature, these topics have been examined from the perspectives of production scheduling, material flow variation, and supply chain synchronization. This review examines these theoretical frameworks, with particular focus on production scheduling structures and the interaction between purchasing and material flow. The aim is to provide a theoretical framework for research and to clarify how scheduling structures and their deviations can influence material flows.

The second main chapter of this thesis, the literature review, is divided into three key sections. The first section (2.1) covers production scheduling theory, schedule instability, and deviations between planned and actual requirement timings. The second section (2.2) reviews the effects of BOM complexity on material flow and on the synchronization between scheduling and purchasing. The third section (2.3) presents process modelling and data analysis methods for analysing production scheduling and purchasing timing. These frameworks provide a broader understanding of the research's theoretical foundations and help address the identified research gap. The theoretical framework of this thesis is illustrated in Figure 3 below.

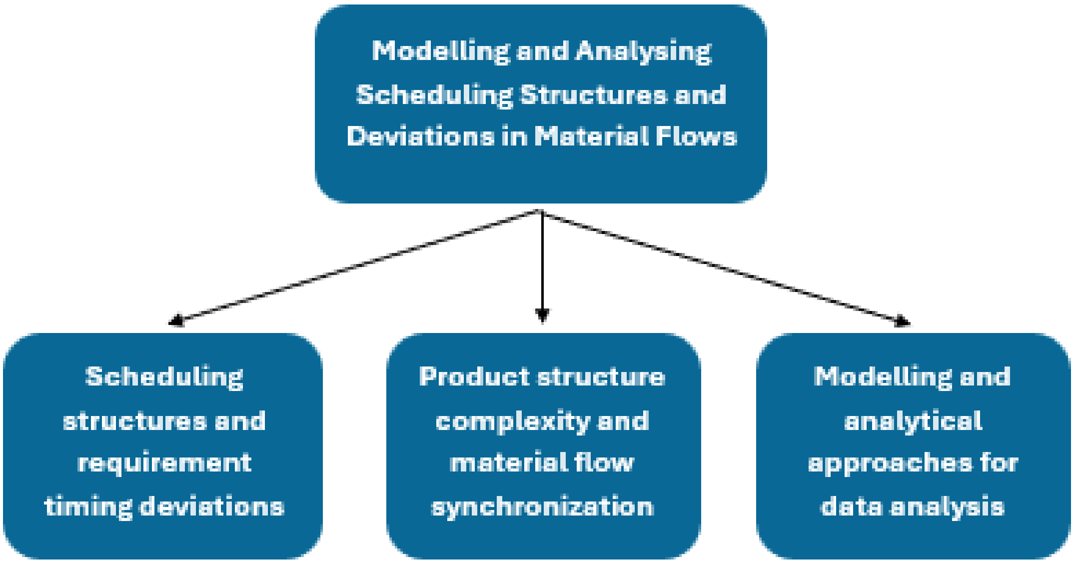

Figure 3. Theoretical framework.

2.1 Scheduling structures and requirement timing deviations

Production scheduling is a crucial part of a manufacturing company's planning system because it determines the timing and sequence of production activities and specifies material requirements for manufacturing processes (Parente et al., 2020). In planning systems such as MRP, material requirements are derived from production schedules and product structures (Jacobs et al., 2018). However, differences between planned and actual execution can lead to deviations in requirements, affecting material availability and supply operations (Law & Gunasekaran, 2010). This first section of the literature review explores the theoretical foundations of production scheduling and the occurrence and impact of requirement timing deviations in manufacturing environments. These subsections aim to connect theory to research and to answer RQs closely related to schedule structures and variations in requirement timings.

2.1.1 Production scheduling foundations

According to Parente et al. (2020), production scheduling is a key decision-making process that allocates resources such as components and machines to manufacturing tasks. It determines when and in what order activities occur, based on available production data and prior scheduling outcomes. Its goal is to optimize operations by efficiently using resources and meeting demand. It is defined as the link between production scheduling and purchasing, influencing raw material requirement schedules, which in turn affect material flow management. The production scheduling process is outlined in Figure 4.

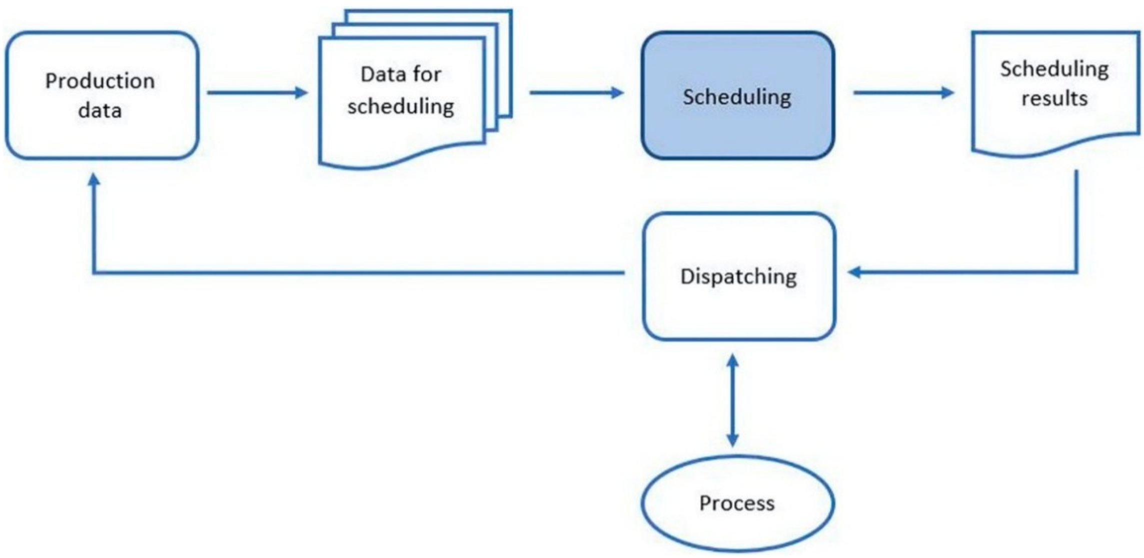

Figure 4. Scheduling process (Pinedo, 2012).

Based on Jacobs et al. (2018), production scheduling develops an optimized production plan using data from resource planning, sales and operations planning, and demand management. This master production scheduling serves as the front end of the ERP system and connects to the organization's core functions, including material and capacity planning. Material and capacity plans, including MRP, directly guide purchasing systems in the back end of the ERP system. Purchasing processes then communicate material requirements and order priorities to external suppliers via POs and planning information, synchronizing scheduling structures with supplier deliveries. This simplified manufacturing system is illustrated in Figure 5 below.

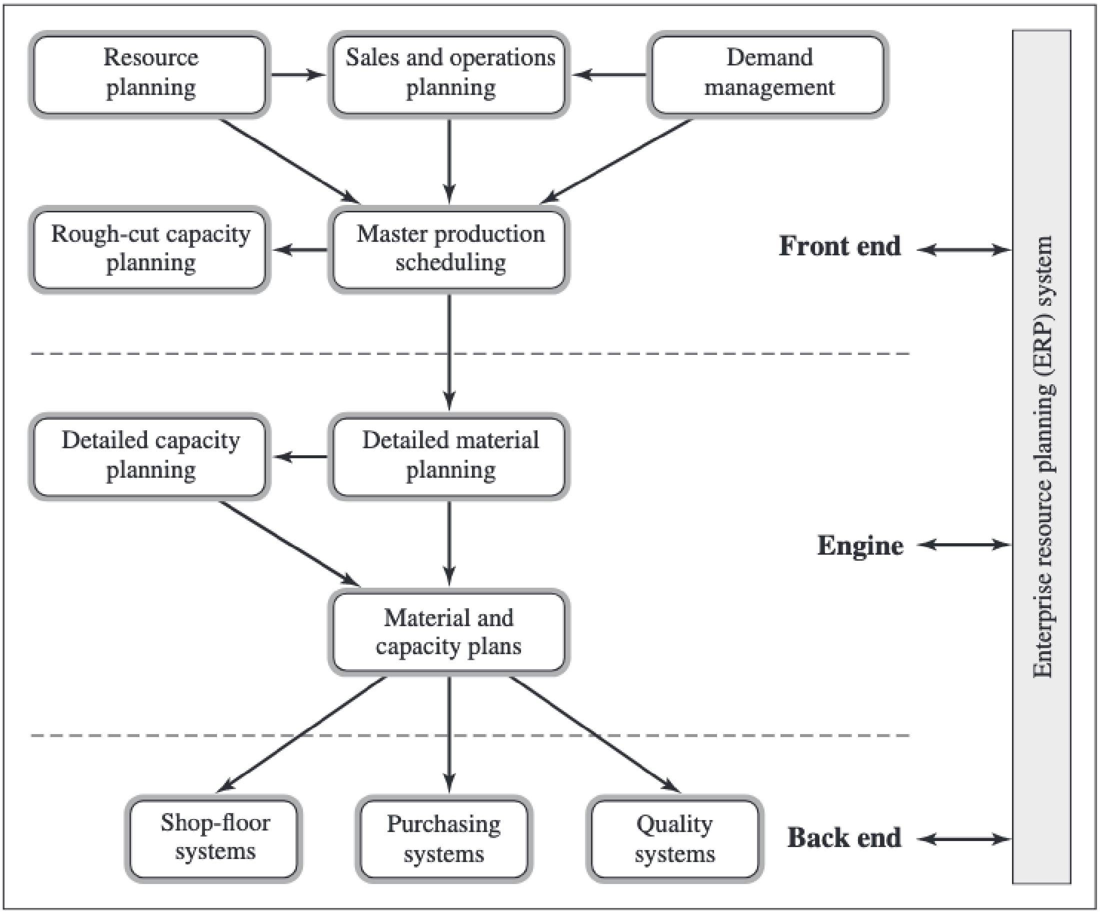

Figure 5. Simplified manufacturing planning system, ERP (Jacobs et al., 2018).

Javadi et al. (2025) define MRP as an intelligent decision-making and information system commonly used in complex manufacturing environments. It determines the raw material type, quantity, and required timing based on data from the MPS, product BOM, and estimated LTs. In this way, the production plan and work-in-process products establish essential schedules for when raw materials are needed in manufacturing processes to meet customer demands without disruptions. According to them, these MRP-based material requirement timings serve as a key reference for purchasing planning and material flow management, as orders to suppliers and their schedules are based on the requirement timings calculated by MRP.

Pinedo (2012) specifies the goal of scheduling as turning released production orders into individual tasks in manufacturing settings, thereby establishing the sequence and timing across different workshops. These tasks are completed in a set order, but their completion can be delayed by unavailable machines or resources, or by higher-priority tasks interrupting ongoing production. Additionally, unexpected events or disruptions, such as machine breakdowns or longer-than-expected LTs, can affect production scheduling. Therefore, a detailed and accurate production schedule is essential for maintaining optimal efficiency and operational control.

Pinedo (2012) continues to clarify that production scheduling is not an isolated task but is intricately connected to production and MRP. For example, MRP determines material availability and purchasing schedules to ensure that production tasks are completed according to the planned timetable. As a result, production planning, scheduling, and material flow management form an integrated system that enables streamlined, efficient production without material shortages or excess inventory. The entire information flow diagram for a manufacturing system is shown in Figure 6.

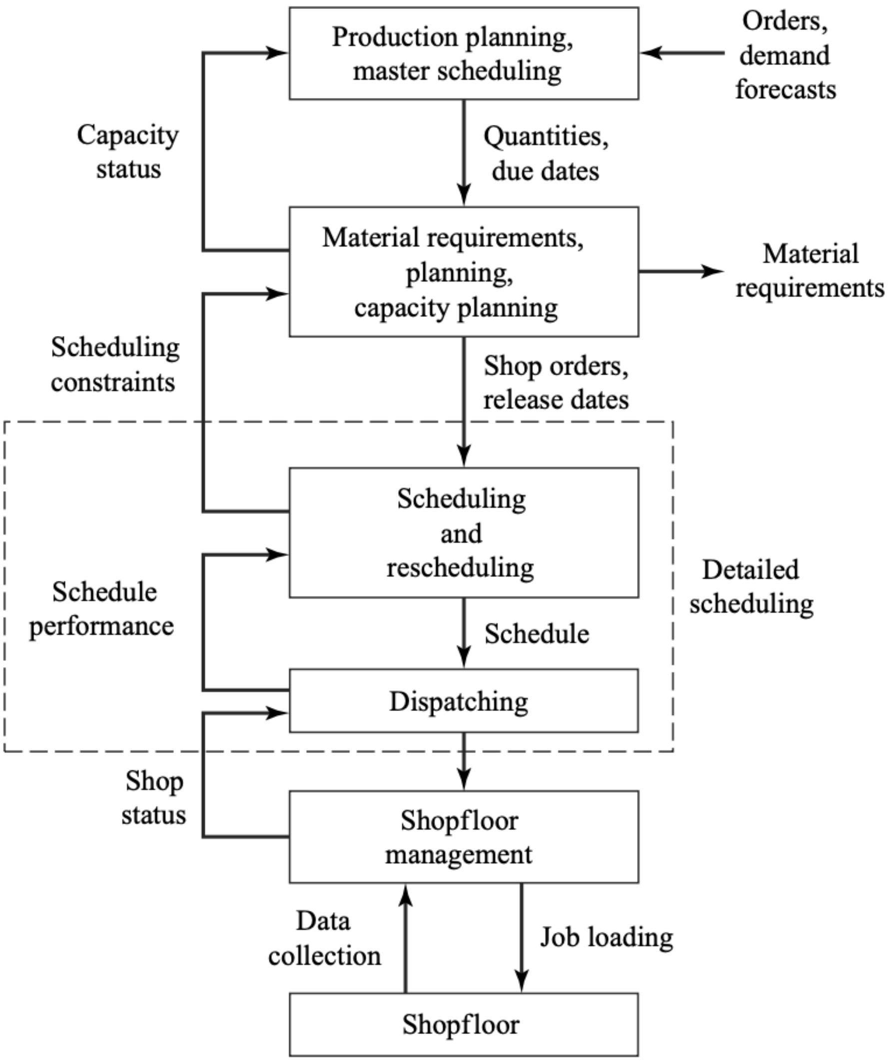

Figure 6. Information flow diagram in a manufacturing system (Pinedo, 2012).

In conclusion, production scheduling provides essential input data for MRP, which in turn directly influences purchasing timelines (Jacobs et al., 2018). Therefore, it is vital that data such as the MPS, product BOM, and estimated LTs be as accurate as possible to ensure consistent output. The output refers to the timely availability of materials for production and relates to RQ1 of the thesis: “How do scheduling structures influence material flows?” These scheduling structures, linked to requirement timings, form the foundation of the MRP ordering process and directly affect material flows. Section 2.1.2 addresses the instability of input data and its impact on purchasing operations.

2.1.2 Schedule instability and nervousness

According to Pinedo (2012), rescheduling is a crucial part of production planning, providing a detailed plan to guide material purchasing. Also known as reactive scheduling, it addresses constraints such as demand changes, capacity limits, and material shortages. This process is vital for creating a practical and efficient supply chain schedule. He states that maintaining the stability of the initial schedule makes rescheduling easier, as fragile schedules require larger adjustments, confuse upstream processes, and lead to schedule instability and overall uncertainty. Small demand fluctuations can therefore cause disproportionately large changes in production plans and material requirements, especially in MRP systems (Herrera et al., 2016).

As a result, rescheduling becomes necessary to maintain an optimal production plan (Pinedo, 2012), but it also introduces nervousness and instability into scheduling structures. Based on Herrera et al. (2016), nervousness is characterized by frequent changes in production scheduling. Because the MPS outlines production capacities and timing over the planning horizon, it is updated frequently, leading to schedule shifts and instability. They believe scheduling nervousness arises from demand fluctuations and the constant need to revise plans. This issue affects production costs, inventory levels, and productivity.

According to Herrera et al. (2016), MPS considers production quantities and resource constraints. The plan aims to schedule production to reduce costs and maximize resource efficiency. Changes occur due to shifts in demand and operational factors such as supplier delays, production issues (e.g., machine breakdowns), and capacity fluctuations (Law & Gunasekaran, 2010). For example, a set of constraints might ensure that two jobs are not assigned to the same machine at the same time (Pinedo, 2012). Therefore, changes in demand lead to adjustments in the production plan, which can create scheduling uncertainty (Herrera et al., 2016).

In Figure 7 below, Law & Gunasekaran (2010) presents a structural model examining factors that influence schedule nervousness and overall performance. The findings indicate that internal operations have a statistically significant effect on both nervousness and performance. The results reveal that internal operations are positively correlated with collective efficacy (0.46) and negatively correlated with schedule nervousness (-0.24). The results indicate that improving internal operations through scheduling boosts efficiency and reduces nervousness. On the other hand, relationships with the supplier and the customer are connected to internal operations but do not have a significant direct effect on schedule nervousness.

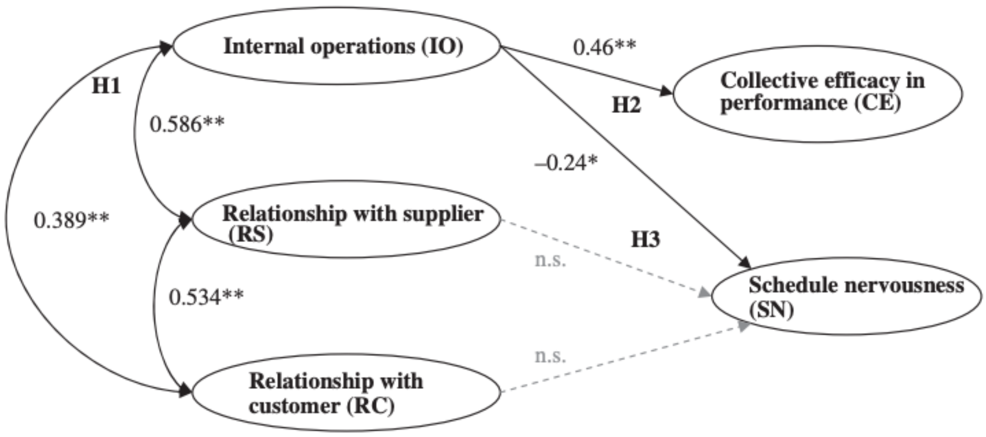

Figure 7. Factors affecting schedule nervousness (Law & Gunasekaran, 2010).

Law & Gunasekaran (2010) explain that variability in supply and demand leads to adjustments in production volumes, LTs, and product mix. In addition, frequent changes in production schedules may cause fluctuations in capacity utilization and increase operational costs as production plans guide material requirements and purchasing timing. They highlight that when the production schedule changes, material requirements change as well, leading to PO changes for suppliers, including advancements, postponements, and cancellations. Frequent schedule changes can cause disruptions in material availability, increase costs, and complicate production scheduling of the supplier.

Production planning can focus on both cost-efficiency and schedule stability. Herrera et al. (2016) emphasize that constant rescheduling increases instability, so stability should be prioritized in planning. They point out that, especially in rolling-planning-horizon environments, production schedules are updated frequently, leading to changes to previous plans. Instability and nervousness can be reduced by considering the impact of rescheduling on production and by limiting unnecessary changes. In their research, two models are compared with respect to costs, production smoothing, and instability: the first model (Mp) uses traditional rescheduling methods, and the second (Mi) aims to reduce instability.

In Figure 8 below, Herrera et al. (2016) illustrates the results of the Mp and Mi comparison across costs (fp), production smoothing (l), global instability (NG), and local instability (NL). The models' performance was assessed using an experimental design that measured production variability and instability during demand fluctuations. Based on the results, improving stability does not necessarily lead to a significant increase in costs. This shows that, in terms of production stability, volatility, and cost fluctuations, the Mi model slightly increases costs but notably reduces instability and nervousness. Based on the research of Herrera et al. (2016), minimizing instability is an effective way to reduce scheduling changes and maintain a balance between cost increases and production smoothing.

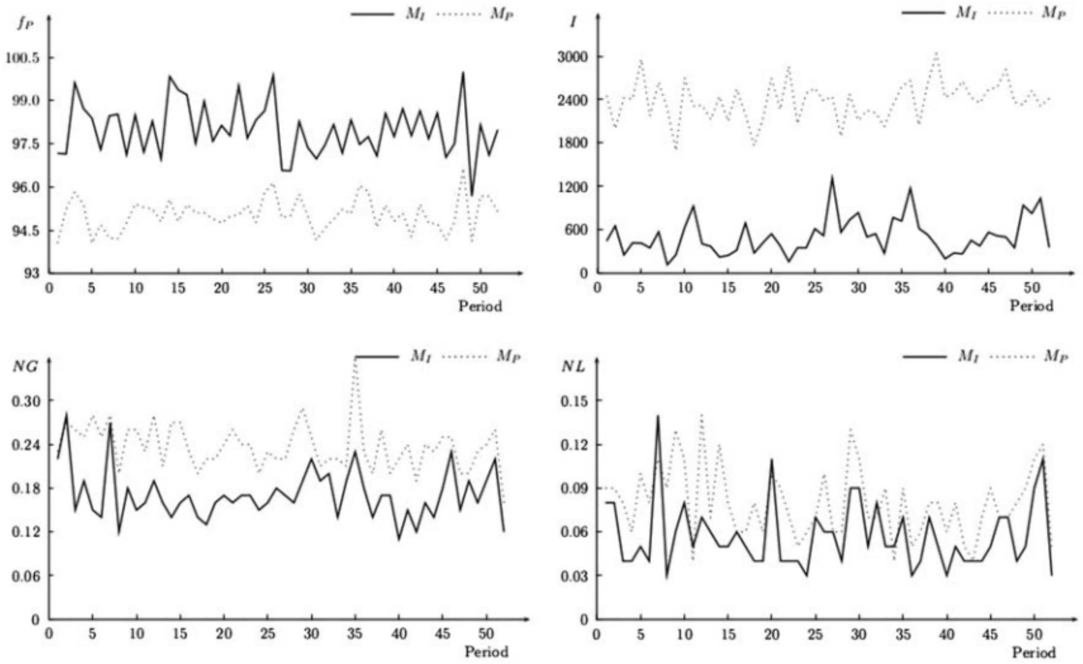

Figure 8. Comparison of costs and instability (Herrera et al., 2016).

In conclusion, nervousness and instability in scheduling systems reduce the efficiency of material flow, especially for external suppliers (Law & Gunasekaran, 2010). Unreliable material flow poses risks, including shortages and conflicts with inventory management. Therefore, unstable scheduling can render crucial components unavailable, leading to delays and lower customer satisfaction (Pujawan & Smart, 2012). Additionally, frequent changes increase the purchasing workload by requiring rescheduling and reactive decision-making (Herrera et al., 2016). Therefore, with reference to RQ1, scheduling structures characterized by instability and nervousness negatively affect material flows by affecting material availability, inventory trade-offs, and associated costs.

2.1.3 Requirement timing deviations and operational consequences

As mentioned earlier Slack et al. (2010), production scheduling involves assigning resources to tasks over a given period and determining the planned start timings for assemblies based on customer orders and forecast demand. Together, these elements form the MPS structure, which is integrated into the company's control systems. Control systems, such as MRP and ERP, connect data, using BOMs and inventory records to lay the foundation for POs, material plans, and work orders. This basic semantic model of an MRP-based system is illustrated in Figure 9 below. However, Law & Gunasekaran (2010) emphasize that production implementation rarely goes exactly as planned because demand changes, material availability, or production disruptions typically shift actual requirement timings relative to the original schedule, creating operational consequences.

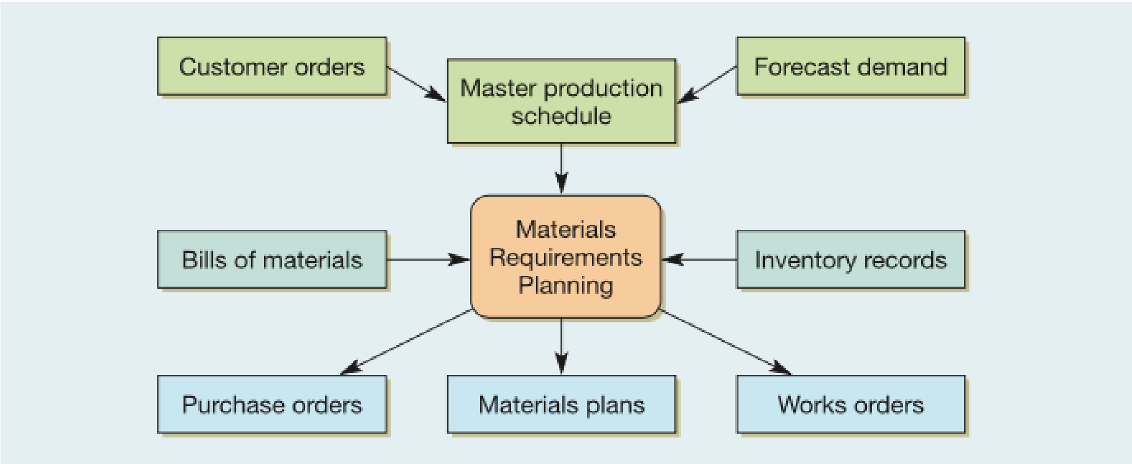

Figure 9. MRP schematic (Slack et al., 2010).

According to current literature, production planning relies on planned timelines, such as the SoA, requirement timings, and ex-works timings, which are essential for coordinating production activities (Slack et al., 2010). Herrera et al. (2016) describe a rolling horizon environment where demand fluctuations render earlier decisions outdated and necessitate new scheduling choices, leading to planned production quantities and requirement timings varying between scheduling cycles. On the other hand, Pinedo (2012) highlights that internal disruptions, such as machine breakdowns, may affect the implementation of scheduling structures.

Slack et al. (2010) discusses delivery reliability, which is how well an organization can produce products when needed. They define dependability as a general measure of operational performance, including the percentage of orders delivered late and the average order lateness. In short, it is the ability to do things on time. They highlight that externally, it is a key part of customer service, and internally, it adds stability and reduces the time and cost of fixing reliability issues. Pinedo (2012) also points out that late deliveries can have operational consequences. For example, lateness on committed delivery timings can lead to sanctions or a loss of goodwill.

Christopher (2009) emphasizes that timely delivery becomes a critical competitive factor when JIT delivery targets are set. According to him, timeliness, meaning completing orders on schedule, becomes a key factor in winning business. Additionally, he notes that long delivery times increase forecasting inaccuracies and inventory requirements. Therefore, requirement date deviations are not only internal production issues but also reduce delivery reliability. Figure 10 illustrates the use of the JIT model toward an integrated supply chain with minimal inventory, smooth material flow, and high-quality customer service.

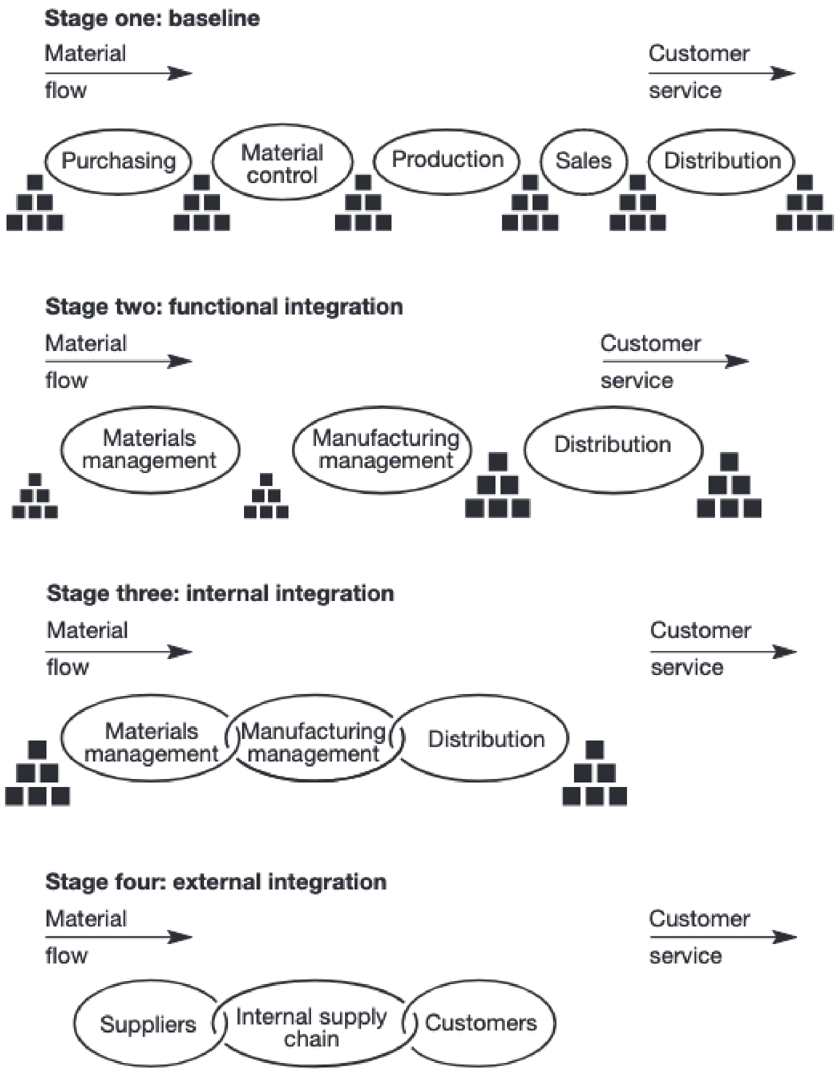

Figure 10. An integrated supply chain (Christopher, 2009).

Christopher (2009) highlights that all forecasts contain errors and that forecast error typically increases with longer forecast horizons, as shown in Figure 11. Additionally, links market volatility, long delivery times, and inventory needs. On the other hand, Abolghasemi et al. (2020) shows that demand fluctuations complicate forecasting, increasing the risk of errors and reducing overall supply chain performance. This is especially true for inventory, delivery, and capacity utilization. Execution errors result from operational disruptions in production and the supply chain. Law & Gunasekaran (2010) list scrap, production overruns, fluctuations in supplier LTs, machine malfunctions, and tooling-related issues as examples of execution errors.

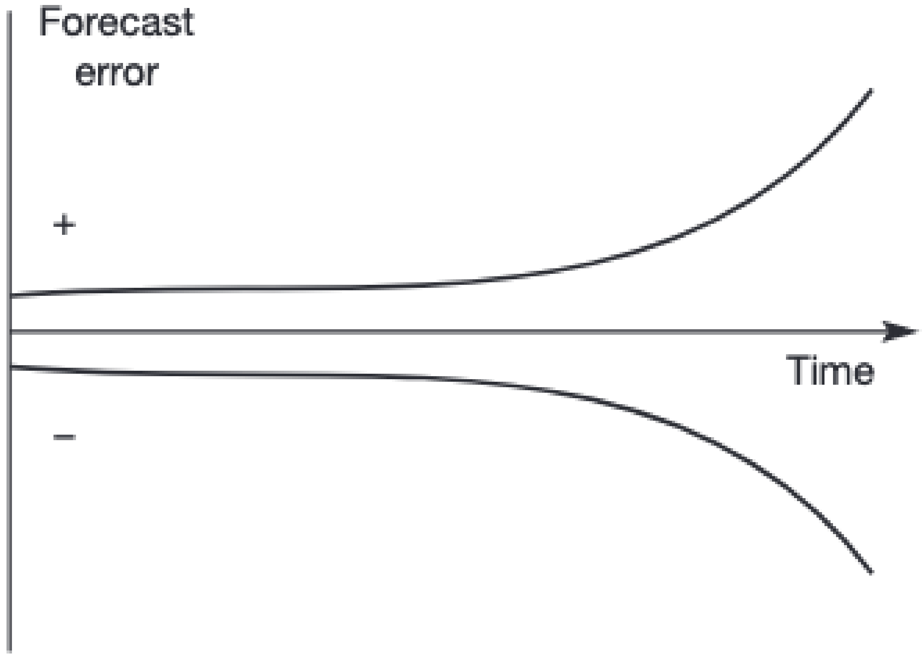

Figure 11. Forecast error in planning horizons (Christopher, 2009).

Law & Gunasekaran (2010) break down the root causes of requirement timing deviations in scheduling structures into internal operations and supply chain partnership factors. They list the trustworthiness of the production scheduling system, personnel planning and scheduling skills, time-fencing practices, and system flexibility as key internal factors. External root causes include demand uncertainty, customer order changes to quantities and timings, and supplier late deliveries. Pinedo (2012) supports this classification from the scheduling perspective, which emphasizes that production scheduling is influenced by both internal and external root causes.

In conclusion, production scheduling relies on planned timelines that guide material requirements and purchasing in MRP- and ERP-based systems (Slack et al., 2010). Based on the reviewed literature, planned scheduling structures usually deviate from actual execution due to demand fluctuations, material availability issues, and production interruptions (Christopher, 2009; Herrera et al., 2016; Law & Gunasekaran, 2010; Pinedo, 2012). These requirement timing deviations modify purchasing timings and requirements, affecting the scheduling process. Referring to RQ1 and RQ2, scheduling structures and deviations between planned and actual requirement timings affect material flows by influencing availability, delivery times, and reliability.

2.2 Product structure complexity and material flow synchronization

Product structure complexity is critical in manufacturing systems because multi-level BOMs create dependencies among components and production orders (Stadtler, 2005). In these environments, synchronizing production scheduling with material flows is crucial to ensure material availability and efficient overall operations (Chankov et al., 2018). When scheduling and purchasing are aligned, delivery timing improves, but weak synchronization can lead to material shortages and excess stock (Ghasemi et al., 2023; Stadtler, 2005). Increasing product structure complexity and demand uncertainty can complicate this alignment and disrupt material flow management (Atadeniz & Sridharan, 2020). This second section examines how BOM complexity and synchronization affect material flows and guides the thesis toward answers to the RQs.

2.2.1 BOM complexity and ripple effects

According to Slack et al. (2010) production structure, the BOM describes the composition of the final product and defines dependencies among components and subassemblies. In multi-level BOM structures, as in Figure 12, demand for the final product is broken down across several component levels, and material requirements and their timing are driven by upper-level production scheduling plans. They note that the same component can appear multiple times in the BOM structure, which requires aggregating unique needs into a total demand. Therefore, the BOM structure serves as a key mechanism linking production plans to material requirements and SCM.

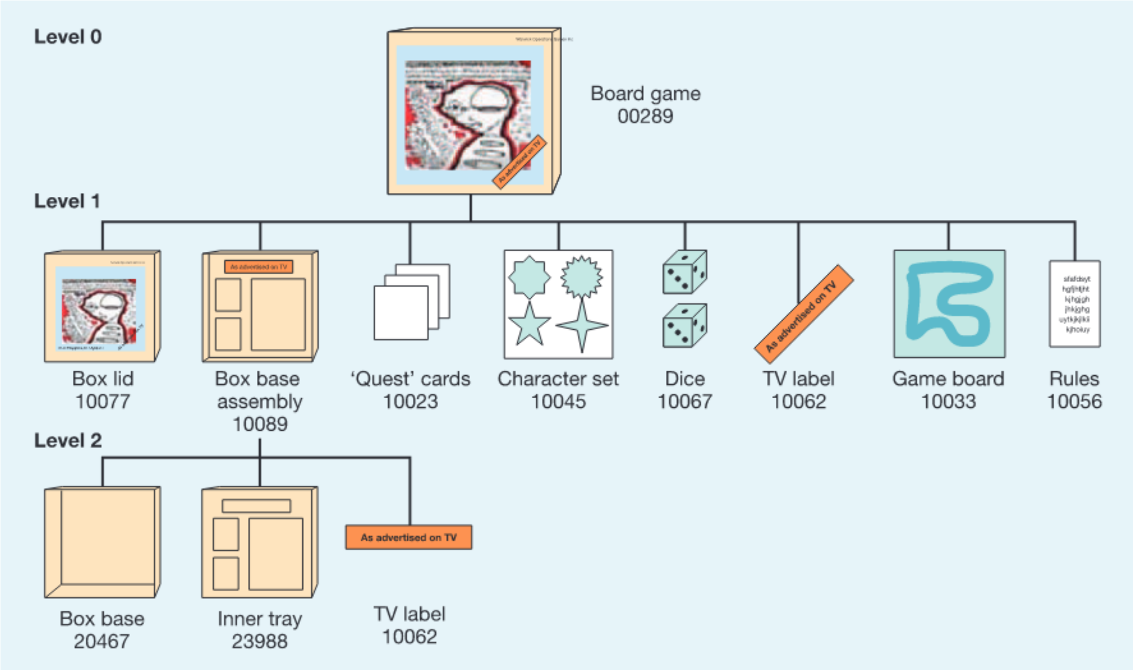

Figure 12. Example of a product structure (Slack et al., 2010).

Slack et al. (2010) continue from a purchasing perspective, with the key factor being how production schedules are converted into purchasing control signals. In MRP systems, the master schedule is broken down through the product structure (BOM explosion). Material requirements are then netted against inventory levels and scheduled backward (back-scheduling), accounting for component LTs. This MRP-related netting process is shown in Figure 13, where material requirements are determined by the MPS and BOM structures. Therefore, production scheduling also specifies material requirement schedules from the purchasing perspective.

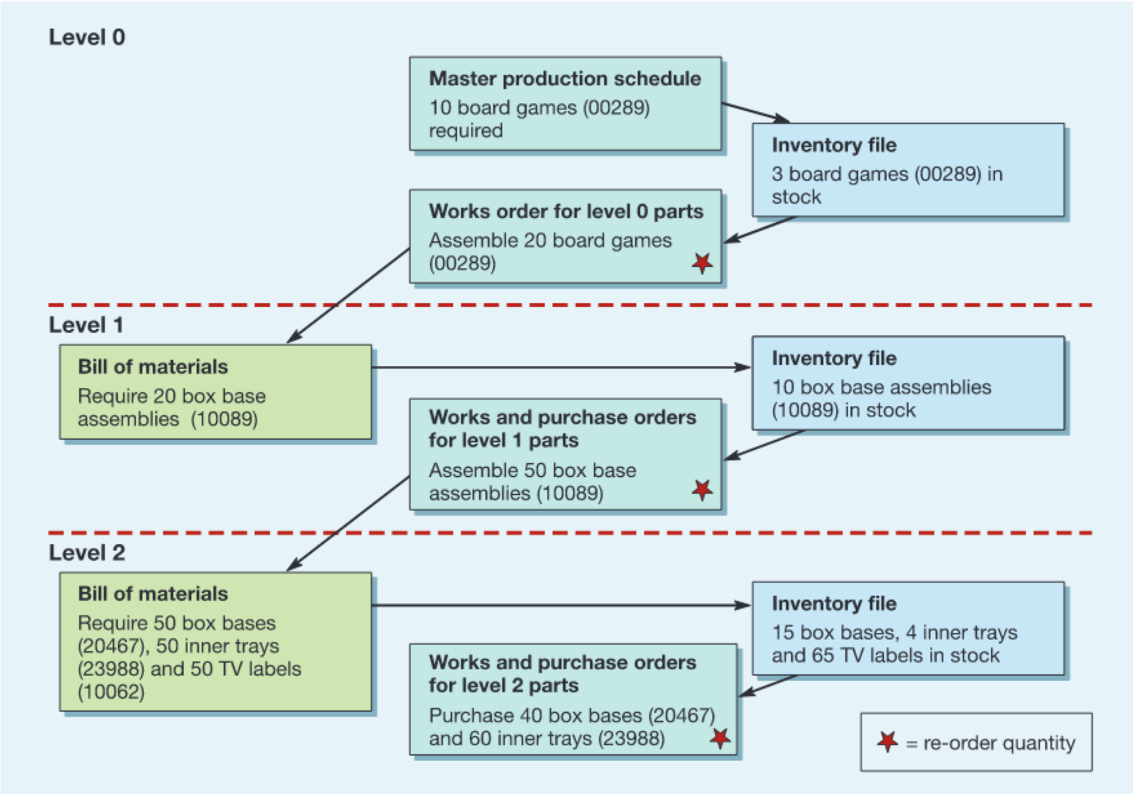

Figure 13. MRP netting process (Slack et al., 2010).

In the literature, production structure is analysed within a broader context in which BOM is linked to process and supply chain structures. Salvador (2007) defines it as product modularity, in which components are grouped into modules that affect production and supply chain structure. In this regard, Fixson (2007) examines the common use of components (commonality), where the same materials can be used across several products. This kind of structure can enhance purchasing performance by integrating material requirements and streamlining material flow management (Christopher, 2009). Meanwhile, it can reduce inventory needs and improve material availability in supply chains.

On the other hand, BOM complexity introduces dependencies among component levels and material flows. Based on Ivanov (2017), this can increase the need for coordination and sensitivity to changes, as shifts in the availability or scheduling of individual components can affect multiple products simultaneously. Therefore, BOM structures have a two-way effect on purchasing performance, as modularity and commonality can improve efficiency and controllability. At the same time, added dependencies can complicate material flow management by increasing operational complexity. Regarding RQ1, BOM complexity affects material flows by determining how scheduling translates into requirements, thereby affecting the availability, timing, and coordination of purchasing activities.

2.2.2 Flow variability and inventory trade-offs

Material flow variability arises when demand, delivery times, and production schedules fluctuate, causing instability in supply chains. Slack et al. (2010) describe how inventory depends on fluctuations between supply and demand, with uncertainty in demand and delivery times increasing the importance of buffers and safety stock. When demand or LTs shift, reordering should occur before a deterministic situation arises to reduce the risk of stockouts. In such cases, buffer stock increases, while short-term material availability can be better safeguarded.

In current research, material flow variability is also studied as part of a broader issue connected to supply chain dynamics. Croson et al. (2014) describe the bullwhip effect as the growing fluctuations that occur as demand information moves upstream in the supply chain, as shown in Figure 14. They explain that the bullwhip effect means that order variability increases as you go further upstream, leading to excess inventory, recurring shortages, poor customer service, and unnecessary capital allocation. On the other hand, Ouyang & Li (2010) define the bullwhip effect as the increasing variation in orders within supply chain networks and emphasize that it leads to high additional costs.

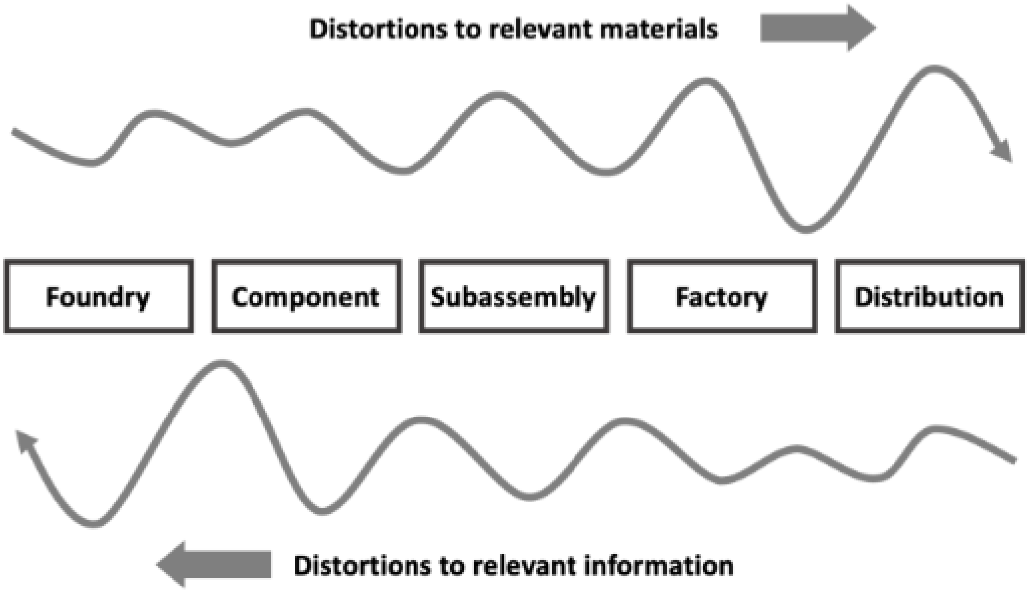

Figure 14. The bullwhip effect (Jaakkola, 2023).

From a production planning perspective, scheduling instability further increases variability in material flow. Law & Gunasekaran (2010) suggest that scheduling nervousness leads to order rescheduling when internal systems and supplier functions are disrupted. Ongoing scheduling changes can cause fluctuations in capacity utilization, rescheduling costs, delivery schedule disruptions, increased inventory, and premium freight costs. Therefore, instability in scheduling structures not only affects planning but also alters purchasing rhythm and material flow management.

According to the literature, inventories primarily serve as buffers against such fluctuations, but they entail a clear trade-off. Christopher (2009) explains lead-time gap problems, in which most organizations have a longer procure-to-make-to-deliver process than the customer's approved waiting time. The traditional way to address this is through inventory, which involves creating forecast-based stock levels based on estimated demand. At the same time, he emphasizes that time in the pipeline includes significant cost-adding time, and that pipeline management aims to eliminate blockages and fractures that cause inventory buildup and longer response times (Figure 15). In other words, inventories can support service levels, but they also incur costs and conceal the longer response times of the process.

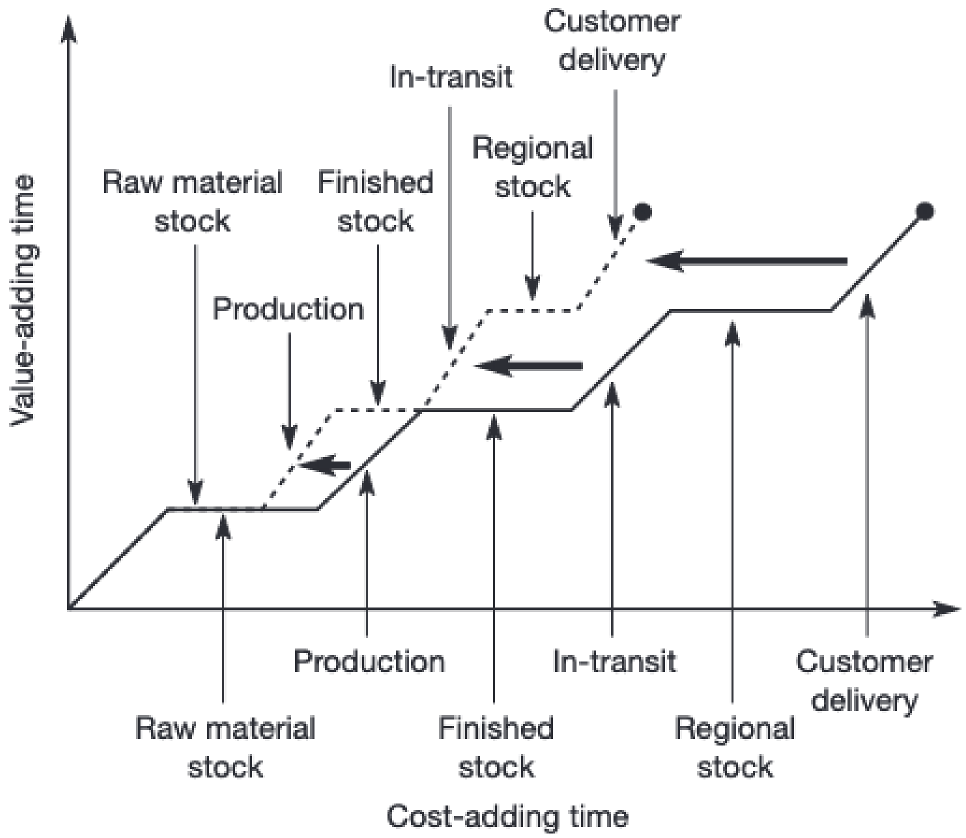

Figure 15. Reducing non-value-added time enhances performance while lowering costs (Christopher, 2009).

Croson et al. (2014) provide a perspective on inventory trade-offs in material flow management. Their research shows that additional coordination stock reduces order oscillation and amplification, even though it does not eliminate the risk of coordination. They differentiate between traditional safety stock and coordination stock: safety stock addresses demand and delivery reliability issues, while coordination stock protects against strategic uncertainties arising from supply chain stakeholders' decisions. Based on their research, coordination stock can, in some cases, reduce variance and total costs if backlog costs are significant.

In conclusion, material flow variability is linked to changes in delivery times, demand, and orders, and these are managed with buffers such as safety stock (Christopher, 2009; Law & Gunasekaran, 2010; Slack et al., 2010). These safety buffers can improve material availability and delivery reliability, but they also add inventory and tie up capital. Therefore, in material flow management, the key issue is the trade-off between inventory shortages and excess inventory. Regarding the RQs, scheduling instability and deviations increase material flow variability, affecting purchasing through availability risks, fluctuating orders, and inventory trade-offs.

2.2.3 Alignment between scheduling and purchasing

SCM is defined by Stadtler (2005) as coordinating a network within an organization, where the integration of materials, information, and cash flows facilitates meeting customer needs and boosting competitiveness. This network is visualized in Figure 16 below as the house of SCM, where the foundations are linked to increased competitiveness through integration and coordination among process stakeholders. At the core of SCM are the processes related to order fulfilment and the associated flow. From an operations management point of view, Slack et al. (2010) views production as a supplier-input-process-output-customer process, in which materials and information flow through the system, forming the core of manufacturing. Therefore, scheduling and purchasing are part of the same whole, in which planning and execution are linked together.

Within an SCM framework, purchasing is essential for ensuring material availability for production and supporting ongoing operations. Based on Slack et al. (2010), purchasing can be seen as a process that transforms demand information into procured materials through supplier selection, PO creation, and delivery management. This process usually includes supplier assessment, agreement negotiations, PO timing, and delivery follow-up. Stadtler (2005) highlights that purchasing is tightly integrated with other supply chain processes, especially MPS, because it is heavily dependent on demand and scheduling information.

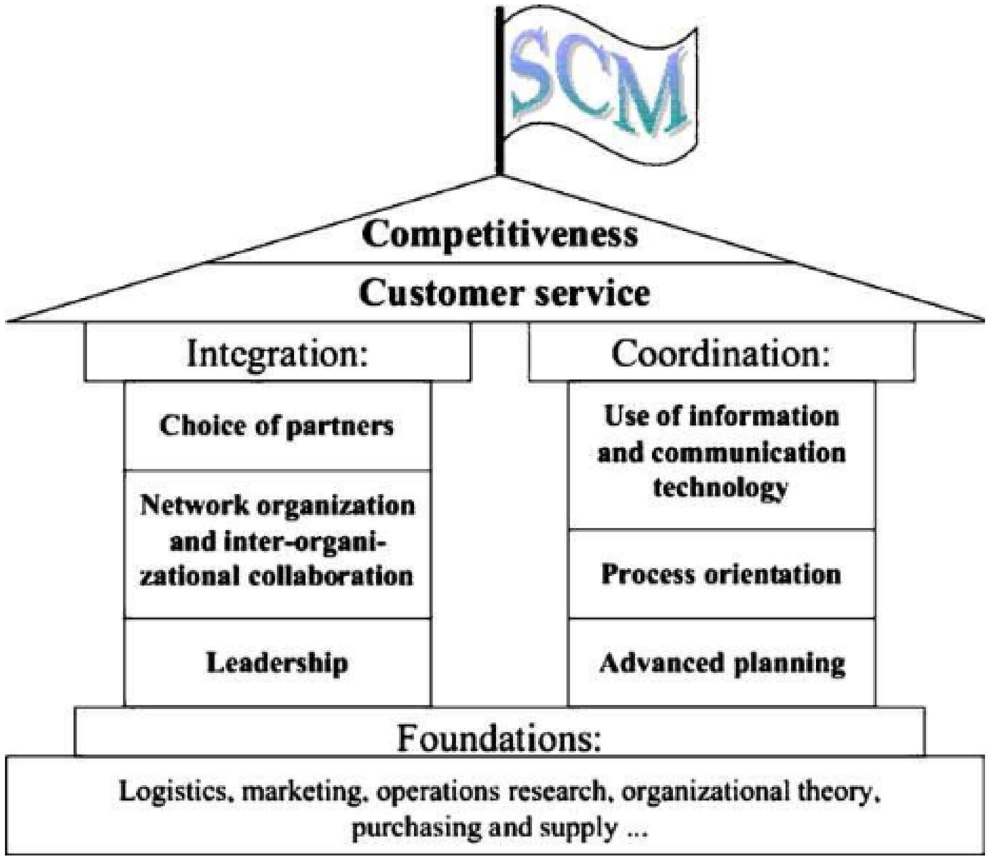

Figure 16. The core of SCM (Stadtler, 2005).

From the system's perspective, purchasing serves as a bridge between external suppliers and internal manufacturing, requiring the synchronization of both information and material flows. As shown in Figure 17, this connection illustrates the forecasting-driven purchasing process, linking external suppliers to internal production activities. Zhao & Lam (1997) brings out that in multi-stage manufacturing environments, purchasing decisions are directly dependent on production schedules via MRP systems. This means scheduling variations are reflected upstream in purchasing operations, affecting order batches, timing, and supplier collaboration. This interdependence highlights the need to synchronize purchasing decisions with scheduling structures to ensure cost efficiency and operational stability.

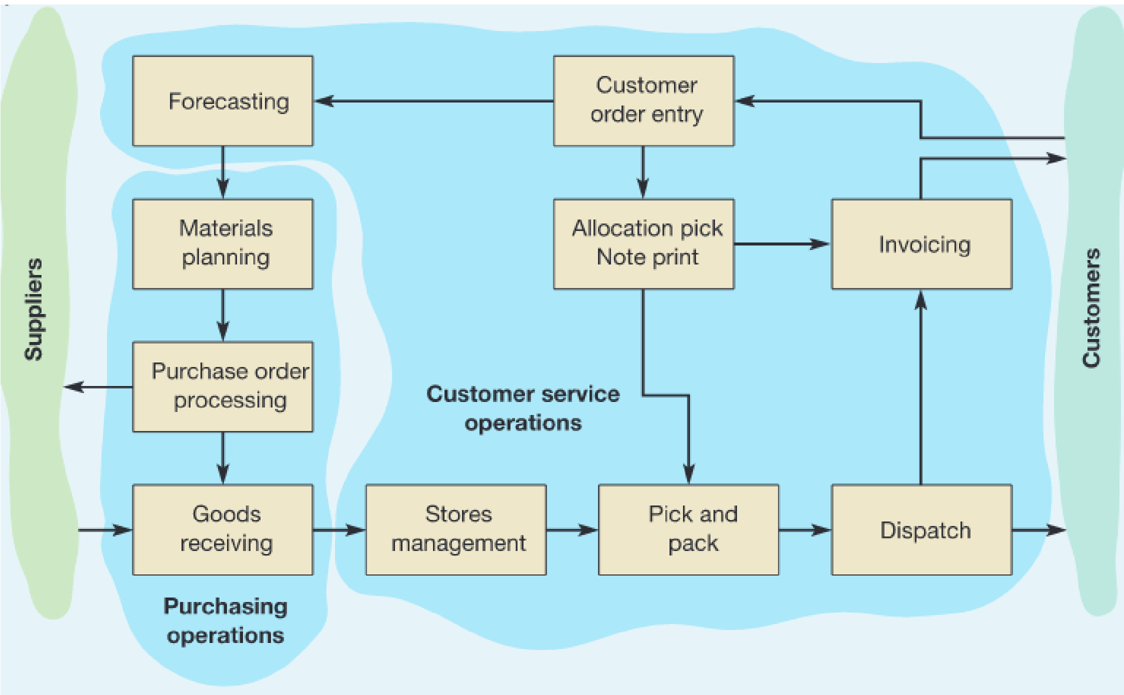

Figure 17. Purchasing operations as a link between external suppliers and internal processes (Slack et al., 2010).

The alignment between scheduling and purchasing is achieved through MRP and production planning. Zhao & Lam (1997) highlight that MRP systems connect schedules and material requirements in multi-stage production systems. In practice, production schedules, such as the MPS, control material purchasing and availability. Minor changes in upper-level requirements can lead to significant variation in lower-level requirements, directly affecting purchasing operations. This phenomenon, also known as scheduling nervousness, may lead to production disruptions, material shortages, and rising costs. The literature also suggests ways to mitigate the effects of nervousness, such as freezing periods and lot-sizing rules.

As mentioned in the previous sections, there are multiple recognized ways to coordinate scheduling and purchasing. Zhao & Lam (1997) especially present production schedule freezing (MPS freezing) as an effective way to reduce the effects of scheduling instability. Also, lot-sizing rules significantly impact both costs and schedule reliability. Their research shows that freezing periods and lot-sizing rules work together to improve MRP system performance. Additionally, in multi-level production systems, these effects are more pronounced because scheduling changes propagate throughout the BOM structure, affecting multiple material flows simultaneously. In conclusion, this section shows that scheduling structures directly affect material flow through MRP. Therefore, with respect to the RQs, analysing schedule stability and changes is vital for evaluating material flow performance.

2.3 Modelling and analytical approaches for data analysis

Modelling approaches are widely used in production scheduling and material flow interface analysis because they enable a systematic review of system operations and performance (Pinedo, 2012). Mathematical models can be used in production planning to analyse scheduling decisions and their impact on instability and costs in dynamic manufacturing settings (Herrera et al., 2016). Additionally, modelling helps to analyse uncertainty arising from fluctuating demand and forecasting errors, which affect planning accuracy and system performance (Abolghasemi et al., 2020; Fildes & Goodwin, 2021). These modelling approaches provide a foundation for requirement data analysis and help explain how scheduling structures influence material flows, guiding the thesis toward relevant results.

2.3.1 Process modelling in manufacturing

Slack et al. (2010) defines process modelling as a method for illustrating how a production system transforms inputs into outputs. This input-process-output thinking is a central model in operations management (Figure 18). Additionally, Munro et al. (2015) bring out Six Sigma thinking by viewing processes as interconnected entities, with each stage forming a hierarchical structure (process, subprocess, step). Process modelling is implemented by describing production process steps and dependencies, for example, using flowcharts like the one in Figure 18. The flowcharts help to recognize material and information flow and process steps.

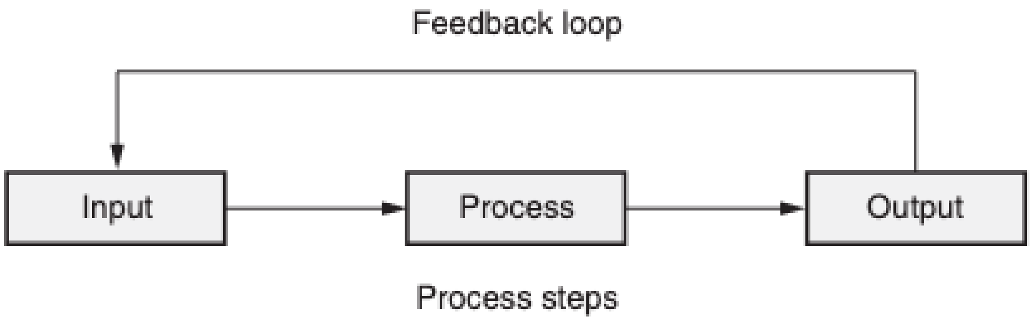

Figure 18. Process steps with feedback loop (Munro et al., 2015).

Modelling also enables the review of feedback loops (Figure 18), in which process performance is measured and continuously guided (Munro et al., 2015). Therefore, it can be analysed how changes that occur together in the process affect the entire system. In scientific and academic research, process modelling is used especially for the analysis and development of production systems. In the SCM context, Stadtler (2005) integrates modelling more broadly into Advanced Planning Systems (APS), in which production and material flow management are reviewed as an integrated whole (Figure 19).

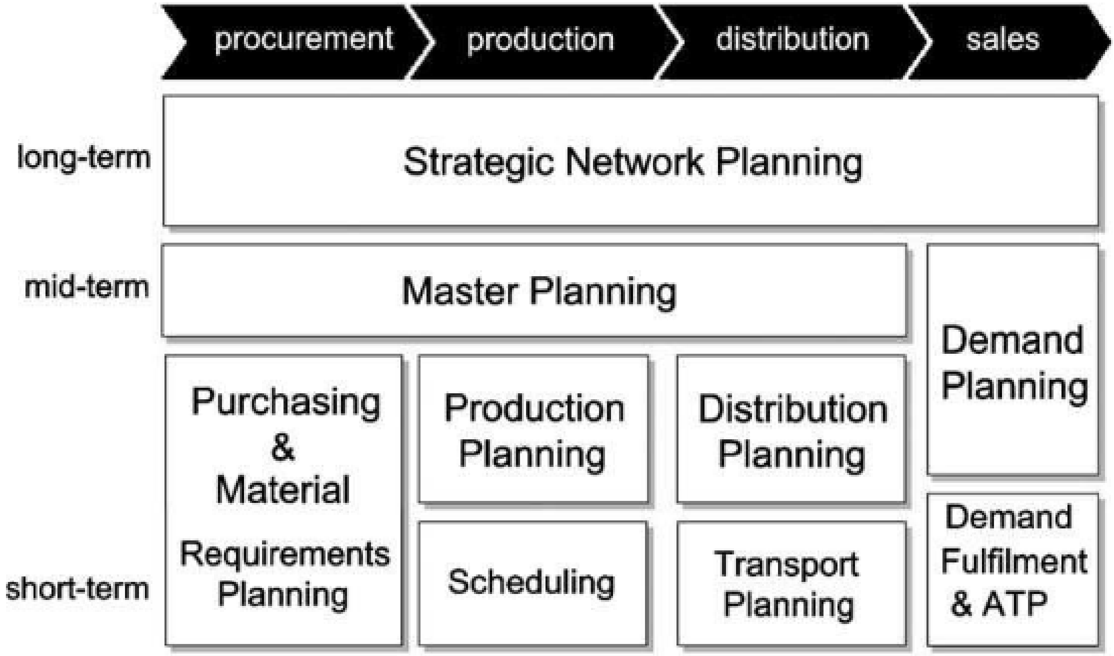

Figure 19. The integrated whole of SCM (Stadtler, 2005).

In conclusion, process modelling supports decision-making by enabling analysis of different scenarios without altering the entire planning system. This is especially important for complex supply chains, where the impact of changes can be significant. Process modelling offers a way to analyse how modifications to scheduling structures influence material flow. It helps identify the mechanisms by which schedule adjustments affect the system and evaluates their impact on production performance, supporting the process of answering the RQs of this thesis.

2.3.2 Data-driven manufacturing analytics

Schoenherr & Speier-Pero (2015) defines data-driven analytics in SCM is the use of quantitative and qualitative methods for production and supply chain planning and decision-making. It belongs to the broader field of data science, which combines methods from various scientific disciplines to make forecasts and improve performance. As Figure 20 shows, data science and data scientists combine data management, business decision-making, and analysis tools. Analytics uses large datasets generated across different production and supply chain stages. These datasets help identify demand fluctuations, operational problems, and forecast future events. Therefore, efficient use of analytics requires data availability, data quality, and the skills to integrate disparate data sources to support decision-making processes.

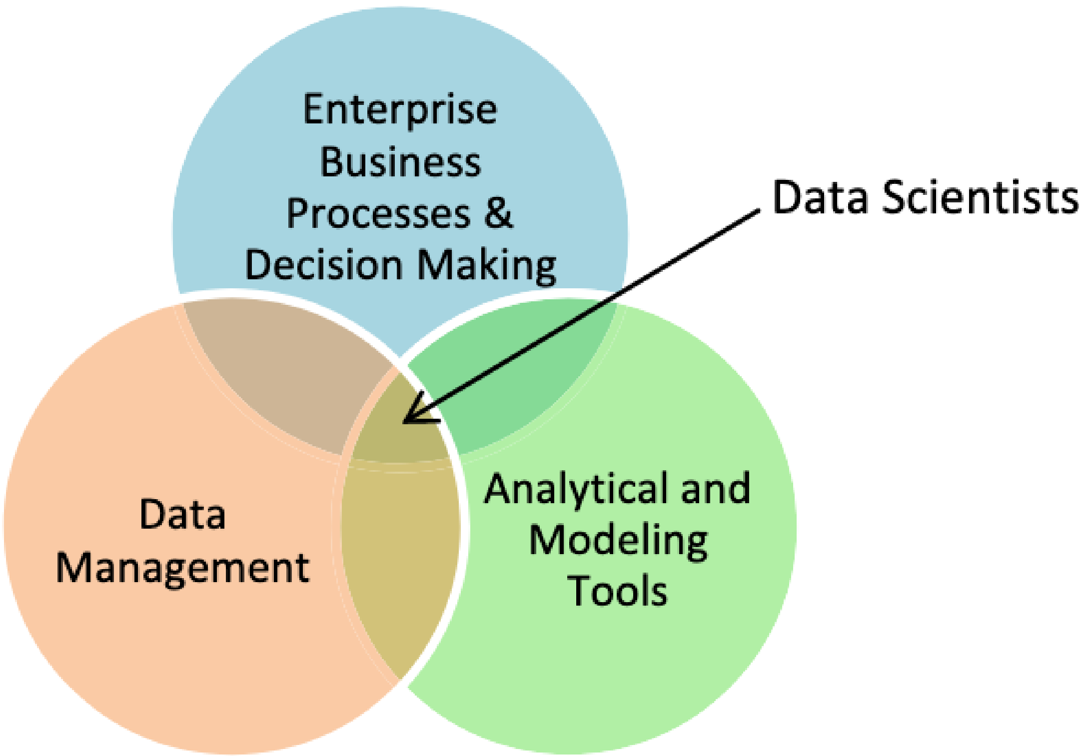

Figure 20. Data science skillsets (Schoenherr & Speier-Pero, 2015).

Based on Schoenherr & Speier-Pero (2015), the use of analytics in supply chains is increasing, but utilization varies significantly across organizations. Some organizations use analytics widely, while others do not use it at all or are unfamiliar with it. Additionally, challenges such as skill gaps and implementation difficulties may limit the potential of data analysis. Data-driven analytics enables quantitative analysis of how scheduling structures affect material flow. It also enables measurement of the effects of schedule changes on factors such as delivery reliability and inventory levels, thereby supporting empirical answers to RQs.

2.3.3 Synthesis of literature and research gap

The literature reviewed in Chapter 2 indicates that production scheduling, material flow management, and purchasing are closely interlinked in manufacturing systems. Production scheduling determines the timing and sequence of operations, which in turn guide material requirements timings and purchasing activities through MRP and ERP systems (Jacobs et al., 2018; Javadi et al., 2025; Pinedo, 2012). However, scheduling structures are dynamic because demand fluctuations, operational disruptions, and capacity constraints necessitate continuous replanning, leading to instability and nervousness (Herrera et al., 2016; Law & Gunasekaran, 2010). These changes affect the entire system and lead to deviations between planned and actual requirement timings, which in turn affect delivery reliability, material availability, and operational performance (Christopher, 2009; Slack et al., 2010).

In addition, product structure complexity and material flow synchronization shape how scheduling decisions translate into purchasing activities and flows. Multi-level BOM structures create dependencies among components, amplifying the effects of scheduling changes throughout the system (Fixson, 2007; Salvador, 2007; Stadtler, 2005). Simultaneously, demand, LT, and scheduling variation introduce uncertainty into material flows and require balancing inventory levels and material availability (Christopher, 2009; Croson et al., 2014; Slack et al., 2010). Then, modelling approaches and data-driven analytics provide tools for systematically reviewing these phenomena, enabling analysis of scheduling structures, deviations, and their effects on material flows using operational data (Herrera et al., 2016; Pinedo, 2012; Schoenherr & Speier-Pero, 2015).

From a research gap perspective, there is limited systematic research examining ERP-based case data on production scheduling structures, particularly deviations between planned and actual requirement timings. Additionally, only a few studies empirically link schedule stability and deviations to purchasing performance and material flow in a manufacturing context. The impact of both scheduling structure stability and deviations on purchasing performance remains underexplored. This thesis addresses this research gap by analysing ERP-based data on scheduling structures and requirement timing deviations, and by linking these insights to material flows (Figure 1). Therefore, this research provides empirical evidence from the scheduling and purchasing interface and supports data-driven decision-making to improve material flow.

3 Methodology

This third main chapter of the thesis, the methodology, outlines the research design, data sources, and analytical techniques to ensure clarity and reproducibility. The study relies on the case company's secondary operational data. It provides a current-state analysis of production scheduling structures, deviations between planned and actual requirement timings, and the impact of these deviations on material flow performance. This chapter is divided into three sections. The first section (3.1) covers the research design, case context, and data, while the second section (3.2) details the variables used in the analysis, including their operationalization and the analytical methods. The third section (3.3) assesses the study's validity and reliability.

3.1 Research design, case context, and data

This thesis is conducted as a case study, an established empirical approach for analysing real-world processes using organizational data (Flynn et al., 1990; Yin, 2009). The primary data source is operational data retrieved via SQL queries from the case company's ERP-based databases. This is supplemented by the company's internal reports, such as Power BI and Excel reports, which are used especially to analyse variables describing material-specific material flow performance, such as inventory levels and material availability. All data are integrated and transferred to Power BI for processing, modelling, and analysis. The resulting semantic model, illustrated in Figure 21, comprises two complementary components and is restricted to a single product line entity, covering twelve projects (Appendix 1) and materials under the responsibility of the purchasing function.

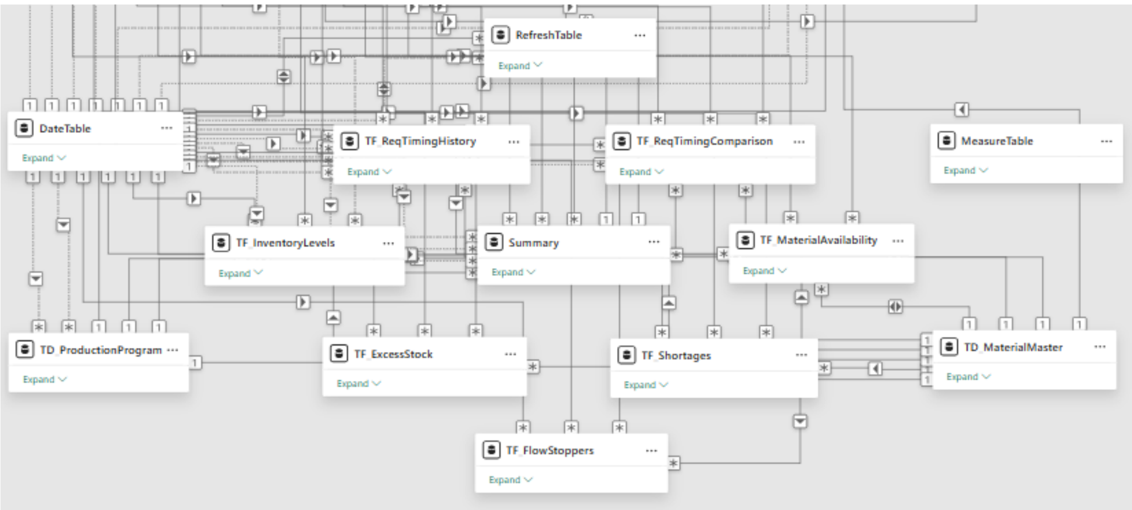

Figure 21. Power BI semantic model.

The first dataset includes planned requirement timings and their historical information across planning cycles. This data is used to analyse the stability of scheduling structures and comprises several million change entries, representing roughly two hundred thousand distinct material requirements and tens of thousands of unique project-material combinations, covering over a thousand anonymized material items. The second dataset includes both planned and actual requirement timings. The actual requirement timing is the point by which the material must be received and recorded as in stock, typically shortly before the requested delivery to production. This dataset is used to analyse requirement timing deviations and comprises a few tens of thousands of cases, representing unique project-material combinations and covering over a thousand anonymized material items. A portion of materials was excluded due to incomplete data availability for subcontracted components.

The unit of analysis is the requirement timing of material, defined relative to the SoA. The data are analysed using multiple categorical variables. Materials are classified into delivery-time categories based on total LT, which combines LT, goods receipt time, and safety time. The classes are defined as follows: short, medium, and long. Additionally, the data are classified by PGR, PR, and project. These classifications enable analysis of scheduling structures and material-flow phenomena across organizational and structural levels. To ensure confidentiality, all company-specific identifiers, including project structures, material-level information, and financial data, were anonymized. Component-level data were grouped into broader categories, and project identifiers were replaced with generic labels. In addition, numerical values were generalized or scaled where necessary, and requirement timings are expressed as relative timing measures instead of absolute calendar-based values. These transformations preserve analytical validity while preventing identification of the case context.

3.2 Operationalisation and analytical methods

The empirical analysis employs descriptive, comparative, and relational approaches to examine the data. This type of empirical analysis is widely used in operations management research (Flynn et al., 1990; Ketokivi & Choi, 2014). The analysis proceeds systematically, with data extracted via SQL queries and internal reports, integrated from multiple sources, cleaned, modelled, and analysed in a Power BI environment, where key metrics are calculated and results are visualized. The applied metrics are derived from established concepts in the literature and operationalized to fit the structure of the available data.

The analysis is divided into three main components aligned with the RQs, examining schedule structures, deviations from the actual situation, and their impact on material flow. The first component assesses schedule stability by tracking changes in planned requirement timings. To do so, the number of changes, the magnitude of changes (in units), the difference between the first and last planned requirement timings, and temporal dispersion relative to the SoA are computed (Appendix 2). These metrics draw on established concepts of schedule instability and nervousness in the production scheduling literature (Herrera et al., 2016; Pinedo, 2012). Results are analysed by projects, PRs, PGRs, and LT classes to pinpoint where schedule instability is most pronounced within the system.

The second component analyses deviations between planned and actual requirement timings. A deviation is defined below as the difference between the planned and actual requirement timings, measured in units. A positive value indicates a delay, while a negative value indicates an early occurrence. The analysis covers the distribution of deviations, their direction (early vs. late), frequency, and temporal development (Appendix 2). Deviations are also examined across classifications, including projects, PRs, PGRs, and LT classes. Deviations between planned and actual requirement timings reflect aspects of operational performance, particularly material availability and dependability (Slack et al., 2010).

Deviation (units) = Actual Requirement Timing – Planned Requirement Timing

The third component of the analysis examines the relationships among schedule stability, deviations, and material flow performance. In this phase, ERP-derived metrics are combined with internal company reports on inventory levels, material availability, and shortages. The analysis focuses on identifying systematic relationships between schedule instability, deviations, and material flow performance metrics across classifications. The reliability of the analysis is supported by consistent ERP-based data, systematically defined metrics, and clearly documented analysis steps, with data extraction logic and calculation methods in Appendix 2.

3.3 Validity and reliability

The validity of the thesis is supported by operational ERP data that illustrate real-world production scheduling and material flow events. The metrics used in the research are derived from concepts identified in the literature review, such as scheduling structure instability, deviations between planned and actual requirement timings, and material flow performance, and are operationalized to align with the structure of existing data. Additionally, the research is directed to a clearly defined case environment, which enables examination of the relationship between scheduling structures and material flow within a unified operational context.

The reliability of the study is reinforced by a systematic, repeatable analysis process. Data is collected from ERP systems via SQL queries and from the purchasing function's internal Power BI and Excel reports. The data is then combined and analysed in a unified Power BI environment. The calculations, logic, and analysis steps for the metrics are clearly documented in the research (Appendix 2), supporting the reproducibility of the analysis. The analysis also relies on standardized classifications, such as total LT categories, PGRs, PRs, and projects, which improve the comparability of results across various levels of analysis.

4 Results

The fourth main chapter of this thesis, the results, presents outcomes of the empirical analysis based on operational ERP data and relative metrics. The objective is to illustrate the scheduling structure's behaviour, deviations between planned and actual requirement timings, and their effects on material flows. The results are presented descriptively, without theory. This main chapter is divided into three key sections in accordance with the RQs (Figure 22). The first section (4.1) reviews the stability of the scheduling structure and the behaviour of planned requirement timings. The second section (4.2) analyses deviations between planned and actual requirement timings. The third section (4.3) examines the effects of stability and deviations on material flows and purchasing performance. Finally, the last section (4.4) summarizes the key results found in the previous parts. The results are presented by projects, PRs, PGRs, and total LT categories, enabling a broader analysis of the data.

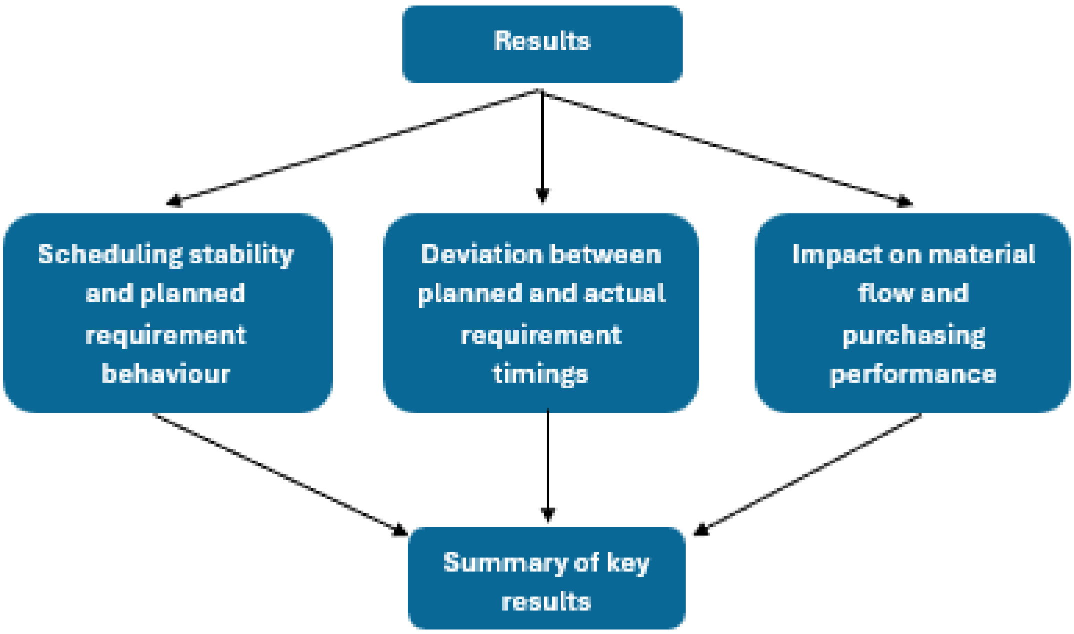

Figure 22. Structure of the results section.

4.1 Scheduling stability and planned requirement behaviour

This first results section reviews the stability of scheduling structures in a complex manufacturing environment and the behaviour of planned requirement timings. This section of the analysis visualizes how planned requirement timings are positioned relative to the planned start of production activities (SoA), the magnitude of variations in planned requirement timings, and how often and by how much planned scenarios change. The review describes metrics for scheduling changes, such as change count, change magnitude, and total variation of requirement timings. The results are presented with segmentation into different classes, such as projects, PRs, PGRs, and total LTs, to identify where scheduling stability is emphasized. Additionally, the analysis examines the temporal evolution of changes, enabling evaluation across planning cycles. Figure 23 presents a dashboard illustrating scheduling stability patterns.

Figure 23. Scheduling stability dashboard (Section 4.1).

4.1.1 Planned requirement timing relative to SoA

This subsection (4.1.1) examines the timing of planned requirement timings and PO structures relative to the SoA. The aim is to describe the general temporal behaviour of requirement timings and purchasing activities in the analysed data set before a more detailed analysis of instability and deviation. Figure 24 below shows the planned requirement timings (in orange) and the PO timings (in blue) relative to the projects' SoA timing. The lighter colour represents the first timing in the data, and the darker colour represents the last timing, illustrating changes across planning cycles. The line chart plots the count of distinct requirements on the y-axis and the offset from the SoA on the x-axis. The chart also includes a horizontal reference line at 0 (the SoA) for comparison.

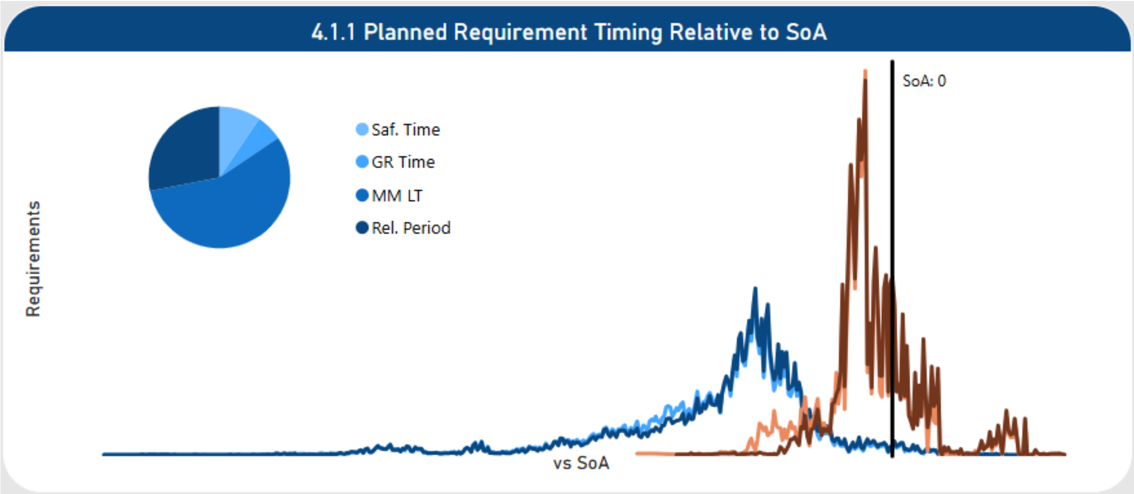

Figure 24. Planned scheduling structure in relation to SoA.

The PO timing (blue line) is derived from planned requirement timing (orange line) using safety times, goods receipt times, and LTs defined in the ERP system. The results show that planned requirement activity is concentrated before the SoA. The highest requirement peak occurs at approximately -13 units relative to the SoA, while the overall average requirement timing is around -8 units, as requirement activity continues after the SoA. Based on requirement timings, purchasing activities are widely distributed due to varying safety buffers, goods receipt times, and delivery times. The highest volume occurs broadly between -120 and -40 units, and purchasing timelines start well before the SoA, with an average of -80 units and a peak of -65 units. Purchasing activity decreases as the SoA approaches, indicating front-loaded purchasing behaviour. Additionally, Table 1 below shows the distribution of averages by project:

Table 1. Project-specific planned requirement timing structures.

Project	Average PO Relative to SoA	Average Requirement Relative to SoA
Project 1	-86 units	-14 units
Project 2	-83 units	-11 units
Project 3	-83 units	-11 units
Project 4	-78 units	-6 units
Project 5	-77 units	-5 units
Project 6	-76 units	-4 units
Project 7	-77 units	-5 units
Project 8	-80 units	-8 units
Project 9	-83 units	-10 units
Project 10	-78 units	-6 units
Project 11	-75 units	-2 units
Project 12	-82 units	-10 units
Total	**-80 units**	**-8 units**

The results indicate that planned requirement timings and PO structures operate on clearly different time horizons relative to SoA. Requirement activity is concentrated closer to SoA, whereas purchasing activity begins significantly earlier and spans a wider temporal range. In addition, differences are observed among PGRs in both requirement and PO timing structures. The following subsection (4.1.2) examines the frequency and magnitude of scheduling changes in more detail to further assess schedule stability within the analysed material flow environment.

4.1.2 Frequency and magnitude of scheduling changes

This subsection (4.1.2) reviews the frequency and magnitude of scheduling changes in the analysed data context. The objective of this section is to describe how often planned requirement timings change and how significant those changes are, on average, across different scheduling structures. The results are analysed by projects, PRs, PGRs, and LT categories, allowing the distribution of changes to be compared systematically across segments. Figure 25 presents the average changes in planned requirement timings for projects. The line and column chart visualizes the average change on the left y-axis, the sum of changes on the right y-axis, and four parameters on the x-axis, which can be switched between projects, PGRs, or total LT categories.

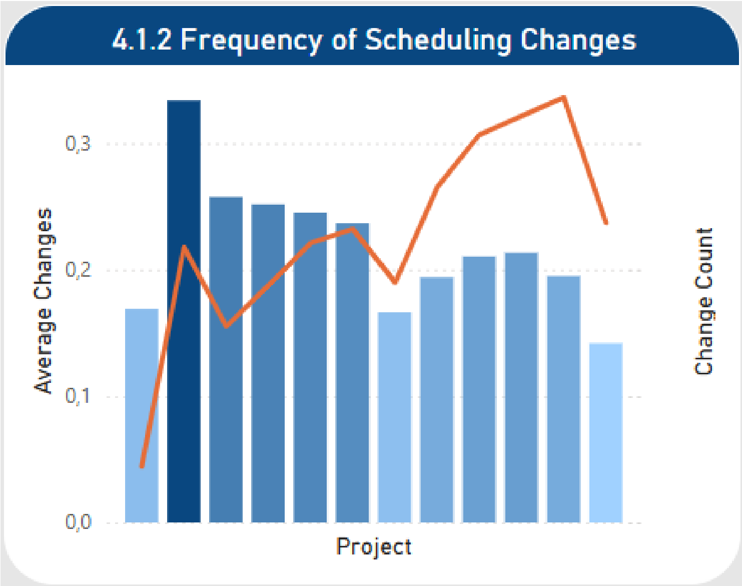

Figure 25. Average scheduling changes for material requirements per project.

The analysed historical data include approximately 10 individual material requirements per project-material combination, representing the planning cycles stored in ERP data for the analysed period. Based on the calculated average change metric, planned requirement timings change about 0.2 times per requirement. This indicates moderate variability, with most requirements remaining stable across planning cycles. At the project level (Figure 25), average change counts range from approximately 0.1 to 0.3 per requirement. The highest change count is observed in the second project, whereas the lowest average change counts are observed in the first and last projects. However, most projects are close to the overall average of 0.2. Regarding PR structures, component group A has the highest average number of changes, at approximately 1.2.

Differences are also observed across PGRs, with change counts ranging from approximately 0.1 to 0.5 changes per requirement. PGR 007 has the highest average change count at around 0.5, while PGRs 004 and 015 have the lowest values. Most PGR classes are close to the overall average of approximately 0.2, though there is moderate variation. For example, PGR 002 matches the average at 0.2 but has the highest number of changes. Across total LT categories, medium LT materials show the highest average change count at approximately 0.2, followed closely by short LT materials, while long LT materials show slightly lower values at around 0.2. Differences between LT categories are less pronounced than those observed in other segmentations. The results indicate that planned requirement timings exhibit measurable deviations in the analysed scheduling structures, occurring across projects, PGRs, and total LT categories.

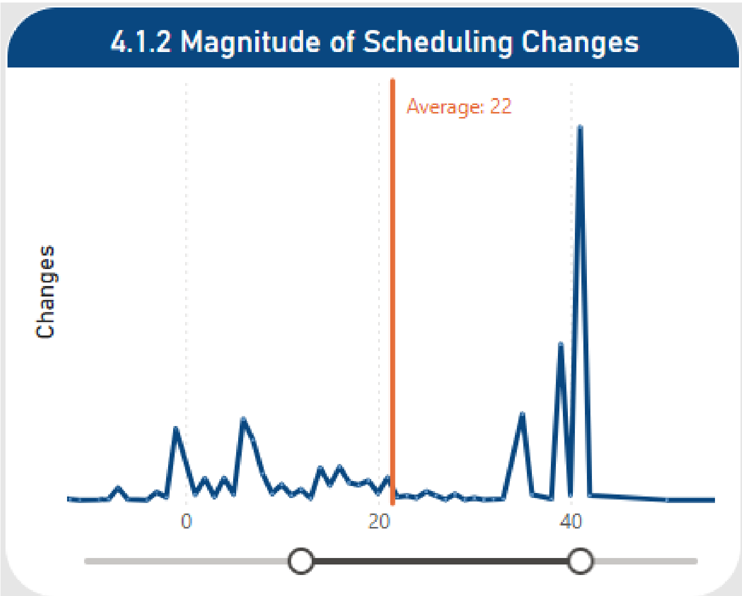

Figure 26. The magnitude of individual scheduling changes.

Figure 26 shows the magnitude of individual changes, with the distinct count of requirements on the y-axis and the magnitude of changes in units on the x-axis. A horizontal reference line marks an average postponement of about 20 units. Positive values indicate delays, and negative values indicate advancements. Based on the case data, scheduling changes are positive, indicating that planned requirement timings were usually rescheduled later. The largest peaks fall roughly within a range of +1 to several tens of units. In contrast, advancements are generally limited to short, single-unit movements. The following subsection (4.1.3) reviews planned changes to requirement timings more specifically through a timing spread analysis.

4.1.3 Timing spread of scheduling changes

This subsection (4.1.3) examines the timing spread of planned requirement changes in the analysed scheduling structure case context. The objective is to illustrate how widely requirement timings have been distributed throughout the planning history. Timing spread is the difference between the minimum and maximum planned requirement timings, measured in units. The analysis is performed for projects, PGRs, and total LT categories, enabling systematic comparison across segments of the material flow. Figure 27 below presents average timing spreads of planned requirement timings for projects. The column chart displays the average timing on the y-axis and the selection of four parameters on the x-axis, which can be switched between projects, PGRs, or total LT categories. In addition, the y-axis features a line representing the overall average.

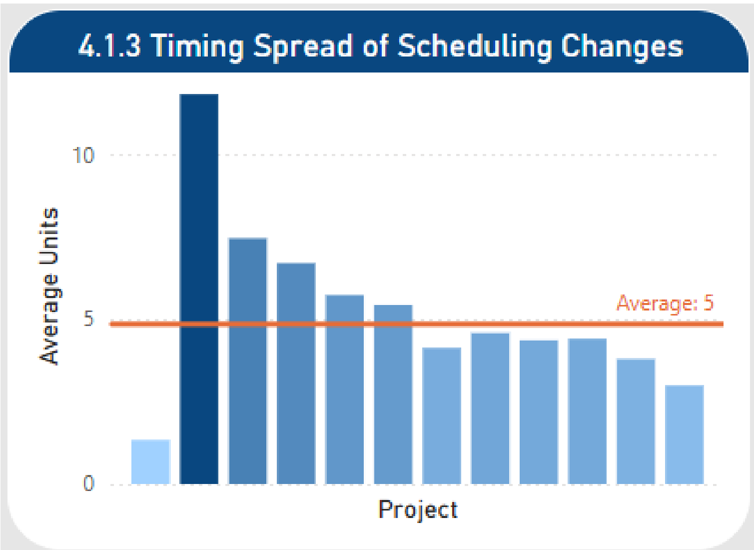

Figure 27. Average timing spreads for material requirements per project.

The average timing spread across the entire dataset is approximately 5 units, indicating that planned requirement timings shift by about this magnitude on average over the planning history. At the project level, the average timing spread ranges from about 1 to 12 units. The highest spread occurs in the second project, and the lowest in the first project. Other projects are close to the overall average of about 5 units (Figure 26). At the PR level, timing spread values vary widely, ranging from 0 to several tens of units. The highest spreads occur for component groups A and B. In other PR categories, changes remain close to the overall average of about 5 units.

Among PGRs, variation is moderate, with timing spread ranging from approximately 2 to 7 units. The highest timing spread occurs for PGR 001, and the lowest for PGR 007. Most PGRs fall within the 3-5-unit range. Across LT categories, medium LT and short LT show the highest timing spread of around 5 units, while long LT materials remain at a lower level of timing spread, with approximately 4 units. However, differences between LT categories are smaller than at other levels of comparison. The results indicate that the timing spread varies only moderately, with most projects and PGRs remaining close to the overall average. There is temporal variation within individual projects and PGRs during the planning history. The following subsection (4.1.4) reviews total variation more specifically for planned requirement timings in the analysed scheduling structures.

4.1.4 Instability across projects, PRs, PGRs, and total LT categories

This subsection (4.1.4) examines changes in the analysed scheduling structure environment, which is segmented into four classification categories. Table 2 presents the sum of changes, average changes, average timing spread (TS), and average total variation (TV) across twelve projects. Instability is measured by total variation, which captures the difference between the earliest and latest planned requirement timings. A positive value indicates a delay, and a negative value indicates an advance. The data is also broken down by project to identify which projects, PGRs, and total LT categories show the greatest variation in planned requirement timings in the analysed historical data for the case context. The total variation for the whole dataset is approximately +5 units. However, the results indicate significant variation across the classification categories.

Table 2. Planned requirement timing instability across projects.

Project	Change Count	Average Changes	Average TS	Average TV
Project 1	1,400	0.2	1 unit	+1 units
Project 2	3,200	0.3	12 units	+12 units
Project 3	2,600	0.3	8 units	+7 units
Project 4	2,900	0.3	7 units	+7 units
Project 5	3,200	0.2	6 units	+6 units
Project 6	3,300	0.2	5 units	+5 units
Project 7	2,900	0.2	4 units	+4 units
Project 8	3,700	0.2	5 units	+5 units
Project 9	4,100	0.2	4 units	+4 units
Project 10	4,200	0.2	4 units	+4 units
Project 11	4,400	0.2	4 units	+4 units
Project 12	3,400	0.1	3 units	+3 units
Total	**39,300**	**0.2**	**5 units**	**+5 units**

At the project level, the smallest total variation, approximately +1 unit, occurs for the first project, where planned requirement timings remain stable over the planning horizon. The highest total variation, around +12 units, occurs for the second project, where schedules change both more frequently and over longer periods. Notably, total variation shows a downward trend starting with the second project. At the PR level, total variation varies across structures. The highest average total variation occurs for component groups B and A, with several tens of units. In other PR categories, changes remain close to the overall average of approximately +5 units.

Among PGRs, clear differences in total variation are evident. Based on the overall data (Table 2), the highest total variation is observed for PGRs 001 (+6 units), 010, and 007, while the lowest variation is observed for PGRs 004 (+2 units), 003, and 006. For other PGRs, the average total variation is closer to the overall average. Across total LT categories, short- and medium-LT materials exhibit greater total variation than long-LT materials at the overall level (Table 2). However, differences across total LT categories are smaller than those across projects and PGRs. The results indicate that total variation is explained more by individual PGRs and projects than by total LT categories alone.

The total variation matrix results for the first project indicate noticeably lower variability across all segments. In most classifications, average total variation remains within a +1- to 3-unit range, indicating a stable planned requirement structure, with an overall average of approximately +1 unit. In contrast, the second project shows significantly greater variability across several classifications, with an overall average variation of around +12 units. Overall, the results show that total variation in planned requirement timings varies significantly across projects and PGRs. The most significant differences are observed between the first and second projects, with the second project showing notably higher total variation in all analysed segments. The following subsection (4.1.5) examines the timing of the changes in relation to SoA.

4.1.5 Temporal patterns of scheduling changes

This subsection (4.1.5) examines temporal change patterns relative to the SoA point. The objective is to show at which stage of the project timeline changes to planned requirement timings occur and how they are distributed across projects. Figure 28 below presents the schedule changes for planned requirement timings. The line chart plots the sum of changes on the y-axis and the offset to the SoA on the x-axis. The y-axis values are also divided by all twelve projects, as shown in the legend, with the first project in the lightest blue and the last in the darkest blue. In addition, the x-axis includes a line representing the SoA (0 units).

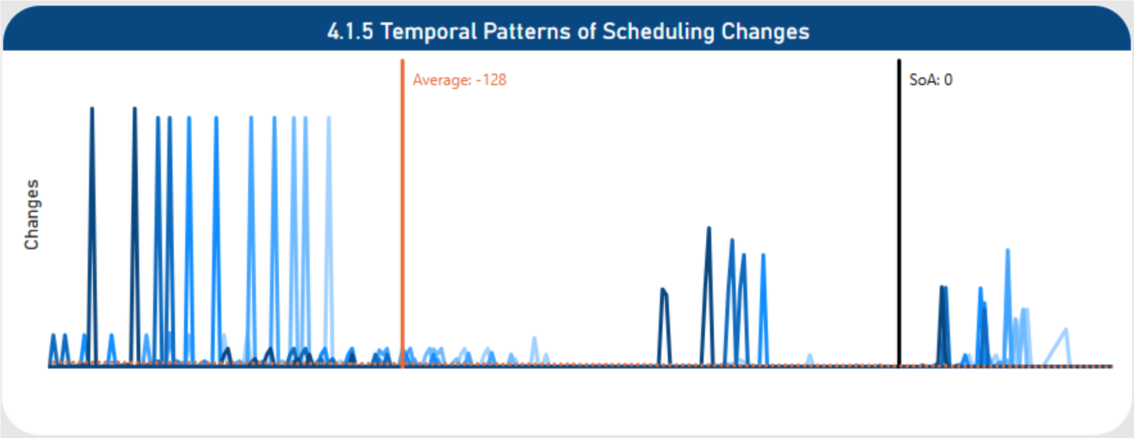

Figure 28. Temporal distribution of scheduling changes relative to SoA.

The results indicate that planned requirement timing changes are clearly concentrated in certain periods relative to the SoA (Figure 28). Most changes occur before the SoA, with an average of approximately -128 units, particularly within the range of -220 to -140 units relative to the SoA. During this period, several projects have shown high change rates. At approximately -60 units relative to the SoA, the total number of changes decreases compared to previous planning stages, but some individual change spikes still appear between approximately -60 and -30 units relative to the SoA. Even after the SoA, changes continue, but the sum remains lower than at the previous points.

Across projects, the sum of planned requirement timing changes in the case data varies. Some projects show pronounced spikes in long-term change before the SoA, whereas in others, changes are more evenly distributed across several periods. In general, the changes focus on the earlier stages of project planning. On average, PGR-specific change peaks are close to the overall average (Table 3). Overall, the results indicate that planned requirement timing changes are not evenly distributed across the timeline but are concentrated in earlier planning stages. As the zero point is approached, the sum of changes decreases markedly, although individual changes also occur near and after the SoA.

Table 3. Average positioning of project-specific changes relative to the SoA.

Project	Average Change Relative to SoA
Project 1	-117 units
Project 2	-117 units
Project 3	-119 units
Project 4	-120 units
Project 5	-121 units
Project 6	-124 units
Project 7	-126 units
Project 8	-130 units
Project 9	-135 units
Project 10	-137 units
Project 11	-136 units
Project 12	-144 units
Total	**-128 units**

4.2 Deviation between planned and actual requirement timings

The second results section analyses deviations between planned and actual requirement timings, comparing the plan with the realization (Figure 29). The objective is to visualize the magnitude, direction, and frequency of deviations and to assess how well the planned environment aligns with the actual operational environment. Deviation is defined as the difference between planned and actual requirement timings, and the analysis covers both negative (early) and positive (late) deviations. These results are examined across distributions, directions, and temporal trends, and are segmented by projects, PRs, PGRs, and total LTs. This allows identification of where deviations are larger and where they occur systematically. Figure 29 presents a dashboard illustrating the magnitude, direction, and frequency of deviations between planned and actual requirement timings.

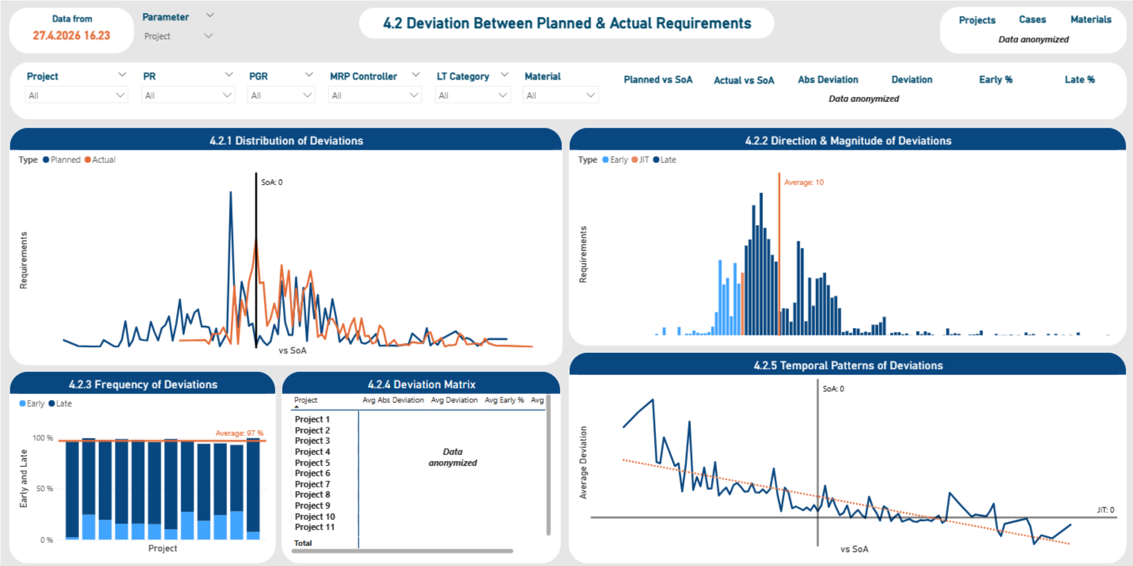

Figure 29. Deviation analysis dashboard (Section 4.2).

4.2.1 Distribution of deviations

This subsection (4.2.1) examines the distribution of planned and actual requirement timings relative to the SoA. It compares actual requirement timings with the corresponding planned requirement timings and identifies general patterns of deviation in the data context. Figure 30 below presents the planned (in blue) and actual (in orange) requirements relative to the SoA. The line chart plots the count of distinct requirements on the y-axis and the offset from the SoA on the x-axis. The chart also includes a horizontal line at 0 representing the SoA. Additionally, the visualization includes a pie chart showing the relative distribution of deviations into early, late, and JIT.

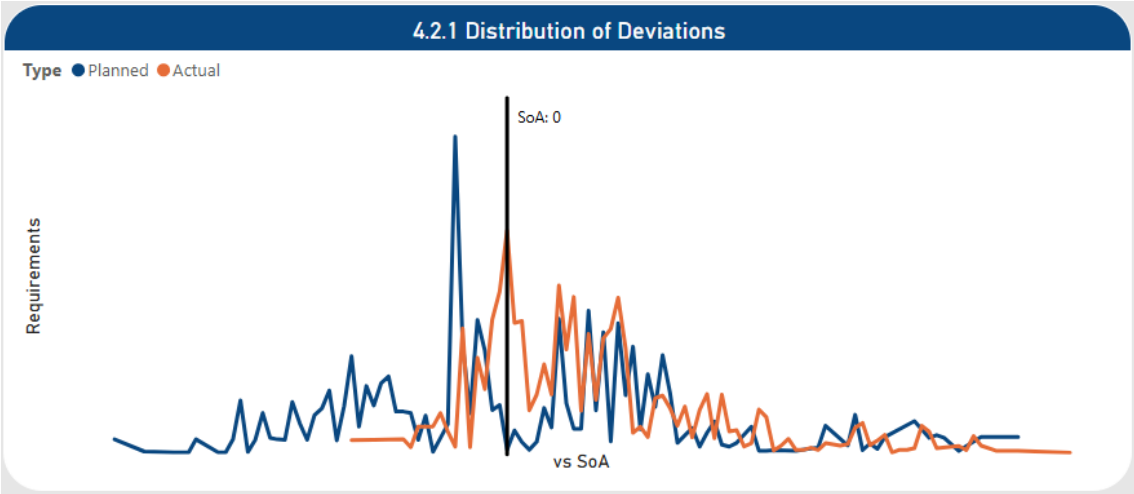

Figure 30. The distribution of planned and actual requirement timings.

Figure 30 shows that planned requirement structures are primarily concentrated just before the SoA and in its immediate vicinity. The highest individual planned requirement spike occurs -7 units relative to the SoA, after which requirements decline rapidly. By contrast, actual requirement structures are distributed more widely over the period following the SoA than planned structures. In addition, the actual requirement data show greater variation and a longer duration following the SoA, with the highest spike at the SoA. Based on the averages, the planned requirement timings fall on average at +1 units, and the actual requirement timings are approximately +11 units relative to the SoA. The results indicate that the actual requirement timings occur later than the planned requirement timings and correspond to an average deviation of approximately +10.

When examining the direction of deviations, late actuals are the largest category in the analysed data. Late deviations account for approximately 80% of all observations, while early deviations make up around 17%. JIT-deviation share remained small, at 3% of all requirements. According to the results, actual requirement timings occur most often later than the original plan. The visualization shows differences across segments. Therefore, the more detailed deviation behaviour of projects, PRs, PGRs, and total LT categories will be examined in the next subsections. In summary, planned and actual requirement timings show systematic deviations relative to the SoA. Actual requirement structures are, on average, located later than planned requirement structures, and most deviations consist of late outcomes. The following subsection (4.2.2) reviews the direction of deviations in more detail.

4.2.2 Direction and magnitude of deviations

This subsection (4.2.2) reviews the direction and magnitude of deviations between actual and planned requirement timings. Deviations are categorized into three classes, namely advanced (early), in accordance with the original plan (JIT), and postponed (late). This data is visualized in Figure 31 below, a stacked column chart that illustrates the direction and magnitude of deviations, color-coded by deviation type. The column chart plots the distinct count of requirements on the y-axis and the deviation in units on the x-axis. Additionally, the visualization includes a horizontal line on the x-axis representing the overall average of +10 units, which reflects systematic delays in material consumption relative to planned requirement structures.

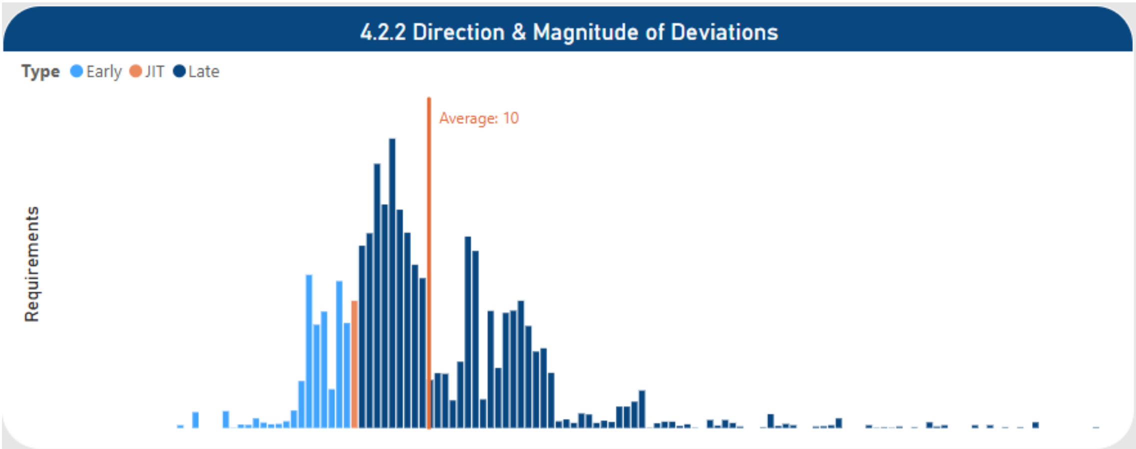

Figure 31. Direction and magnitude of deviations.

Referring to Figure 31, advanced actual requirement timings are near JIT-level, and the magnitude of these deviations remains small, with the highest spike at -6 units relative to the planned requirement timing. The requirements that have been brought forward fall within a 7-unit period relative to the planned structure, and early deviations account for 17% of the total. Perfectly aligned JIT rows make up 3% of the total requirements, a small share. Late actual requirement timings account for 80% of the case data, ranging from +25 to +30 units relative to the planned requirement timing, with a distribution centred around the mean. This indicates that most deviations are close to zero, but there are also individual cases of significant deviations in magnitude.

The results indicate that material flow implications do not align with the planned requirement structures, with 97% of requirements deviating. On average, actual requirement timings are delayed by 10, and the timing spread increases. Both significant negative and positive deviations can create uncertainty in material flows, with negative values potentially causing material availability issues and positive values potentially leading to storage costs. The following subsection (4.2.3) reviews the frequency of scheduling deviations and their distribution across projects, PRs, PGRs, and total LT categories in greater detail.

4.2.3 Frequency of deviations

This subsection (4.2.3) examines the frequency of deviations between actual requirement timings and planned schedules. As noted earlier, early deviations account for 17% of the total, while late deviations make up 80%. Figure 32 below shows total deviations as a percentage across different segment levels, in this case projects. The stacked column chart plots deviations on the y-axis and selectable analysis classes of projects, PRs, PGRs, and total LT categories on the x-axis. The y-axis column is stacked, combining percentages of early (in light blue) and late (in dark blue) deviations. Additionally, the visualization includes a single horizontal line on the y-axis at the overall average of 97%, indicating systematic delays in material consumption relative to planned requirement timings.

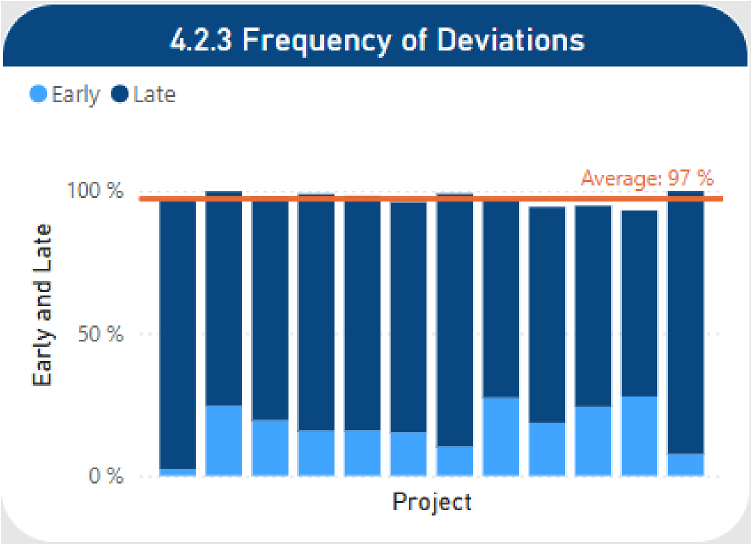

Figure 32. Occurrence of deviation types by project.

Based on the results, requirement timing deviations occur across all review classes (97%), with the main emphasis on late deviations, averaging 80%. At the project level, Figure 32 highlights differences among twelve case products. The overall frequency of deviations remains high and stable, even though early and late deliveries show moderate variation. For example, the first project has the smallest share of early deviations at 2% but the highest share of late deviations at 94%. By contrast, the eleventh project shows the opposite pattern, with 28% early deviations and 65% late deviations. At the PR level, differences in the direction of deviations are observed. Some PR structures show 100% late deviations, while, for example, component groups D and E have more early realizations. PR structures also follow a trend in which deviations are late.

Across PGRs, deviations remain close to the overall average, though some differences persist. For instance, two PGRs, 001 and 003, have lower total deviation shares of 88% and 89%, respectively. There are also differences in the shares of early and late implementations, indicating that PGRs 004 and 015 have only late deviations in the case context. Two PGRs also show higher early-occurrence peaks, with PGR 001 at approximately 35% of early items and PGR 010 at 31%. When reviewing total LT categories, short LT and medium LT materials have similar statistics, while long LT materials have a similar overall deviation share but with greater emphasis on late deviations. The results suggest that actual requirement timings differ from planned requirement timings, with deviations primarily toward late deliveries. The following subsection (4.2.4) reviews deviations in more detail across projects, PRs, PGRs, and total LT categories.

4.2.4 Deviation by projects, PRs, PGRs, and total LT categories

This subsection (4.2.4) examines deviations between planned and actual requirement timings, segmented into four classification categories for projects, PRs, PGRs, and total LT. The review is based on summary tables, such as Table 4, which present the average absolute deviation of requirements (Avg Abs Deviation), average deviation of requirements (Avg Deviation), and the shares of average early and late requirements (Avg Early % and Avg Late %) for each of the twelve case projects. The data is intended to help identify the direction and magnitude of deviations in requirement timings across different classification levels of material flows. In general, the average absolute deviation is 12 units, the average deviation is +10 units, and 17% of requirements are realized early and 80% are realized late.

Table 4. Requirement timing deviation across projects.

Project	Average Absolute Deviation	Average Deviation	Average Early %	Average Late %
Project 1	11 units	+11 units	2%	94%
Project 2	9 units	+6 units	25%	75%
Project 3	12 units	+10 units	19%	79%
Project 4	10 units	+9 units	16%	83%
Project 5	11 units	+10 units	16%	83%
Project 6	11 units	+9 units	15%	81%
Project 7	14 units	+13 units	10%	89%
Project 8	11 units	+9 units	27%	70%

Project 9	12 units	+10 units	19%	76%
Project 10	12 units	+9 units	24%	71%
Project 11	11 units	+7 units	28%	65%
Project 12	17 units	+14 units	8%	92%
Total	**12 units**	**+10 units**	**17%**	**80%**

At the project level, the magnitude of requirement timing deviations varies clearly. The absolute deviation ranges from 9 to 17 units, with the largest spike in the last project, which has an average absolute deviation of 17 units and an average deviation of +14 units. Similarly, the smallest deviations occur in the second project, with an average absolute deviation of 9 units and a deviation of +6 units. The results also indicate that the proportion of late deviations across all projects is clearly higher than that of early deviations. In the first project, the share of late deviations is 94%, while advancements account for only 2% of the total. Overall, at the project level, requirement timing deviations are systematically skewed toward the positive side, indicating that planned requirement timings are required later.

PR reviews show significant variation in deviations, with the highest occurring in component groups F and G. These groups have average deviations of over +50 units, and 100% of requirements are late, indicating that requirement timing deviations are entirely positive. The results indicate that some material groups are more vulnerable to differences in requirements than others. At the same time, the review showed that material flow performance is not standardized. Between PGRs, volatility is lower than at the PR level, yet clear differences remain. The average absolute deviations fluctuate between 4 and 19 units, while the average deviations range from +3 to +18 units. The highest overall deviation is for PGR 006, and the lowest for PGR 003. The tables show differences among PGRs in the accuracy of requirement timing.

Among the LT categories, long LT materials show the highest average deviations, at +12 units, compared with short and medium LT at +9 and +10 units, respectively. Absolute deviations across all LT categories follow the same trend, with late deviations exceeding early realizations. Long LT materials account for 90% of late deviations, while short and medium LT materials remain lower, at 78% and 79%. The results indicate that long LT components are associated with greater deviations in requirement timings and a stronger emphasis on delays. At the overall level, deviations between planned and actual requirement timings vary significantly across classification categories, but late deviations account for the largest share. This suggests that actual requirement timings systematically shift later than initially planned. The following subsection (4.2.5) reviews the temporal patterns of requirement timing deviations.

4.2.5 Temporal patterns of deviations

This subsection (4.2.5) examines temporal patterns of requirement-timing deviations relative to the start of production (SoA). The objective is to understand how deviations evolve over time and to identify potential patterns in the analysed data. Figure 33 below shows the temporal variation of deviations relative to the SoA. It is formed by plotting the average deviation in units on the y-axis and the offset to the SoA on the x-axis, using the planned requirement timing. Therefore, negative values indicate time before the SoA, and positive values indicate time after the SoA. The line chart also includes a trend line that describes the general trend in deviations during the review period.

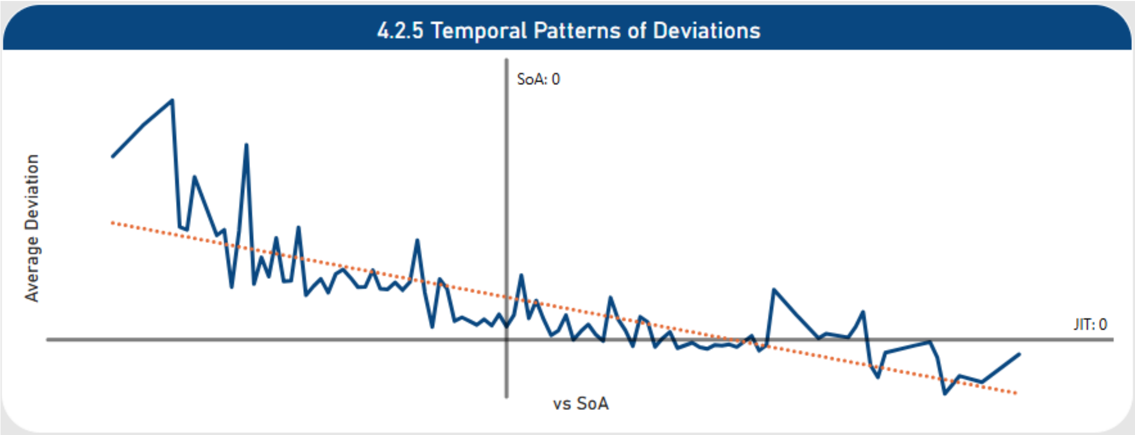

Figure 33. Temporal variation of deviations relative to SoA.

The results indicate that, on average, deviations are positive early in the review period, reflecting that actual requirement timings are realized later than initially planned, especially well before the SoA. The highest mean deviation spikes occur approximately -30 units relative to the SoA, shifting the actual requirement closer to the SoA. Closer to the SoA, deviations begin to settle, and variation stabilizes. At the end of the review cycle, deviations fall below the zero line, indicating that actual requirement timings occur before the planned requirement timings. The trend line confirms this finding across all observation categories, PGRs, and total LT categories. The downtrend reflects the stabilization of planned scheduling structures as the SoA is approached, while actual requirement timings move closer to the SoA.

At the project level, a notable difference across the twelve projects is that the first project has only positive average deviations during the review period. This indicates that actual requirement timings are systematically later than planned, even after SoA. However, this project also shows a downward trend, indicating that the magnitude of deviations decreases over time in the review period. In summary, deviations between actual and planned requirement timings decrease over time, with realizations occurring later than planned at the beginning, aligning closer to the SoA, and occurring even earlier than initially planned at the end (Figure 33).

4.3 Impact on material flow and purchasing performance

The third results section examines the effects of scheduling structure stability and deviations from the plan on material flows and performance (Figure 34). It examines how scheduling changes and deviations between planned and actual requirement timings relate to inventory levels, material availability, and shortages and surpluses. The analysis combines metrics from the previous sections into key figures describing material flow performance and reviews these connections across different classes. Thus, the results are presented segmented by projects, PGRs, total LTs, and months, and the data is also reviewed on a month-over-month basis to identify trends over time. Figure 34 presents a dashboard illustrating the relationship between scheduling stability, deviations, and material flow performance metrics.

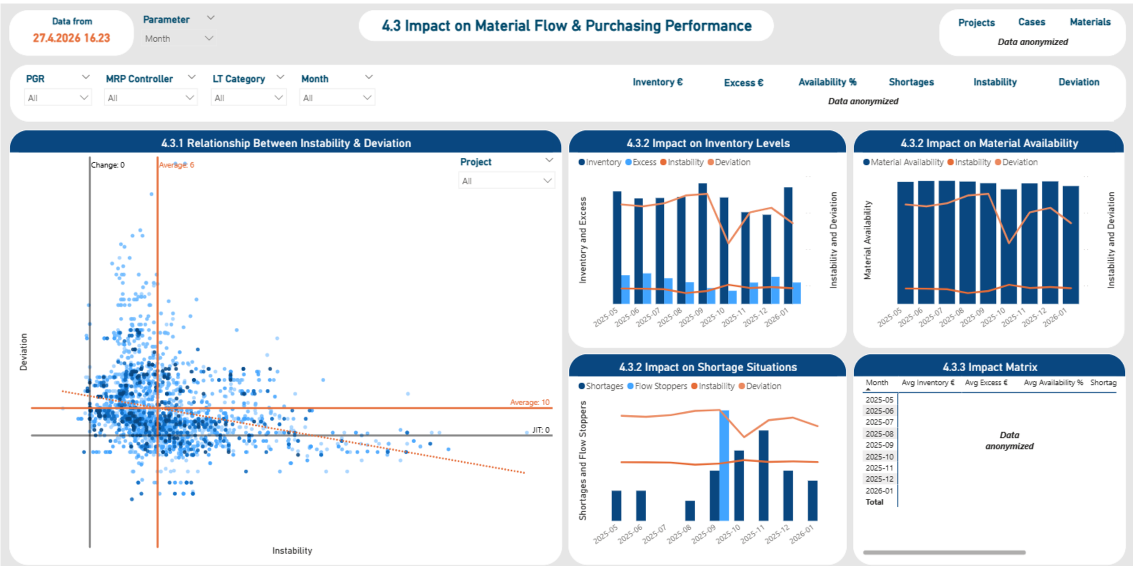

Figure 34. Material flow performance dashboard (Section 4.3).

4.3.1 Relationship between instability and deviations

This subsection (4.3.1) examines the relationship between instability in the planned scheduling structure and the deviation between planned and actual requirement timings, using a scatter chart. The chart plots instability (average total variation) on the x-axis and deviation (average deviation) on the y-axis. Each data point represents a material requirement, and the colours indicate different PGRs. The scatter plot in Figure 35 describes the overall situation, but it can also be divided into categories such as projects, PGRs, total LT categories, and months under review. Additionally, the plot includes one constant line per axis, representing overall averages of +6 units (instability) and +10 units (deviation). The trend line, on the other hand, is used to estimate the general relationship between instability and deviation in the scheduling structures.

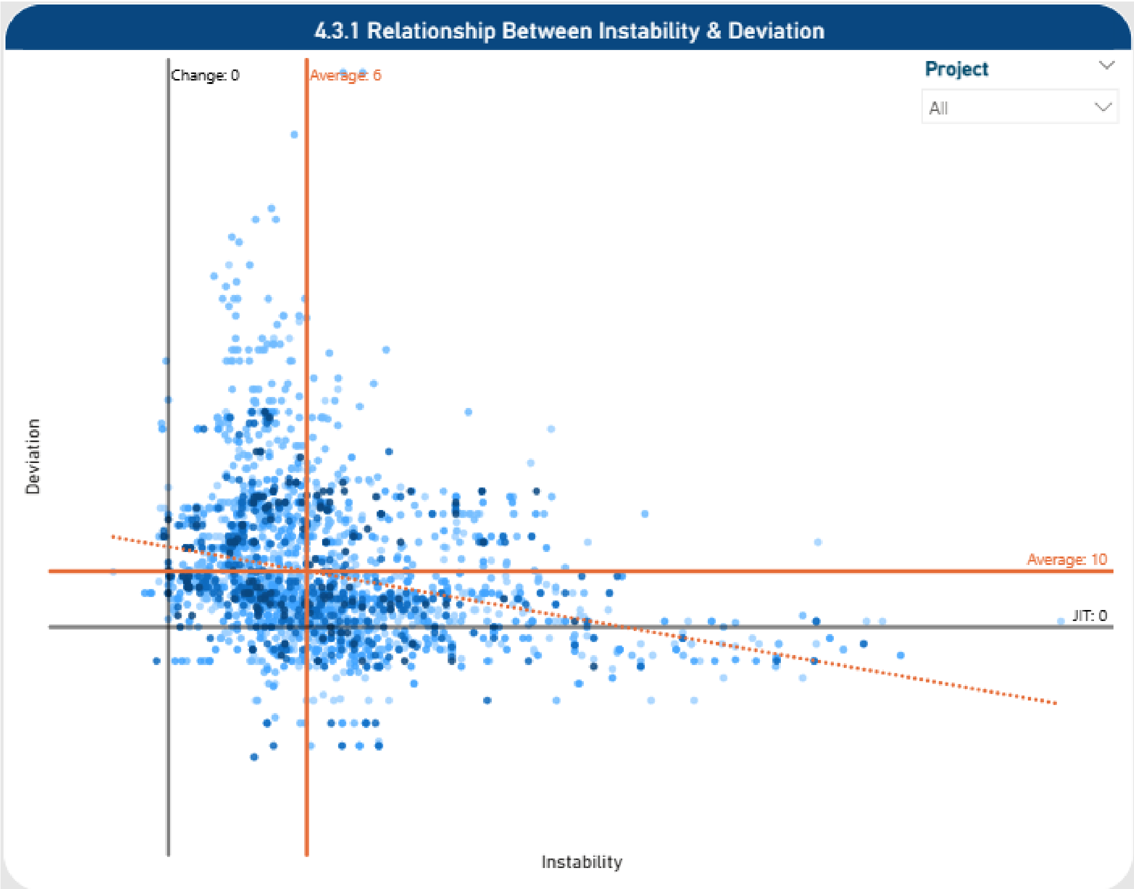

Figure 35. The relationship between instability and deviations.

The results indicate that instability values are almost entirely positive, meaning that planned requirement timings are systematically postponed over the research horizon. The range of instability is relatively limited, with most observations falling between -2 and +38 units. In contrast, the timing spread for deviations is larger, spanning from -23 to +100 units. This suggests that actual requirement timings fluctuate more than planned requirement timings and include more early realizations. An analysis at different classification levels showed that the visualizations for the projects, PGRs, and total LT categories were similar in structure, and the trend line was downward in almost all cases. The most notable exception was the first project, where the trend was positive, and deviations increased with instability, indicating systematic delays.

As noted in the previous paragraph, the downward trend line in the scatter plot indicates that as instability increases, the average deviation decreases. This suggests that when planned requirement timings are updated more frequently, actual requirement timings remain closer to the planned environment. Similarly, in more stable planned-requirement environments, deviations tend to be larger, indicating that the planned scheduling structure does not respond quickly enough to changes in the production material flow. Furthermore, in the range of high instability values, some postponed planned requirement timings resulted in earlier actual requirement timings relative to the updated plan. The following subsection (4.3.2) reviews the impact of instability and deviations on material flow metrics.

4.3.2 Impact on material flows

This subsection (4.3.2) reviews the impact of scheduling stability and deviations in requirement timing on material flows by comparing these effects with inventory levels, material availability, and monthly shortage situations. Figures 36, 37, and 38 are combined line and stacked column charts, with the columns representing material flow performance metrics and the lines showing instability and deviation levels over the nine-month research period (from May 2025 to January 2026). The x-axis shows the months mentioned above, with the left y-axis depicting the corresponding material flow metric and the right y-axis showing levels of planned scheduling stability and deviations between planned and actual implementations.

In the analysis of inventory levels (Figure 36), the columns represent the total inventory value and the excess inventory amount per month, while the lines illustrate trends in instability and deviation. The results indicate that instability remained relatively stable during the review period, whereas deviation changed more noticeably. As deviation decreased, inventory and excess stock values also declined. This suggests that when material requirements are met earlier than planned, less material is tied up in inventory, thereby reducing inventory levels.

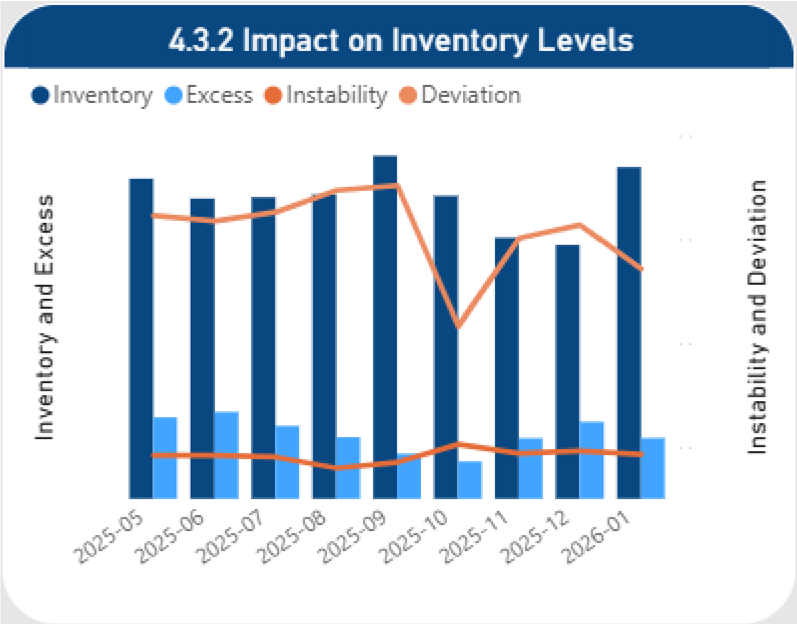

Figure 36. Impact on inventory levels.

In the material availability analysis (Figure 37), the columns show the monthly material availability percentage for relevant POs, and the line charts display instability and deviation levels for the same period. Availability generally remained high throughout the analysis period, but as deviation decreased, material availability declined noticeably. This indicates that when material requirements are realized earlier than planned, a larger share of POs is delayed. Instability also remained relatively stable in this analysis, highlighting the stronger link between deviation and material availability.

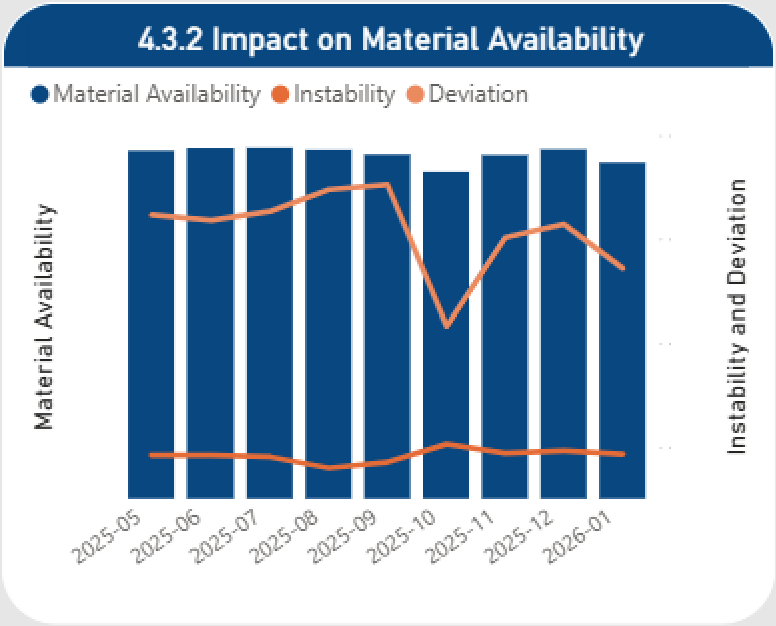

Figure 37. Impact on material availability.

In the analysis of shortage situations (Figure 38), the bars represent the monthly counts of shortages and flow stoppers, while the line charts show instability and deviation levels. The results show that the number of shortages and flow stoppers increased, particularly during periods when the deviation level decreased, suggesting that earlier realized material requirements increase the risk of material shortages and production disruptions. Overall, the results indicate that lower deviation reduces buffers, which lowers inventory but also weakens material availability. In this analysis, instability remained relatively stable throughout the analysis period, suggesting that changes in material flow performance were more strongly linked to fluctuations in deviation levels than to scheduling instability. The following subsection (4.3.3) reviews the impact in more detail across months, PGRs, and total LT categories.

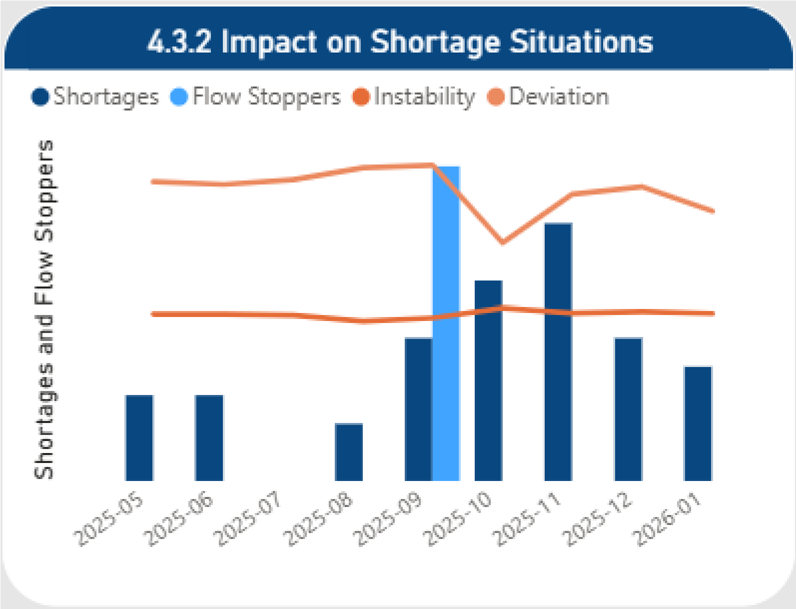

Figure 38. Impact on shortage situations.

4.3.3 Impact across PGRs, total LT categories, and months

This subsection (4.3.3) examines material flow performance across levels of analysis using impact matrix tables, consistent with the approach in sections 4.1.4 and 4.2.4. The analysis is organized by monthly, PGR, and total LT categories. The tables compare average inventory and excess stock indices, average material availability percentages, average shortage indices, and average instability and deviation metrics. The aim is to identify how variations in requirement timing deviations and scheduling instability are reflected in material flow performance across classifications. Table 5 shows the monthly impact of instability and deviation.

Table 5. Monthly impact of instability and deviation.

Month	Average Inventory Index	Average Excess Inventory Index	Average Availability %	Average Shortage Index	Average Instability	Average Deviation
2025-05	1.06	1.26	96%	0.71	+6 units	+11 units

2025-06	0.99	1.34	97%	0.71	+6 units	+10 units
2025-07	1.00	1.13	97%	0.00	+6 units	+11 units
2025-08	1.01	0.95	96%	0.47	+6 units	+11 units
2025-09	1.14	0.69	95%	1.18	+6 units	+11 units
2025-10	1.00	0.58	90%	1.66	+6 units	+8 units
2025-11	0.86	0.93	95%	2.13	+6 units	+10 units
2025-12	0.84	1.19	96%	1.18	+6 units	+10 units
2026-01	1.10	0.94	93%	1.00	+6 units	+9 units
Total	**1.00**	**1.00**	**95%**	**1.00**	**+6 units**	**+10 units**

A monthly analysis shows that inventory values fluctuate between 0.84 and 1.14, and excess inventory between 0.58 and 1.34 during the analysed period. At the same time, the material availability percentage remains largely high but declines significantly in October 2025 to approximately 90%. This period was also characterized by higher shortage levels and a lower deviation level. The results support the phenomenon observed in previous analyses, in which deviation decreases, material availability weakens, and shortage situations increase. Instability remains relatively stable month to month throughout the entire analysis period.

An analysis at the PGR level reveals clear differences in material flow performance across PGR classes. For example, PGR 002 stands out for the highest shortage levels and a lower availability percentage than other classes. PGR 005 and 006, on the other hand, have the highest deviation levels, yet their shortage levels remain low and their availability percentages high. Additionally, some PGR classes, such as 004, exhibit high material availability and relatively low instability. The results suggest that material flow performance varies significantly across material groups and that the effects of deviations do not manifest uniformly across PGR classes.

In the total LT category analysis, long LT materials have the highest inventory and excess stock levels and the largest average deviation. At the same time, their availability percentage is lower than that of short and medium LT materials. In the medium LT category, the highest shortage volume is observed, even though the deviation level remains close to the overall average. Short LT materials achieve the highest availability percentage and the lowest inventory values. The results suggest that longer LT categories face greater material flow challenges, particularly in inventory commitment and material availability.

4.4 Summary of key results

The fourth and concluding section of the results presents the key findings. The objective is to summarize the main observations on scheduling structure stability, deviations between planned and actual requirement timings, and material flow performance, with limited interpretation to support clarity of the empirical findings. The summary compiles the most important results of the analysis and forms the basis for the analysis of the results and the conclusions presented in the following chapter. In addition, the summary highlights the key differences among the various levels of analysis (projects, PRs, PGRs, and LT categories) and describes the timing of the findings relative to the SoA to ensure a clear overall picture of the distribution and occurrence of the results.

The results on the stability of the schedule structure indicate that instability is not evenly distributed across the dataset under examination but is concentrated in certain projects and material structures. At the project level, the most significant variations are observed in the second project, where both the number of changes and the total variation are clearly higher than in other projects, while the first project represents the most stable structure with the lowest values. There are also clear differences between PGR classes, while the differences between overall LT categories are relatively small. Changes occur mainly in the early design phases, particularly before the SoA point, and are concentrated between approximately -220 and -140 units.

An analysis of deviations between planned and actual requirement timings reveals a systematic gap between the plan and the actual results. The average deviation is positive (+10 units), indicating that actual requirement timings are most often met later than planned. Late actuals account for most observations (80%), early actuals are less common (17%), and cases that exactly follow the plan are rare (3%). Most deviations fall within a 25-unit delay, though larger individual deviations are present. Deviation frequency is high across all categories examined, with 97% of requirements deviating from the planned schedule. However, projects vary in the nature and size of these deviations. Differences are also seen at the PR and PGR levels, with certain structures more susceptible to deviations than others. Overall, long LT materials show larger average deviations and a higher proportion of late completions than short and medium LT materials.

Regarding material flow performance, the results show clear correlations among deviations, inventory levels, and availability. As deviations decrease, inventory levels and excess inventory decline, but material availability also falls and shortages rise. Conversely, higher deviations are associated with higher inventory levels and better availability. Schedule instability remains largely unchanged over the observation period, whereas changes in material flow performance are more strongly linked to deviations than to schedule-structure stability. These findings collectively answer RQ1–RQ3 by showing that scheduling structures influence material flows through instability, that deviations are systematically delayed, and that deviations ultimately determine material flow performance.

5 Conclusions

The fifth and final main chapter of this thesis, the conclusion, reviews the results in relation to the RQs and the theoretical frameworks presented in the literature review. The objective is to interpret the empirical findings and assess how instability in the scheduling structure and deviations in requirement timings affect material flows. Additionally, this chapter identifies opportunities to improve synchronization at the scheduling-purchasing interface. This main chapter is divided into five sections. The first section (5.1) presents key research results and their interpretation in relation to the RQs. The second section (5.2) compares the findings with the theoretical frameworks presented in the second chapter. The third section (5.3) reviews the practical significance of the results and offers recommendations to improve material flows. The fourth section (5.4) assesses the study's reliability and limitations. The last section (5.5) proposes topics for future research.

5.1 Key findings

This thesis offers empirical evidence on how production scheduling structures influence material flows, showing that requirement timing deviations are the primary control mechanism for performance in the analysed ERP-based environment. The first central observation is that scheduling instability is not evenly distributed across case projects and material classes but is concentrated in certain projects and structures. These changes are mainly targeted at the early planning stages, well before the SoA, indicating that schedules are fine-tuned significantly in advance of the SoA. Therefore, regarding RQ1, it can be concluded that scheduling structures influence material flows through changes that transfer from the MRP system to purchasing operations, causing variation in requirement timings.

The second central observation concerns the systematic deviation between planned and actual requirement timings. The results indicate that actual requirement realizations occur 10 units later than planned, and that 80% of observations reflect late deviations. Simultaneously, only 3% of cases are implemented exactly on the planned schedule, and 97% of requirements deviate from the planned schedule. Therefore, with respect to RQ2, the answer is that the deviations are primarily positive delays, averaging about 10 units, and covering nearly all the cases examined.

Thirdly, the analysis reveals the relationship among scheduling structures, deviations, and material flow performance. Although schedule instability itself is not the primary driver of performance, deviations are the central mechanism through which scheduling structures influence material flow outcomes. As deviations decrease, inventory levels and excess stock decline, but material availability worsens and shortages become more frequent. Conversely, greater deviations are associated with higher inventory levels and greater material availability. Based on this, the key finding for RQ3 is that improving material flow performance requires managing deviations and establishing better coordination between production scheduling and purchasing. Together, these findings show that scheduling structures affect material flow performance indirectly through deviations, which serve as the key mediating mechanism.

Overall, the results indicate that scheduling structures influence material flow performance through recurring delays, which serve as the key mechanism linking production scheduling and purchasing. These delays shape material flow performance by influencing inventory levels, material availability, and shortages, indicating that deviations, rather than scheduling structures alone, ultimately determine material flow performance. This study contributes to the existing literature by empirically demonstrating that deviations between planned and actual requirement timings are the key mediating mechanism through which scheduling structures influence material flow performance in an ERP-based manufacturing environment. Additionally, Figure 39 below illustrates the average material flow in the case environment.

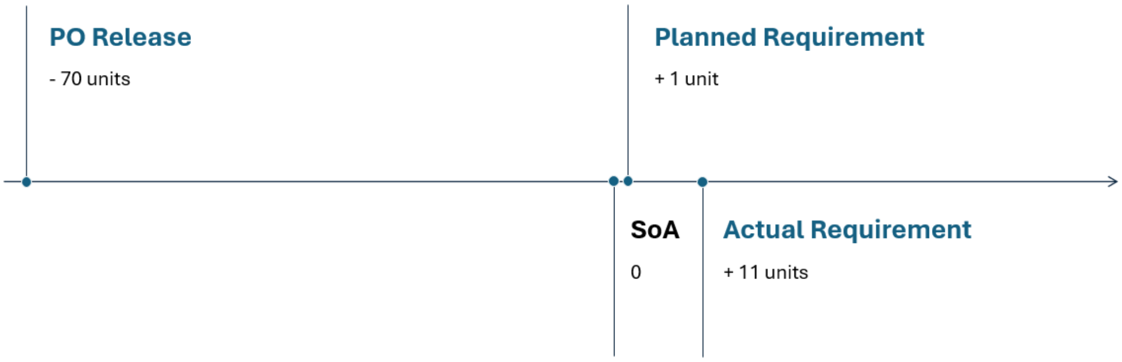

Figure 39. Average material flow in the case context.

5.2 Discussion

While prior literature highlights schedule instability as a key driver, findings suggest that instability alone does not explain material flow performance without accounting for deviations in requirement timings. Consistent with the earlier review in Chapter 2, instability in production planning and schedule nervousness arises mainly from rescheduling, demand fluctuations, and disruptions, which affect material requirements and purchasing (Herrera et al., 2016; Law & Gunasekaran, 2010; Pinedo, 2012). In this thesis, scheduling changes occur mostly before the SoA, consistent with the literature on schedule dynamics. Results also show that instability is concentrated in certain projects and material structures, deepening understanding of how schedule instability occurs.

The results also reinforce the view presented in the literature that production planning, MRP, and procurement form an integrated whole in which schedules determine the timing of material requirements and, consequently, the rhythm of purchasing activities (Jacobs et al., 2018; Slack et al., 2010; Zhao & Lam, 1997). In this thesis, a systematic difference was observed between planned and actual requirement timings, with actual requirements occurring, on average, later than planned and deviations occurring in almost all cases. This reinforces the view that planned requirement timings do not materialize as is, but reality takes shape based on demand variation, material availability, and production disruptions (Christopher, 2009; Herrera et al., 2016; Law & Gunasekaran, 2010; Pinedo, 2012).

Based on the data, these requirement-timing deviations are not isolated variations but constitute a key mechanism linking schedule structures to the performance of the material flow. The results show that schedule instability did not fluctuate significantly month to month, whereas changes in deviation levels were more clearly linked to inventory levels, material availability, and shortages. Thus, the results support the view presented in the literature. Although schedule-related nervousness increases uncertainty in planning and purchasing (Law & Gunasekaran, 2010; Slack et al., 2010), the findings of this study indicate that these effects are particularly manifested through the deviation between planned and actual requirement timings.

The results are also consistent with the literature on fluctuations in material flow and the trade-off between inventories. The literature emphasizes that fluctuations in demand, LTs, and schedules increase the need for buffers and inventory, but also raise tied-up capital and costs (Christopher, 2009; Croson et al., 2014; Slack et al., 2010). A similar pattern was observed in this study, as deviations decreased inventory levels and excess stock. Conversely, higher deviations were associated with higher inventory levels and better availability. The results thus refine the trade-off described in the literature by showing that balance is achieved through deviations from requirements.

Furthermore, the literature review highlights the importance of BOM structures, material groups, and delivery times in determining how schedule changes are reflected in purchasing and material flow (Fixson, 2007; Ivanov, 2017; Salvador, 2007; Stadler, 2011). The results of this study also support this view, as variations were observed across projects, PR structures, PGR classes, and LT categories. Materials with long LTs exhibited greater deviations and poorer availability than those with short or medium LTs, consistent with the literature indicating that longer LTs increase the importance of uncertainty and inventory commitment in material flow management.

Overall, the study confirms the view presented in the literature that production scheduling, purchasing, and material flow are closely interlinked. At the same time, however, it empirically shows that deviations between planned and actual requirement timings are a key link between scheduling structures and material flow performance. Thus, the results not only support previous theory regarding scheduling instability, MRP, and material flow trade-offs, but also demonstrate that material flow performance is primarily determined by deviations in an ERP-based operational environment.

5.3 Managerial implications

The results offer several concrete actions to improve the connection between purchasing activities and material flow management. First, efforts to improve schedule stability should focus on the early planning stages when most changes occur. In practice, this means strengthening planning discipline, limiting unnecessary changes, and applying a "frozen period" approach. These actions reduce variation in scheduling structures and improve forecasting accuracy. Second, alignment between production scheduling and purchasing should be strengthened. Because actual requirement timings consistently occur later than planned, MRP-based requirement timing alone is not a sufficient basis for guidance. Therefore, planning parameters (e.g., LT and safety time) should be calibrated to better reflect actual operational outcomes. This reduces the structural gap between planned and actual requirement timings.

Thirdly, managing deviations should become a central part of material flow management. A concrete first step is to introduce a deviation key performance indicator that tracks both the average deviation in units and the share of requirements exceeding a predefined threshold. This key performance indicator should be reviewed regularly at the project, PGR, and LT-category levels to identify where deviation behaviour is structurally highest. In addition, deviation monitoring should be extended across projects to enable benchmarking and support systematic, continuous improvement. More broadly, this implies shifting from static planning optimization to dynamic process that explicitly accounts for deviations.

To support this, a cross-functional deviation management process should be established between production scheduling and purchasing. For example, a weekly deviation review can identify recurring patterns, prioritize critical materials, and agree on corrective actions before deviations affect availability or inventory levels. Based on these requirements, a monitoring tool can be developed to track requirement-timing deviations in near real time. In practical terms, the tool should provide (1) deviation key performance indicator trends over time, (2) deviation hot spots by project, PGR, and LT category, and (3) threshold-based alerts for materials exceeding agreed limits. This enables proactive operational decision-making and systematic follow-up across projects.

5.4 Limitations

There are limitations to this thesis that should be considered when interpreting the research results. One limitation is that the empirical analysis is confined to a single product line comprising twelve projects. Therefore, the generalizability of the results to other projects, product lines, and operating environments is limited. The thesis also relies on descriptive analysis to identify phenomena and relationships between scheduling structures and material flows. Thus, the research does not provide strong evidence of causal relationships among scheduling stability, planning deviations, and material flow performance.

The limitations of the study also include the availability and quality of data. The analysis draws on data from the ERP system and the case company’s internal Power BI and Excel reports, so the thesis depends on the accuracy and coverage of the data stored in these systems. Material flow performance metrics, such as inventory level reviews, are based on monthly reporting, which limits analysis of short-term variations. Additionally, historical changes in ERP data do not necessarily capture all operational decisions or manual changes, which could have affected the material flow.

5.5 Future research

This thesis focused on the relationships among scheduling structures, planning deviations, and material flows in a single-case context. In future research, the analysis could be expanded to include multiple projects, product lines, or manufacturing environments, enabling comparisons across operational contexts and improving the generalizability of the results. Additionally, longer-term data would enable further analysis of the behaviour of scheduling structure stability and material flows across different planning cycles.

Further research could also examine the relationship between time-series volatility and material flow in greater depth using causal or predictive analyses. For example, machine learning models could be used to predict material shortages, scheduling deviations, or changes in inventory levels. Additionally, the thesis could be supplemented with qualitative methods, such as interviews or process flowcharting, to better understand policies at the production-purchasing interface and the decision-making processes for scheduling changes.

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Appendices

Appendix 1. Case projects

This appendix outlines the scope and structure of the case project, including key scheduling data such as SoA orders. The data are drawn from a single-product-line project comprising twelve engines and serve as the basis for the empirical analysis.

SoA Order	**Project**
1	Project 1
2	Project 2
3	Project 3
4	Project 4
5	Project 5
6	Project 6
7	Project 7
8	Project 8
9	Project 9
10	Project 10
11	Project 11
12	Project 12

Appendix 2. Data extraction and measures

This appendix outlines the data extraction process and the key calculation metrics used in the analysis. It describes the data extraction logic and defines the metrics for assessing scheduling stability, deviations, and material flow performance, ensuring transparency and reproducibility of the analysis.

A2.1 Data extraction

The data used in this study were extracted from an ERP-based database using SQL queries. The extraction focused on planned requirement timing history, final planned requirement timings, and actual requirement timings.

For confidentiality reasons, the exact SQL queries are not disclosed. The data extraction process included:

- Retrieval of planned requirement timing history across planning cycles, including validity periods and historical changes.
- Extraction of final planned requirement timings, representing the latest planning state.
- Extraction of actual requirement timings, based on material movements.

The extracted datasets are cleaned, transformed, and combined in Power BI using Power Query. The transformation process includes filtering data, standardizing formats, and merging relevant datasets. The final dataset is structured to enable comparison of planned and actual requirement timings and to support subsequent analysis and visualization.

A2.2 Definitions and base calculations

Definitions and base calculations establish the key variables used in the analysis. In this study, requirement timings are examined relative to the SoA, which serves as a common reference point. All planned and actual requirement timings are expressed relative to the SoA, enabling consistent comparison across observations. Deviation measures quantify the difference between planned and actual requirement timings.

A2.3 Stability measures

Scheduling stability was assessed using measures that capture the variation in planned requirement timings over time.

Change Count = Number of changes in Planned Requirement Timing across planning cycles

Change Magnitude = Planned Requirement Timing (current) – Planned Requirement Timing (previous)

Timing Spread (TS) = Maximum Planned Requirement Timing – Minimum Planned Requirement Timing

Total Variation (TV) = Last Planned Requirement Timing – First Planned Requirement Timing

Instability = Average TV across requirements

A2.4 Deviation measures

Deviation measures quantify requirement timing deviations, defined as the difference between actual and planned requirement timings.

Deviation = Actual Requirement Timing – Planned Requirement Timing

Absolute Deviation = |Actual Requirement Timing – Planned Requirement Timing|

Early Deviation = Deviation < 0

JIT Deviation = Deviation = 0

Late Deviation = Deviation > 0

Early % = (Number of early Deviations / Total requirements) × 100

Late % = (Number of late Deviations / Total requirements) × 100

Deviation % = Early % + Late %

A2.5 Material flow performance measures

Material flow performance was evaluated using operational metrics derived from internal ERP data.

Inventory Index = Inventory Value / Average Inventory Value

Excess Inventory Index = (Total Inventory – Short Term Required Inventory) / Average Excess Inventory

Material Availability % = (On-time delivered POs / Total POs) × 100

Shortage Index = Material Shortages / Average Material Shortages

These measures enable systematic analysis of scheduling stability, requirement timing deviations, and their impact on material flow performance while safeguarding confidential system-specific details.