THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Digitalization for flexible and resilient production planning and scheduling in customer-driven manufacturing

Transforming Manufacturing to the future

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Abstract

Engineer-to-order (ETO) manufacturing companies worldwide are improving their production planning and scheduling efficiency to become more flexible and resilient to overcome the customer-driven manufacturing segment's uncertainty, product complexity and volatility. The fourth industrial revolution that promotes digitalization provides new opportunities for modernizing production systems, especially production planning and scheduling systems. Technological support is essential to overcome the various production planning and scheduling challenges. The thesis aims to understand the (i) main challenges for performing production planning and scheduling operations in manufacturing companies that follow an ETO strategy and (ii) how digitalization could facilitate production planning and scheduling operations in ETO manufacturing. The Design Research Methodology (DRM) approach was adopted in the thesis with theoretical and empirical studies.

The thesis explores and categorizes the ETO production planning and scheduling challenges. The categorization of the challenges indicates that replanning or rescheduling production plans or schedules is a vital activity and a significant concern for manufacturing companies that follow an ETO strategy, and a collaborative planning environment is essential in achieving effective replanning and rescheduling. The thesis also explores the strategies and solutions for facilitating production planning and scheduling operations in ETO manufacturing companies. The thesis emphasizes the importance of integration from an organizational perspective (horizontal and vertical) and integration from a technical perspective (between planning tools and systems) as crucial elements to achieve a collaborative planning environment in ETO manufacturing. The thesis studies the application of digital tools in the ETO production planning and scheduling environment and indicates that digital tools like simulation and data analytics could facilitate replanning or rescheduling in uncertain situations and thereby enhance production planning and scheduling in manufacturing companies in the ETO segment. Thus, the thesis results provide strong arguments that the application of digitalization supports the development of flexible and resilient production planning and scheduling systems in ETO manufacturing.

Keywords: production planning, production scheduling, engineer-to-order, one-of-a-kind production, digitalization, Industry 4.0, decision support systems

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List of Appended Papers

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Contribution **Ninan Theradapuzha Mathew** is the principal author of the paper. Ninan also planned the study and collected and analyzed the data. Björn Johansson contributed to improving the paper's overall structure, reviewing the paper, and providing feedback.

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List of Abbreviations

ETO	Engineer-to-Order
DRM	Design Research Methodology
CPS	Cyber-Physical Systems
IoT	Internet of Things
AI	Artificial intelligence
AM	Additive manufacturing
MPC	Manufacturing Planning and Control
PPC	Production Planning and Control
MTS	Make-to-Stock
MRP	Material Resource Planning
JIT	Just-in-Time
ERP	Enterprise Resource Planning
S&OP	Sales and Operations planning
MPS	Master Production Scheduling
SFC	Shop Floor Control
PAC	Production Activity and Control
MTS	Make to stock
ATO	Assemble to order
MTO	Make to order
OKP	One-of-a-Kind products
DTO	Design-to-Order
APP	Aggregate Production Planning
OPP	Operational Production Planning
IT	Information Technology
ICT	Information and Communication Technologies
HCI	Human Computer Interaction
RC	Research Clarification
DS-I	Descriptive Study I
PS	Prescriptive Study
DS-II	Descriptive Study II
CERTH	Centre for Research and Technology

1

Introduction

1.1 Background

Manufacturing companies worldwide are now going through a paradigm shift in their culture, operational procedures, and strategies. By the beginning of the 21st century, the manufacturing segment was moving more from mass production to mass customization, and the trend is more towards personalized or customized production. The transformation towards a more customized production strategy gives many manufacturing organizations a competitive advantage, which signifies the importance of customer-driven manufacturing systems in the modern era. Engineer-to-order (hereafter ETO) manufacturing strategy enables companies to design, develop, manufacture, and deliver customized products (Bhalla et al., 2023). However, the ETO manufacturing industry or the customer-driven manufacturing segment faces challenges like high demand fluctuations and uncertainties in product design, process characteristics, material availability, lead times uncertainties, etc. These challenges affect the manufacturing systems' productivity and efficiency and thus cause delivery issues and customer dissatisfaction. To overcome these challenges, it is crucial for manufacturing companies that follow an ETO manufacturing strategy to adapt their production planning and scheduling operations according to the fluctuations in demand, volume, product variety, etc., in a way that will not affect the delivery plans with the customers.

The fourth industrial revolution, also known as Industry 4.0 (a German Federal Government Initiative), and the need for sustainable development drive innovation in the manufacturing sector by applying advanced digital technologies in manufacturing (Oztemel & Gursev, 2020). In other words, the concept of Industry 4.0 is primarily led by flexible manufacturing through digital transformation. It includes the application of several digital technologies such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Big data and Analytics, Cloud Technology, Blockchain, Simulation and Modeling, Automation and Industrial Robotics, Artificial intelligence (AI), Visualization Technology: Virtual Reality/Augmented Reality and Additive Manufacturing (AM) (Zheng et al., 2021). The application of digital technologies helps manufacturing organizations undergo digital transformation (Ghobakhloo, 2020). Digital transformation provides many opportunities for manufacturing companies to gather, visualize, analyze, and manage their production-related data, information, and knowledge in a better way to aid in the development of fully integrated (horizontal and vertical), automated, flexible, and resilient production planning and scheduling systems (Da Silva et al., 2020).

Even though there are studies from the academic and industrial community regarding the significance of digitalization and the application of digital tools in improving production planning and control function in general, there is still a lack of clarity on the appropriate digital tools, especially for developing flexible production planning and scheduling tools in the ETO segment. This thesis aims to contribute towards this research gap and explore how digitalization could support and help to achieve flexible and resilient production planning and scheduling in the ETO segment.

1.2 Vision, aim, and research questions

The thesis envisions flexible production planning and scheduling in the ETO manufacturing segment through digitalization or applying digital tools. Here, flexibility means the ability to efficiently replan or reschedule production plans or schedules to cope with the uncertainty and volatility in the ETO manufacturing segment.

The thesis aims to investigate the challenges regarding production planning and scheduling in ETO manufacturing and explore the potential of digitalization in achieving flexible production planning and scheduling in the ETO manufacturing segment. Attaining a proper understanding of the capability of digitalization in improving the flexibility of production planning and scheduling process will help manufacturing companies in the ETO segment become more resilient to unexpected production disturbances, which will help manufacturing companies reduce productivity loss and improve delivery reliability and customer satisfaction.

Two research questions have been designed to achieve the thesis aim.

Due to its highly customized product strategy, the ETO manufacturing segment's production planning and scheduling process faces many uncertainties or challenges. These uncertainties or challenges demand flexible production planning and scheduling in the ETO manufacturing segment. Therefore, it is necessary to have a clear picture of the several types of challenges and how they affect the smooth functioning of the production planning and scheduling process before investigating how digitalization could enhance the production planning and scheduling process in the ETO segment. Hence, research question 1 aims to explore and understand the significant challenges associated with the ETO manufacturing segment's production planning and scheduling process.

RQ1: What are the main challenges for performing production planning and scheduling in manufacturing companies with an ETO strategy?

With a better understanding of the significant challenges regarding the production planning and scheduling process in the ETO segment, the next step is to explore and find out how digitalization could help improve the production planning and scheduling process. Hence research question 2, aims to explore and develop an understanding of how digital tools could be applied and used to enhance the production planning and scheduling process in the ETO segment.

RQ2: How do digitalization or digital technologies help improve production planning and scheduling operations in manufacturing companies with an ETO strategy?

1.3 Delimitations

The main scope of the thesis extends to a practitioner’s view on the impact of digitalization on the production planning and scheduling process in the ETO segment. Hence the focus is on the challenges regarding the production planning and scheduling process faced by stakeholders (personnel who conduct the production planning and scheduling process) in manufacturing companies that only follow an engineer-to-order strategy. In this thesis, digitalization refers to a broader spectrum of digitalized technologies, and the application of digitalization does not mean the development of digital technologies but their adoption to enhance the flexibility of the production planning and scheduling process. The thesis targets ETO segment manufacturing companies and is not limited to any manufacturing sector. However, the proposed solutions in the thesis are developed based on the specific requirements of manufacturing organizations participating in the case studies. They could apply to a broad spectrum of manufacturing companies that follow an ETO strategy with some modifications requiring further investigation.

The thesis is delimited in the following manner.

- The thesis delimits the investigation of challenges and the application of digitalization in the ETO segment from an overall supply chain perspective. The study is limited to the production planning and scheduling operations within a single manufacturing company that follows an ETO strategy.
- The thesis delimits the development and application of production scheduling approaches using scheduling algorithms, dispatching rules, mathematical models, and other heuristic methods.
- The thesis delimits installing and implementing digital technologies in ETO manufacturing companies.
- The thesis delimits the quantitative measurement of digitalization's impact on the ETO segment's production planning and scheduling process.
- The thesis delimits the financial aspects regarding adopting, implementing, and using digital technologies in the ETO segment.

1.4 Thesis Structure

After the introduction (first chapter), the thesis is divided into five more chapters. The summary of thesis chapters two to six is given below:

Chapter 2 **Frame of Reference** (second chapter) provides the theoretical foundation behind the thesis. The chapter includes the concepts of manufacturing systems, manufacturing planning and control, ETO manufacturing strategy, ETO manufacturing planning and control, Industry 4.0 (fourth industrial revolution), and digital tools.

Chapter 3 **Research Methodology** (third chapter) provides details about the research paradigm, research approach, research design, research methods and the data collection methods used in the thesis work.

Chapter 4 **Results** (fourth chapter) describes the thesis results as a summary of appended papers and the contributions to research question 1 and research question 2.

Chapter 5 **Discussion** (fifth chapter) answers the research questions, reflects on thesis contributions to industry and academia, reflects on thesis methodology and gives an outlook on future research work.

Chapter 6 **Conclusion** (last chapter) concludes this thesis.

2

Frame of Reference

The frame of reference chapter describes the theoretical framework guiding this thesis. The chapter is divided into six subsections, including concepts on manufacturing systems, manufacturing planning and control, manufacturing planning and control framework, manufacturing strategies, ETO manufacturing strategy and ETO production planning and control and finally, Industry 4.0 and digitalization.

2.1 Manufacturing System

Manufacturing and its environment include the flow of materials, the flow of resources, and the flow of information between the production system, management system, suppliers and customers (Dauzère-Péres & Lasserre, 1994). The material flow inside the manufacturing company consists of raw materials, components (parts), and other semi-finished items needed to produce the customer's products, and suppliers are the entities that provide the materials required for manufacturing (Jonsson & Mattsson, 2009). Thus, a manufacturing environment has suppliers on one end and customers on the other (Dauzère-Péres & Lasserre, 1994). Figure 1 below represents the interactions between the management system, production system and environment.

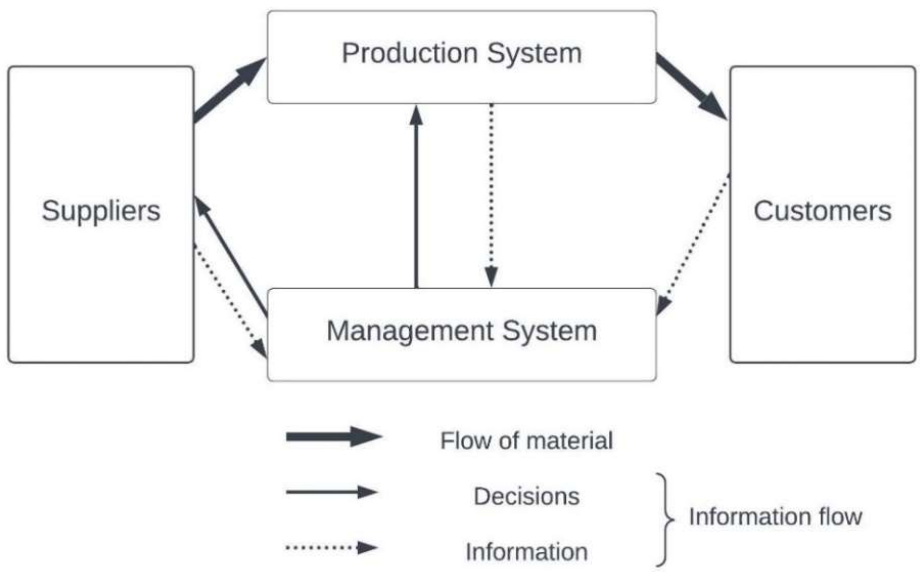

Figure 1. Interactions between management system, production system and environment (Dauzère-Péres & Lasserre, 1994)

In the manufacturing environment, materials are processed during the production process. Thus, a production system includes resources (workers and machines) required to transform raw materials into finished products (Dauzère-Péres & Lasserre, 1994). The value-adding activity in a manufacturing environment occurs during production and is made possible by the flow of production resources (Jonsson & Mattsson, 2009). The finished products are delivered to customers. The monetary flow in the manufacturing environment happens when the customer pays the manufacturing company for finished products, and the manufacturing company, in turn, pays the supplier for the materials supplied. The material flow, resource flow and money flow in the manufacturing environment are initiated by the flow of information (Jonsson & Mattsson, 2009).

2.2 Manufacturing Planning and Control (MPC)

From a managerial point of view, the flows within manufacturing could be controlled from a material perspective (material management) and a production perspective (production management) (Jonsson & Mattsson, 2009). Both the materials flow and production flow (flow of resources) in a manufacturing environment are interconnected, and the joint management of both these concepts could be termed Manufacturing Planning and Control (hereafter MPC) or Production Planning and Control (hereafter PPC). (Jonsson & Mattsson, 2009) defines Manufacturing Planning and Control as follows: *"It is one part of the subject area of logistics, often defined as planning, development, coordination, organization, management and control of material flows from raw materials suppliers to end users"*. (Jacobs et al., 2011), also provides a similar description of an MPC system - *"the main task of an MPC system is to manage efficiently the flow of materials, to manage the utilization of people and equipment, to respond to customer requirements by utilizing the supplier capacities and that of the internal facilities and in some cases that of the customers to meet customer demand"*. (Kiran, 2019) defines production planning and control like this: *"Production planning and control (PPC) is the brain and the nervous system of the production program and is responsible for ensuring the availability all materials, part of assembly at the right time, at the right place, and in right quantities to enable the progress of operations according to the predetermined schedules at the minimum possible costs"*. From all these definitions, it is evident that MPC activities are critical for meeting customer expectations.

The history behind MPC could be separated into the period before and after the 1950s, as until the 1950s, manufacturing activity was based on customer orders (Jonsson & Mattsson, 2009). During the 1950s, product complexity increased, leading to an increase in production lead time, but at the same time, there was a demand for faster or shorter product delivery times (Jonsson & Mattsson, 2009). From a manufacturing strategy perspective, the production activity became forecast-oriented, and the make-to-stock (hereafter MTS) strategy started to appear in manufacturing companies (Jonsson & Mattsson, 2009). These changes brought new requirements in production planning, and the concept of MPC or PPC was introduced during the 1950s (Jonsson & Mattsson, 2009). However, during the 1950s and 1960s, the material management perspective and production management perspective were considered separately (Jonsson & Mattsson, 2009). From a material management perspective, material resource planning (hereafter MRP) systems were introduced during the 1960s (Jonsson & Mattsson, 2009), (Kiran, 2019). By the 1970s, manufacturing companies realized a more integrated approach was required to provide an effective MPC process rather than considering the materials or production perspective alone (Jonsson & Mattsson, 2009). Thus, MRP II was introduced with a more integrated approach, considering the materials perspective and the production perspective and importance was also given to reporting from manufacturing (Jonsson & Mattsson, 2009), (Kiran, 2019).

By the beginning of the 1990s, flexibility had become an essential aspect of manufacturing, and there was a demand for more product variants and shorter delivery times (Jonsson & Mattsson, 2009). At the same time, concepts like lean production and just-in-time (hereafter JIT) were introduced to MPC to attain more flexibility in planning and control (Jonsson & Mattsson, 2009). These changes led to the development of Enterprise Resource Planning (hereafter ERP) systems (Jacobs et al., 2011). The ERP systems helped multiple functions in a manufacturing company to involve in MPC activities simultaneously using different interfaces available in the ERP tool for various activities like forecasting, material procurement, customer order management, material flow planning and production control (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). After the 1990s, the ERP systems were developed further to facilitate MPC from a supply chain (multi-company perspective) and led to new concepts like ERP II or Extended ERP systems (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). Nowadays, ERP systems are becoming more open in a way that helps integrate processes between multiple companies. The MPC frameworks discussed further in this chapter are based on an ERP system perspective (Jonsson & Mattsson, 2009).

2.3 Manufacturing Planning and Control Framework

The MPC framework usually has a hierarchical structure (Dauzère-Péres & Lasserre, 1994), and one method of defining the MPC framework is based on the levels of control (Jonsson & Mattsson, 2009). The different control levels are defined as Strategic, Tactical and Operative, including execution and control systems (Dauzère-Péres & Lasserre, 1994).

Strategic Control Level

Strategic Control is aimed at deciding the company's position in the business environment. At the strategic level, different decisions are taken like the product mix, the range of product variants, market-based production footprint or common production facility, the decision on production capacity sizing, the decision on manufacturing strategy whether to deliver products from stock or directly to customer orders and decision on supplier structure (Dauzère-Péres & Lasserre, 1994), (Jacobs et al., 2011). The level of detail in the planning information at this level is limited, the precision level of the information is also low, and the general period of strategic control level decisions could be a year or more (Dauzère-Péres & Lasserre, 1994), (Jonsson & Mattsson, 2009).

Tactical Control

At the tactical control level, the focus is to adapt and develop the company structure based on the decisions made at the strategic level. The different decisions at the tactical control level include preparing the sales and production plans, choosing the manufacturing layout, centralized or decentralized planning, the decision on the planning system and planning methods, and decision regarding order quantities and safety stocks (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). The planning information at the tactical control level is more detailed and precise when compared to the strategic control level, and the time span of tactical control level decisions could be from 6 months up to a year (Dauzère-Péres & Lasserre, 1994), (Jonsson & Mattsson, 2009).

Operative Control

The lowest level of control is the operative control level, aimed at putting into practice the decisions made at the strategic and tactical control levels. In other words, operative control focuses on planning and controlling ongoing activities and daily planning decisions (Dauzère-Péres & Lasserre, 1994), (Jonsson & Mattsson, 2009). The different decisions at the operative control level include setting customer delivery dates, monitoring delivery dates, short-term capacity and workload planning, prioritizing orders on the shop floor, and inventory management (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). The planning information at the operative control level is highly detailed and precise when compared to the strategic and tactical control levels, and the period of operative control level decisions could be days or weeks (Dauzère-Péres & Lasserre, 1994), (Jonsson & Mattsson, 2009).

Another method of defining the MPC framework hierarchical structure is based on different time horizons, levels of details and precision of details (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). According to these three factors, the MPC framework could be structured into different planning levels such as Sales and Operations Planning (hereafter S&OP), Master Production Scheduling (hereafter MPS), Order Planning, Execution and Control, and Procurement (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). The relationship between different planning levels from the materials and capacity perspectives is given in Figure 2.

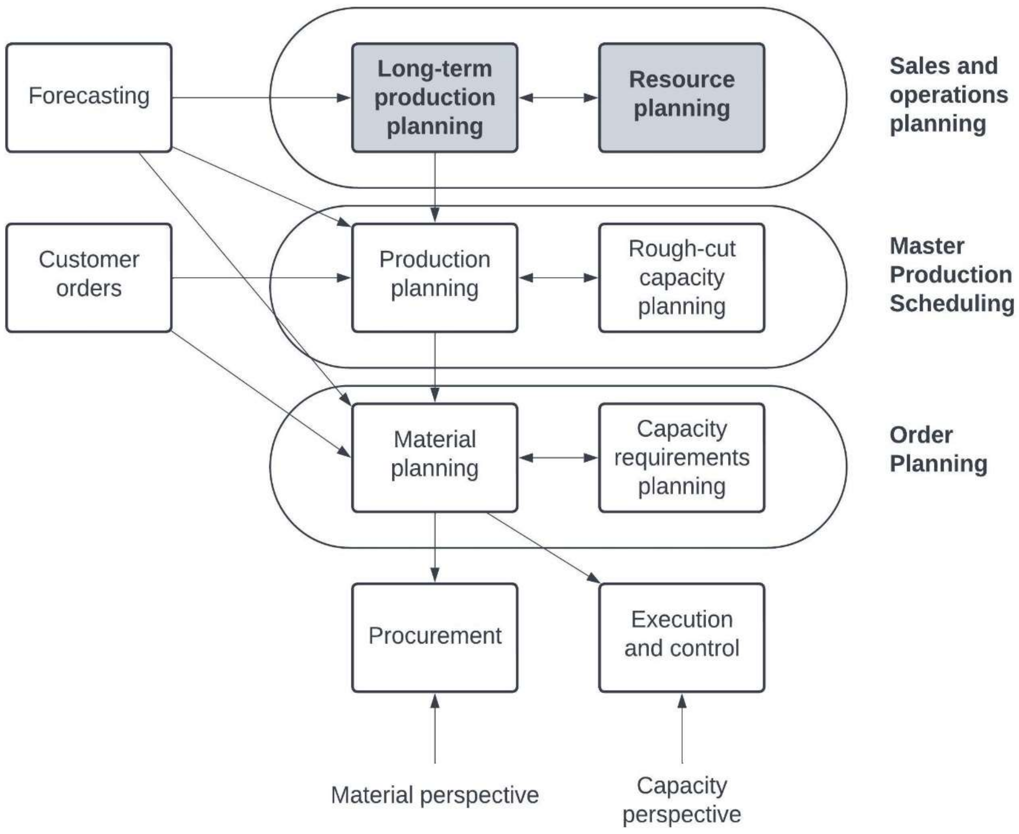

Figure 2. Planning from the materials and capacity perspectives (Jonsson & Mattsson, 2009).

Another method of defining the MPC framework hierarchical structure is based on different time horizons, levels of details and precision of details (Jonsson & Mattsson, 2009), (Jacobs et al., 2011). According to these three factors, the MPC framework could be structured into different planning levels such as Sales and Operations Planning (hereafter S&OP), Master Production Scheduling (hereafter MPS), Order Planning, Execution and Control, and Procurement (Jonsson & Mattsson, 2009), (Jacobs et al., 2011).

Sales and Operations Planning

The S&OP is the highest planning level; hence, the details in the planning information are low and with the least precision (Jonsson & Mattsson, 2009). S&OP has the most extended planning horizon with one or two years (Jonsson & Mattsson, 2009). The planning process is at the company's top management making decisions on sales and production plans based on the company's business goals and strategies (Jonsson & Mattsson, 2009). In other words, S&OP balances the sales/marketing plans of the organization with the available production resources (Jacobs et al., 2011). S&OP is sometimes called Aggregate Planning (Chapman, 2006), (Kiran, 2019). The planning objects at this level are in the form of product groups (product families), and plans are usually made based on forecasts or future demand for company products (Chapman, 2006), (Jonsson & Mattsson, 2009).

Master Production Scheduling

MPS is the second-highest planning level, and the planning horizon at this level is from six months to a year (Jonsson & Mattsson, 2009). The planning information at this level is more detailed and precise when compared to the S&OP planning level (Chapman, 2006), (Jonsson & Mattsson, 2009). MPS could be defined as a disaggregated version of S&OP (Chapman, 2006), (Jacobs et al., 2011), (Kiran, 2019). MPS is usually expressed as manufacturing orders with information on delivery dates, order quantities and production schedules based on customer orders and forecasts (Jonsson & Mattsson, 2009). The planning objects at the MPS level are products (Chapman, 2006), (Jonsson & Mattsson, 2009).

Order Planning

The third planning level is Order planning, which is more related to planning the materials and capacity in a more detailed manner when compared to the first two levels (Chapman, 2006), (Jacobs et al., 2011). The planning horizon at the Order planning level is typically two to six months (Jonsson & Mattsson, 2009). The focus at the order planning level is to make sure that all the required raw materials, purchased items or components, and other semi-finished items are either purchased or manufactured and thereby made available in the right quantities at the right time so that the master production schedules established at the second planning level could be performed smoothly (Chapman, 2006), (Jacobs et al., 2011). Order planning is expressed in the number of planned manufacturing orders, and the planning objects at this level are components or semi-finished items used in various products (Jonsson & Mattsson, 2009).

Execution and Control

Execution and Control is the lowest planning level with the shortest planning horizon of days or weeks (Jonsson & Mattsson, 2009). The other names for Execution and Control are Shop Floor Control (hereafter SFC) and Production Activity and Control (PAC) (Chapman, 2006), (Jonsson & Mattsson, 2009). The planning information at this level is highly detailed and precise, and the execution and control system could be divided into three subgroups-shopfloor systems, purchasing systems (procurement) and quality management systems (Jacobs et al., 2011). This level focuses on releasing manufacturing orders to the shop floor along with material availability checks and manufacturing order sequencing on manufacturing resources (Jonsson & Mattsson, 2009). The planning object at this planning level is manufacturing operations (manufacturing steps) belonging to planned manufacturing orders at the Order planning level (Jonsson & Mattsson, 2009). Combining both methods for defining the MPC framework, the operative control level consists of planning levels such as Order Planning from a materials perspective and Execution and Control from a capacity perspective.

Based on the characteristics of manufacturing environments, the planning level could be integrated, or the planning activities could overlap between different planning levels (Jonsson & Mattsson, 2009). Sometimes, the planning activities belonging to S&OP and MPS planning levels are combined to form one planning level called Master planning (Jonsson & Mattsson, 2009). In lean manufacturing environments, where the material flow is based on a pull system, the execution and control level could be integrated with the order planning level (Jonsson & Mattsson, 2009). On the other hand, in manufacturing environments with uncertainty, long lead times, discrete, non-repetitive material flows and capacity requirements, the execution and control level planning are done extensively (Jonsson & Mattsson, 2009), (Kiran, 2019). In general, the requirements from an MPC system are related to the company's production process, the degree of supply chain integration, customer expectations and the company management's needs (Jacobs et al., 2011). At all planning levels, the materials and capacity perspectives are important. From a longer planning horizon perspective, more importance is given to capacity when detailed information is not available on products or materials (Jonsson & Mattsson, 2009). Hence for the S&OP planning level, capacity planning is more significant (Jonsson & Mattsson, 2009). However, as the planning horizon gets reduced, as in MPS and Order Planning levels, there is less and lesser margin to make capacity adjustments (Jonsson & Mattsson, 2009). At the Execution and Control level, it is more challenging to make capacity adjustments as there could be many resource limitations, and therefore, importance is given to effective capacity utilization by prioritizing material flows and order sequencing (Jonsson & Mattsson, 2009). However, not only the factory needs but also the manufacturing strategy of the organization also plays a crucial role in deciding the MPC system structure, needs and requirements (Jacobs et al., 2011). Based on the manufacturing strategy of the organization, more emphasis would be on various parts of the MPC system to meet customer expectations (Jacobs et al., 2011).

2.4 Manufacturing Strategy

Production Systems could be classified or categorized into different typologies based on the extent to which the manufacturing operations are customer-order initiated, and this categorization could be further defined based on the concept of Customer Order Decoupling Point (hereafter CODP) (Jonsson & Mattsson, 2009). CODP could be defined as the position in the bill of material from which material supply and value-added activities are initiated by customer order (Jonsson & Mattsson, 2009). In other words, the point in the bill of material from which the material planning or the flow of goods is not rooted in forecasts but is customer-driven (Wikner & Rudberg, 2005). Based on the position of the CODP, the production systems could have different manufacturing strategies. They are commonly Make to stock (MTS), Assemble to order (ATO), Make to order (MTO), and Engineer to order (ETO) (Wikner & Rudberg, 2005), (Chapman, 2006), (Jonsson & Mattsson, 2009). Figure 3 below provides different manufacturing strategies based on different CODP (Olhager, 2010).

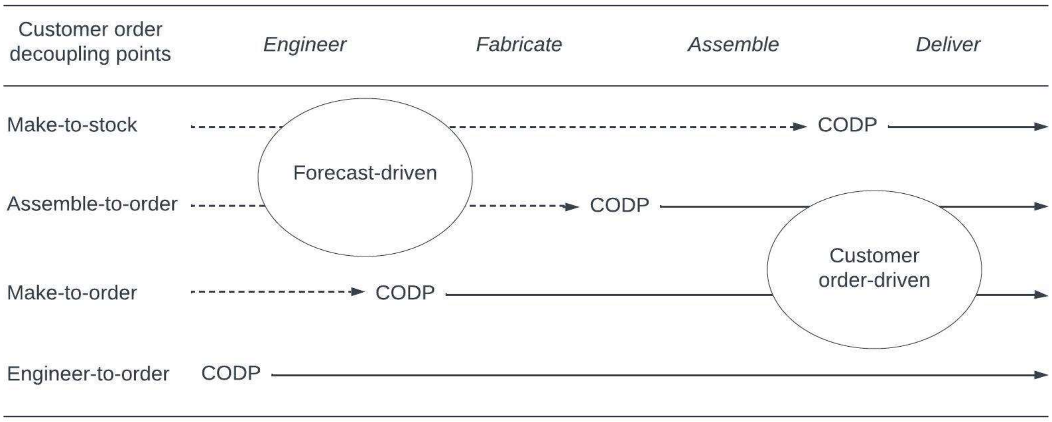

Figure 3. Manufacturing strategies based on different CODP (Olhager, 2010)

2.5 Engineer-to-order manufacturing strategy

According to the ETO manufacturing strategy, each product has a degree of customization and, to a greater extent, is designed and manufactured based on the requirements of individual customers. In other words, each product is either engineered from scratch or re-engineered from an existing design based on customer requirements (Adrodegari et al., 2015). Hence, the ETO strategy is highly suitable for manufacturing companies that produce highly customized and non-repetitive products (Amaro et al., 1999), (Pandit & Zhu, 2007). For companies that follow an ETO strategy, the manufacturing process generally consists of two stages: a non-physical stage (includes activities like tendering, engineering, design, and project management) and a physical stage (includes activities like component manufacturing, sub-assembly, assembly, and logistics) (Bertrand & Mutslag, 1993), (Amaro et al., 1999), (Wikner & Rudberg, 2005), (Gosling & Naim, 2009). The combination of non-physical and physical stages forms the basis for the ETO segment's PPC framework. Products manufactured using the ETO strategy are also referred to as one-of-a-kind products (OKP) (Caron & Fiore, 1995). Some papers have used OKP as an acronym for highly customized products or to refer to products from a particular domain (Wortmann et al., 1996), (Tu, 1997a). Hence ETO manufacturing is also known as one-of-a-kind production. Another paper (Stavrulaki & Davis, 2010) defines ETO as design-to-order (DTO), which describes DTO like OKP, where products are highly customized according to customer requirements and preferences.

Most ETO companies are independent entities (Anderson Jr et al., 2000). As the products are highly customized and unique, the number of customer orders and production volume is low in companies with an ETO strategy when compared to other strategies like MTO, ATO and MTS (Gelders, 1991), (Tu, 1997a), (Wikner & Rudberg, 2005). However, the production variation is high, and products could have complex, multilayered and deep bill of materials (Gelders, 1991), (Hicks et al., 2001), (Wikner & Rudberg, 2005). Due to the uniqueness and complex nature of the products, the lead times are long (both delivery and supply aspects), and results in higher product unit cost with the ETO strategy (Adrodegari et al., 2015). Regarding product design and development, engineering changes could happen during the production phases; therefore, the ETO strategy has concurrent design and production activities (Hameri & Nihtilä, 1998), (Hicks et al., 2001). Customer integration is high for manufacturing companies with an ETO strategy (Jonsson & Mattsson, 2009). In the case of demand forecasting, the accuracy is low; hence, production planning activities are carried out based on customer orders rather than forecasts (Anderson Jr et al., 2000), (Olhager, 2003). Each customer order is usually considered a project in the ETO segment (Hicks et al., 2001). Regarding material procurement, purchasing is done based on project requirements and supplier relationships are either formed based on partnerships or contractual basis (Caron & Fiore, 1995), (Hicks et al., 2001), (Wikner & Rudberg, 2005). Overall, the ETO strategy corresponds to much uncertainty in terms of product specifications, product mix, product volume, supply and delivery lead times and production process and high level of volatility as the market itself could vary drastically and within one year to another, the volume of customer orders could change by more than 50% (Anderson Jr et al., 2000), (Adrodegari et al., 2015).

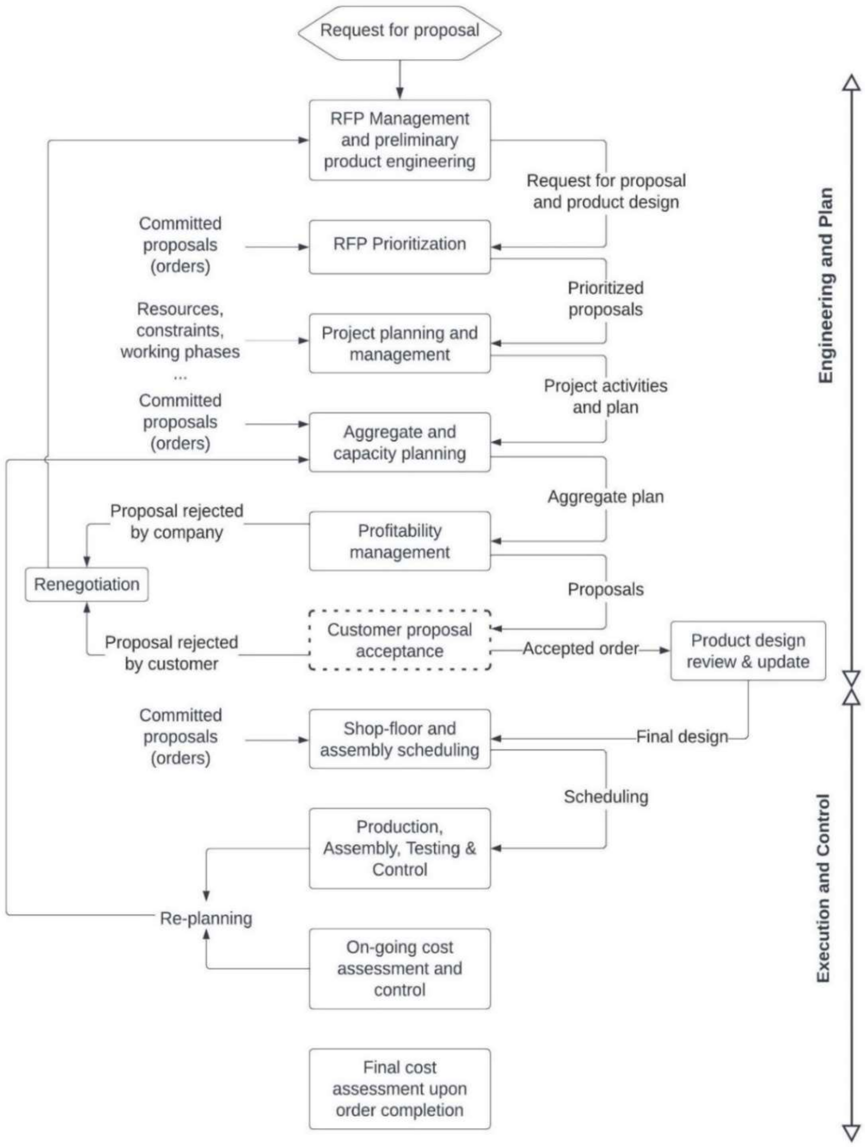

Figure 4. Production planning and control process reference framework for engineer-to-order manufacturing organizations (Adrodegari et al., 2015)

The high volatility and uncertainty in the ETO segment have made PPC activities highly relevant and significant in manufacturing companies that follow a customer-driven manufacturing strategy. However, only a few PPC frameworks are available for production management in the ETO segment (Amaro et al., 1999), (Spring & Dalrymple, 2000). One of the earliest production planning and control frameworks for customer-driven manufacturing was proposed by (Wortmann et al., 1996). (Wortmann et al., 1996) has organized the production control aspects in customer-driven manufacturing based on the planning or production control horizon. The first or higher level corresponds to *Aggregate Production Planning (APP)*. At the APP level, long-term and medium-term planning activity is done where available resource capacity is matched to capacity requirements at an aggregate level (Wortmann et al., 1996). The lower or second production control level is *Operational Production Planning (OPP)*. Here, short-term planning activity is done, and the coordination of production control activities is more detailed (Wortmann et al., 1996). The main aim is to assign the available resource capacity to individual products, and significant activity is the timing of work orders or work order scheduling or work order sequencing (Wortmann et al., 1996). Along with these two production control levels, (Wortmann et al., 1996) also introduces one more planning level, the *Interface between Production and Sales* (Wortmann et al., 1996). Another major framework proposed, especially for manufacturing companies that follow an ETO strategy, is by (Adrodegari et al., 2015). The empirical high-level production planning and scheduling reference framework includes all activities in the order fulfilment process, from the proposal request to the final cost assessment upon order completion (Adrodegari et al., 2015). The reference framework by (Adrodegari et al., 2015) is given in Figure 4 above.

(Little et al., 2000) states a general lack of tools for production planning and control activities in the ETO segment. There needs to be more clarity on what Information Technology (IT) systems are suitable for the ETO industry (Gosling & Naim, 2009). Due to the lack of specific tools for production planning and control in the ETO segment, there is a general practice of using business models or Information and Communication Technologies (ICT) tools that have been developed for other manufacturing strategies in the ETO segment (Hicks & Braiden, 2000). However, due to the complex nature of the ETO strategy, where multiple projects are carried out at the same time, at different stages of the production process, with different levels of completion and delivery times, and also subjected to frequent changes, the process of adopting methods that provide successful results in other manufacturing strategies like MTO, ATO and MTS, may not provide the same results when it comes to the ETO segment. As a result, the ICT tools used for production planning and control in the ETO segment are standalone applications or have low integration with the company ERP system (Adrodegari et al., 2015).

2.6 Industry 4.0 and Digitalization

The manufacturing industry has gone through three industrial revolutions and is currently going through the fourth industrial revolution. The first industrial revolution, or Industry 1.0, happened with the invention of steam engines, and the usage of steam power transformed the manufacturing industry (Kiran, 2019). While the second industrial revolution, Industry 2.0, happened with the usage of electric power in the manufacturing industry, which paved the way for mass production (Kiran, 2019). Computer-integrated manufacturing or the wide application of computer software to control production led to the third industrial revolution or Industry 3.0 (Kiran, 2019). However, in production planning and control, the ERP system (material planning perspective) and the machine control processes (resource planning perspective) remained nonintegrated, thus separating Industry 3.0 from Industry 4.0 (Kiran, 2019).

The concept of Industry 4.0 was first initiated by the German government as a project to promote computerization at advanced levels in German manufacturing during the beginning of the 21st century (Kiran, 2019). At the Hannover Fair in October 2012, implementation recommendations regarding Industry 4.0 were presented. From there onwards, the concept has gathered much attention in the academic and industrial communities. One definition of Industry 4.0 from the Network World website goes like this, "Industry 4.0 is digital transformation applied to manufacturing, bringing with it all the change, opportunities, and challenges that it represents. Industry 4.0 connects the supply chain and the ERP system directly to the production line, forming integrated, automated, and, potentially, autonomous manufacturing processes that better use capital, raw materials, and human resources" (Kiran, 2019). Another definition from McKinsey states that "Industry 4.0 is the next phase in the digitization of the manufacturing sector, driven by four disruptions: the astonishing rise in data volumes, computational power, and connectivity, especially new low-power wide-area networks; the emergence of analytics and business-intelligence capabilities; new forms of human-machine interaction such as touch interfaces and augmented-reality systems; and improvements in transferring digital instructions to the physical world, such as advanced robotics and 3-D printing" (Kiran, 2019). Primarily, the concept of Industry 4.0 is led by flexible manufacturing and real-time data exchange (Lopes de Sousa Jabbour et al., 2018) and is enabled by the advancement of digital technologies or digitalization (Nascimento et al., 2019).

Digitalization could be defined as applying digital technologies (Ritter & Pedersen, 2020). Another definition from (Legner et al., 2017) describes digitalization as "the manifold sociotechnical phenomena and processes of adopting and using these (digital) technologies in a broader individual, organizational and societal context". The paper (Zheng et al., 2021) provides a list of Industry 4.0 enabling digital technologies such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Big data and Analytics, Cloud Technology, Blockchain, Simulation and Modeling, Automation and Industrial Robotics, Artificial intelligence (AI), Visualization Technology: Virtual Reality/Augmented Reality, and Additive manufacturing (AM). The definition of technologies from an Industry 4.0 perspective is given below in Table 1.

Table 1. Industry 4.0 enabling digital technologies

Technologies	Definition	References
Cyber-Physical Systems (CPS)	A collection of transformative technologies that enable systems to be integrated with their physical assets and computational capabilities. The primary aim here is to monitor physical assets through virtual copies. CPS provides intelligent connectivity and continuous data management but requires substantial advancement in ICT infrastructure.	(Lee et al., 2015), (Monostori et al., 2016), (Alguliyev et al., 2018)
Internet of things ((IoT)	An information network of physical objects (sensors, machines, cars, buildings, and other items) that enables data collection and exchange, allowing interaction and	(Tilson et al., 2010), (Trappey et al., 2016), (Oztemel & Gursev, 2020b)

	cooperation of these objects. In other words, IoT connects machines equipped with sensors and actuators to the Internet and enables the machines to generate, process and communicate data to humans or machines in real time.	
Big data and analytics	The series of techniques used for the collection, analysis, and process of acquiring intelligence from large amounts of available data (big data), where data are processed in higher volumes (magnitude of data), with higher velocities (the rate of data generation and the speed at which it should be analyzed) and in greater variety (the structural heterogeneity in a dataset).	(Vera-Baquero et al., 2014), (Gandomi & Haider, 2015), (Fosso Wamba et al., 2015)
Artificial intelligence (AI)	A system that can think humanly and rationally based on six main disciplines: natural language processing, knowledge representation, automated reasoning, machine learning, computer vision and robotics. Industrial AI is the integration of AI with computer science and domain knowledge and the application in the industrial environment where the principal aim is to make the hidden problems in an industrial system explicit and then to manage and avoid them while they remain hidden.	(Monostori, 2003), (Russell & Norvig, 2010), (Lee, 2020)
Cloud technology	Systems providing online storage services for all applications and data in a virtual server without requiring installation. In a cloud manufacturing system, various manufacturing resources and abilities can be intelligently sensed and connected to the broader internet and automatically managed and controlled using IoT technologies.	(Tao et al., 2011), (Xu, 2012)
Simulation and modelling	Technologies that help create a virtual replica of physical world data, such as machines, products, and humans. In simulation and modelling, the virtual replica can be used for testing and analysis to simplify the physical systems' design, creation, and live operation for improving affordability and efficiency.	(Monostori et al., 2016), (Ghobakhloo, 2018), (Oztemel & Gursev, 2020a)
Blockchain	Distributed ledger technology, or, in other words, an electronic database, can hold	(Sikorski et al., 2017), (Ghobakhloo, 2018),

	information (records, events, or transactions) and define rules on which the information can be used. In an industrial environment, blockchain can be used to develop trusted and autonomous relationships among different components of smart factories, suppliers and even customers, as it can provide transparent, secure, fast, and frictionless financial transactions, fully autonomous without human intervention in the IoT environment.	(Viriyasitavat et al., 2020)
Visualization technology (Augmented and virtual reality)	Virtual Reality: The idea is to develop an advanced human-computer interface using computer technology. The interactive interface simulates the realistic environment and develops a connection between the participant and the created environment. The users control the virtual object and the whole virtual scene in real-time. Augmented Reality: A set of innovative Human-Computer Interaction (HCI) techniques that turn the real environment into a digital interface by interacting with virtual objects in the real world.	(Latta & Oberg, 1994), (Mujber et al., 2004), (Reif & Walch, 2008) (Yew et al., 2016), (X. Wang et al., 2016), (Ang et al., 2017)
Automation and industrial robots	Machinery, including collaborative robotics, can automize operational processes, allowing humans and machines to work in the same shared environment.	(Cherubini et al., 2016), (Ghobakhloo, 2018)
Additive manufacturing	An additive and automated process of joining materials in successive layers to produce objects from 3D model data (digital data). In additive manufacturing, fabrication may occur directly through the digital model, eliminating the need for process planning. Additive manufacturing provides immense potential for mass customization.	(Gibson et al., 2015), (Esmaeilian et al., 2016), (Durão et al., 2017)

3

Methodology

This chapter covers the research approach adopted in this thesis and is divided into three subsections. The first section includes the research paradigm, the second subsection is the research design, and the last subsection elaborates on the research questions, methods, and data collection techniques used in this thesis.

3.1 Research Paradigm

The research approach can be considered the plan or proposal to conduct research. According to (Creswell, 2013), the research approach involves the interconnection of three aspects: philosophical worldviews, research designs, and specific methods. Figure 5 below shows the research framework from (Creswell, 2013).

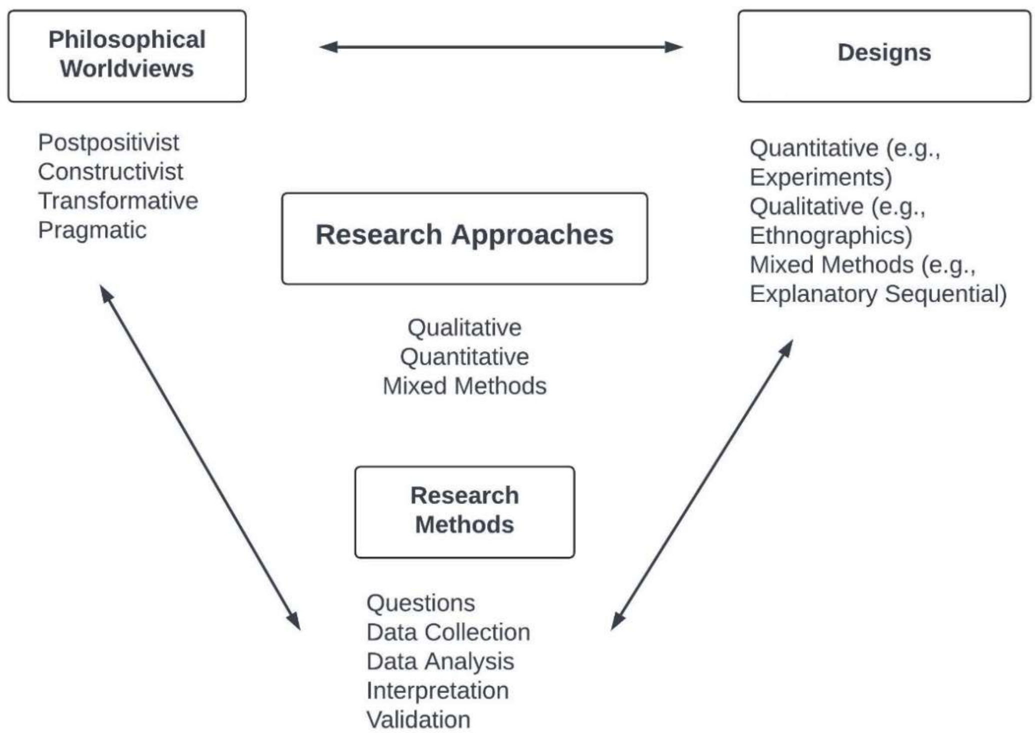

Figure 5. A Framework for Research—The Interconnection of Worldviews, Design, and Research Methods (Creswell, 2013)

The meaning behind worldviews can be considered as the basic set of beliefs that guide action (Guba, 1990). The worldviews are also considered paradigms (Lincoln & Guba, 2000), (Mertens, 2010). There are four worldviews regarding research paradigms (Creswell & Clark, 2018). They are postpositivism, constructivism, transformative and pragmatism (Creswell, 2013). Postpositivism believes that cause leads to outcomes or effects and aims to test theories (theory verification) as in experiments (Creswell, 2013). A postpositivist begins their research with a theory, collects data that supports or rejects it, makes necessary changes, and continues with more theory testing (Creswell, 2013). In constructivism or social constructivism philosophy, the researcher believes individuals develop meanings from their experiences (Creswell, 2013). Social constructivists study other people's meaning of the world rather than starting with a theory, as in postpositivism (Creswell, 2013). According to a transformative worldview, research should relate to politics and a political change agenda regarding social issues and have an action agenda that could change the lives of the research participants and the researcher (Mertens, 2010). Finally, the pragmatism philosophy focuses on research problems rather than research methods (Rossman & Wilson, 1985). The pragmatic paradigm is followed in this research.

According to (Creswell, 2013), the pragmatism worldview relates to actions, situations, and consequences and not to antecedent conditions (as in postpositivism). The main concern is with applications – what works and solutions to problems (Cherryholmes, 1992), (Patton, 2002). Hence, pragmatist researchers have more freedom and can choose different methods, techniques, and procedures to help them best meet their research needs and purposes (Creswell, 2013). The main idea of this research is to improve production planning and scheduling operations in production systems following an engineer-to-order manufacturing strategy using digital tools. Production systems following any manufacturing strategy comprise many components like machines, materials, humans, operations, and subsystems. These components are interconnected, continuously interact, and depend on each other for the effective functioning of a production system. Therefore, improving any part of a production system will also influence the different parts. In other words, improving production planning and scheduling operations in production systems with the help of digital tools will affect the humans, machines, materials, operations, and subsystems associated with the planning and scheduling. Hence, in this research, improving the production planning and scheduling process with the help of digital tools is exploratory, and it is necessary to assess each production planning and scheduling case individually and choose the best methods that would satisfy the requirements. Therefore, adopting the pragmatism research approach in this research, the researcher can explore and understand how digital tools will enhance production planning and scheduling operations more from a practical perspective (based on what works).

3.2 Research Design

The main topic of this research is to find out how digital tools can improve production planning and scheduling operations in manufacturing organizations with an engineer-to-order strategy. While considering the research topic, the effects of digitalization or digital technologies on production planning and scheduling processes are still in the exploration phase. Therefore, more studies and analyses are needed to draw more concrete conclusions. Exploration and theory-building are the central research approaches when the currently available knowledge is not mature (Creswell, 2013). The exploration could be based on existing theoretical knowledge from prior research and real-life observations. Hence, as a pragmatist, I wanted to understand the current challenges regarding production planning and scheduling in the ETO segment, identify the needed support, and propose solutions using digital tools to improve the current scenario.

A research methodology could be used flexibly and opportunistically to adapt to the specifics and requirements of the research topic and other engaging scenarios that could emerge while doing research (Blessing & Chakrabarti, 2009). As mentioned earlier, pragmatists emphasize the research problem more and could depend on pluralistic research approaches, both quantitative and qualitative, for data collection and analysis. Design Research Methodology (DRM) allows various research approaches and enables the selection of suitable methods and combinations of methods (Blessing & Chakrabarti, 2009). Therefore, DRM was chosen as the methodology for this thesis to investigate the research topic systematically and rigorously. Another research approach that could be beneficial from a pragmatist perspective could be Mixed methods research. The core idea behind Mixed methods research is the combination of qualitative and quantitative approaches to provide a more comprehensive understanding of the research problem.

DRM includes four stages, and they are Research Clarification (stage 1), Descriptive Study I (DS I), Prescriptive Study (PS), and Descriptive Study II (DS II) (Blessing & Chakrabarti, 2009). Figure 6 below shows the relationship between these four stages, the basic means used in each stage and the main outcomes (Blessing & Chakrabarti, 2009). The bold arrows indicate the main process flow in the framework, and the light arrows show the iterations (Blessing & Chakrabarti, 2009).

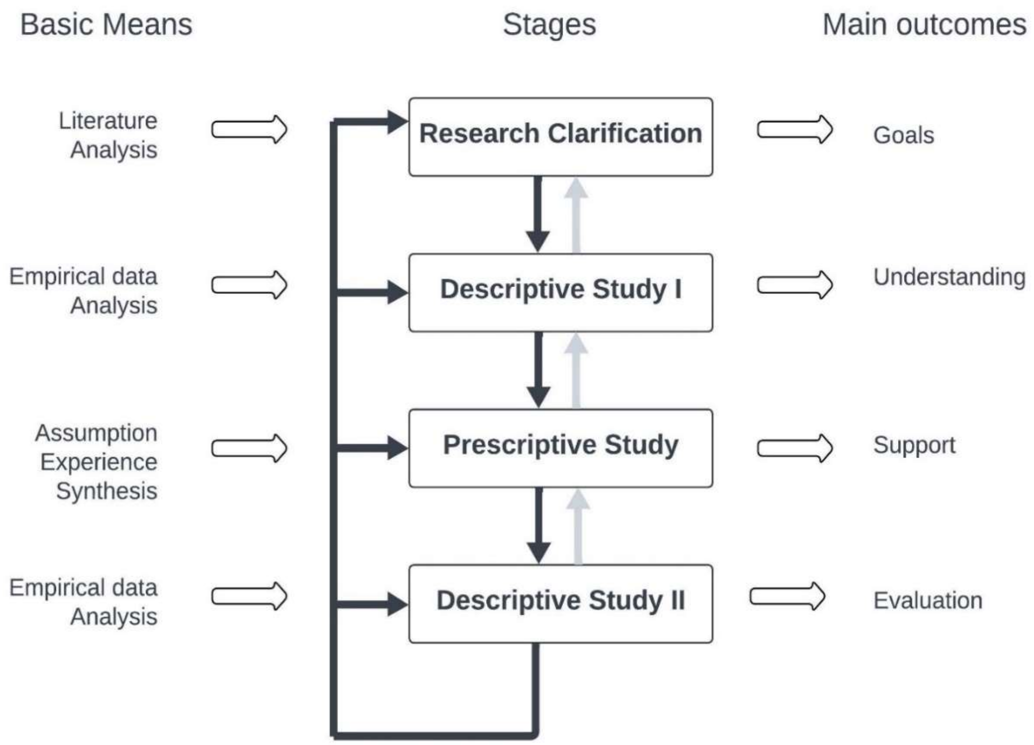

Figure 6. DRM framework (Blessing & Chakrabarti, 2009)

In the Research Clarification (RC) stage, the researchers develop an initial description of the existing situation and find evidence and indications that support their assumptions to formulate a description of the desired situation (Blessing & Chakrabarti, 2009). Information about the existing situation or challenges is gathered by analyzing the existing literature on the research topic (Blessing & Chakrabarti, 2009). In the DS I stage, the researchers aim to increase the understanding of the existing situation by investigating the research topic through literature reviews and, if the reviews are not sufficient, by undertaking empirical research and, in addition, through reasoning (Blessing & Chakrabarti, 2009). By the end of DS I, the researchers could have sufficient information to describe the existing situation, highlight the problems and point out the factors most suitable to address the improvement of the existing situation or the changes that would help to achieve the desired situation (Blessing & Chakrabarti, 2009). In the PS stage, the researchers use the increased understanding of the existing situation to develop a correct and elaborate description of the desired situation and then start the systematic development of the support that would lead to the realization of the desired, improved situation (Blessing & Chakrabarti, 2009). In the final stage, DS II, the researchers analyze the impact of the developed support and its capability to realize the desired situation with the help of empirical studies (Blessing & Chakrabarti, 2009). The thesis corresponds to the first two stages in the DRM Methodology – Research Clarification & DS-I. The remaining DRM stages, like the PS and DS-II, will be part of future research.

3.3 Research Questions, Methods, and Data Collection

From a DRM approach, research questions are essential to undertake research (Blessing & Chakrabarti, 2009). Two research questions were formulated to explore the research topic theoretically and empirically. While research questions guide the research, research methods are used to find answers to the research questions. Research methods are the techniques used to perform research (Kothari, 2004). Following the DRM approach, the research methods applied in this research consist of theoretical and empirical parts. This section describes the research questions, research studies for both theoretical and empirical parts and the data collection methods used in those studies.

As mentioned earlier, in DRM, the first stage is research clarification, and the main objective is to explore and understand the research topic. Therefore, research question 1 examines the literature to determine the main challenges and difficulties in production planning and scheduling in manufacturing companies using an ETO strategy. By thoroughly understanding the challenges, it will be easier to understand why digital tools are required, what digital tools could be used, and how they could be applied to improve production planning and scheduling operations. Research question 1 is given below:

RQ1: What are the main challenges for performing production planning and scheduling in manufacturing companies with an ETO strategy?

Literature study 1 (a review-based study) was conducted to collect answers to research question 1 in the Research Clarification Stage of this thesis. Therefore, literature study 1 focused on identifying the challenges and difficulties in production planning and scheduling for companies that follow an ETO manufacturing strategy. The Scopus database was used for the literature search. Four inclusion criteria were formulated to select relevant papers for literature study 1. The final number of papers used for literature study 1 consists of 48. The selected papers were read, and information regarding production planning and scheduling challenges was gathered. The production planning and scheduling challenges identified from literature study 1 were classified into four categories. Even though the production planning and scheduling challenges are interconnected and dependent on each other, the categorization helped identify the requirement for replanning or rescheduling as one of the main challenges for manufacturing organizations that follow an engineer-to-order strategy. The results from literature study 1 are provided in Paper 1.

The second stage of DRM aims to enhance further the understanding of the research topic from information obtained from stage 1. It will facilitate the research to collect all the required information to develop a desired design or model in stage 3. Therefore, the second research question was formulated to explore the potential and capability of digital tools in enhancing production planning and scheduling in the ETO segment both theoretically and empirically. Research question 2 is given below:

RQ2: How do digitalization or digital technologies help improve production planning and scheduling operations in manufacturing companies with an ETO strategy?

In DS I, the theoretical findings from stage 1 are enhanced with the help of a comprehensive study that includes a review-based study (literature study 2) and two empirical studies (two industrial case studies). Literature study 2 explored strategies and technical solutions for improving production planning and scheduling in manufacturing companies with an ETO strategy. The database used for the literature search was Scopus. Five inclusion criteria were formulated to select relevant papers for literature study 2. The final number of papers used for literature study 2 consists of 20. The results of the second literature study provided evidence of operational strategies and digital technologies applied to facilitate production planning and scheduling in manufacturing companies with an ETO strategy, which is mentioned in paper 2.

From an empirical perspective, two industrial case studies were performed in manufacturing organizations that follow customer-driven manufacturing or engineer-to-order manufacturing strategies. Both case studies were field studies, and qualitative methods were used for data collection. Onsite visits were conducted to gather data. The primary data collection methods for both case studies were interviews, field notes and observations. During the onsite visits, the production planning team at the case company explained the processes and operations. Direct observations were made to understand the current planning and scheduling process. Field notes were collected during the onsite visits. These onsite visits also helped to identify the right personnel for interviews. For the interviews conducted, the interview material analysis starts right after the first interview. The following interview was affected by the results of the first interview. Data collection and analysis go together; new findings will drive further data collection. This approach was adopted because the main requirement put forward by the case companies was to identify the critical issues in their production planning and scheduling processes and identify the appropriate digital tools to facilitate the production planning and scheduling processes. Hence, the adapted interview analysis approach helped the researcher explore the research project from a research perspective and steer the case studies to be beneficial for the manufacturing companies involved in the case studies. The results from literature study 2 and both case studies are provided in Paper 2. Table 2 below shows how research questions are connected to research methods and papers.

Table 2. Connection between DRM stages, research methods, research questions, data collection and research papers

DRM Stage	Research Methods	Research Questions	Data Collection	Research papers
Research Clarification	Literature Study 1	RQ1	Scientific papers	Paper 1
Descriptive Study I (DS I)	Literature Study 2	RQ2	Scientific papers	Paper 2
	Case Study 1	RQ2	Onsite visits Interviews Field notes Observations	
	Case Study 2	RQ2	Onsite visits Interviews Field notes Observations	

4

Results

The results chapter is presented in three subsections. A summary of paper 1 is provided in section 4.1, and a summary of paper 2 is given in section 4.2. The thesis results' contributions to research question 1 and research question 2 are pointed out in section 4.3.

4.1 Paper 1

Brief description

The paper aims to identify the main challenges for production planning and scheduling in manufacturing companies that follow an ETO strategy. The research method applied is literature study. The paper results provide an overview of the challenges identified from the papers selected for the literature review, and the challenges are classified into four categories. The categorization of the results helped determine the significance of replanning and rescheduling in the ETO segment.

Detailed Summary

The research study in paper 1 was conducted to find answers to research question 1. The main goal of research question 1 is to explore and discover the main challenges and difficulties that the manufacturing companies in the ETO segment could endure in the production planning and scheduling process. Production planning and scheduling is a continuous activity for manufacturing companies in the ETO environment, and these processes are interconnected and performed collaboratively with other company functions. Hence, different sorts of issues could arise within the production planning and scheduling process, affecting the production planning function and other functions and activities in the supply chain. It is critical to understand the problems clearly to find the right solutions. A proper understanding of various challenges affecting the production planning and scheduling process will also help to find answers for research question 2, which is to find out how digitalization or digital tools could facilitate the production planning and scheduling process in the ETO segment. Therefore, a literature study was designed to explore prior research and determine ETO's production planning and scheduling process challenges.

The Scopus database was used for the literature study. Two keyword combinations were used for the literature search. The papers were selected based on four inclusion criteria, and backward snowballing was used to identify more relevant papers. Fifty papers were selected finally for the literature study. The challenges identified from the literature were classified into four different categories. The categories are defined based on two factors: how the challenges occur and whom the challenges affect. The first category concerns the challenges from a manufacturing strategy perspective, and the second defines the challenges from a planning tool and technology perspective. The third category describes the challenges from a human-resource perspective and the fourth from a research perspective. Table 3 below shows the challenges categorized based on the four categories.

Table 3. Challenges classified into categories (redrawn from (Mathew & Johansson, 2023))

Challenges from a manufacturing strategy perspective	
1	Variation in product volumes or customer demands (volatile markets)
2	Late changes in product design or structure
3	The critical need for flexibility in multiple aspects (for example, product volume, product mix, suppliers, workforce, manufacturing processes, assembly procedures and so on) in the ETO segment and the difficulty for manufacturing companies to attain flexibility in multiple aspects simultaneously resulting in tradeoffs
4	Late deliveries leading to financial penalties, and early deliveries increasing holding costs
5	Frequent replanning or rescheduling of initial production plans or schedules
Challenges from a planning tool and technology perspective	
1	Need for ERP systems that could allow input of partially updated or incomplete data
2	Compatibility issues between external tools and the existing ERP system leading to data inconsistencies
3	The practice of using external tools makes data in the ERP systems outdated, which affects the whole supply chain
4	Lack of tools to provide information on the current production status
5	General lack of clarity in determining the correct ICT tools for ETO
Challenges from a human resources perspective	
1	The unique routing and bill of materials for each product make the work of a production planner highly complex in an ETO environment
2	The quality of the plan depends on the knowledge, skill level, and experience of the planners in ETO
3	Lead-time syndrome, which further results in replanning or rescheduling
4	Frequent replanning or rescheduling could increase the workload and affect the stress level and mental ability of the personnel involved in planning
5	The constant need for communication and collaboration between different functional groups for planning and replanning in ETO manufacturing environment
Challenges from a research perspective	
1	Lack of comprehensive production planning and control framework to support the whole ETO production planning and execution process.

2	Less industry-oriented studies or overall literature regarding the requirements and needs of ETO manufacturing strategy compared to other manufacturing strategies

4.2 Paper 2

Brief description

The paper aims to explore and understand whether digital tools could facilitate the production planning and scheduling process in ETO manufacturing companies. The main research methods applied here are case study research and literature study. The literature study has been performed as a pre-study to identify the solutions used in prior research to mitigate issues associated with production planning and scheduling in the ETO segment. The paper includes two industrial case studies conducted at manufacturing organizations that follow an engineer-to-order manufacturing strategy. The production planning and scheduling processes at both case companies were analyzed, and digital tools were used to help solve the identified issues faced by the case companies. The results from paper 2 provide evidence that the application of digital tools supports replanning and rescheduling processes in manufacturing organizations that follow an ETO strategy.

Detailed Summary

The methodology adopted in paper 2 was to find answers to research question 2: How digital tools or digitalization improve production planning and scheduling in manufacturing companies that follow the ETO manufacturing strategy. The methodology in paper 2 consists of theoretical and empirical parts. The theoretical part consists of literature study 2, and the empirical part consists of two case studies with manufacturing organizations with ETO strategy. The literature study explored the solutions applied to or suggested to improve production planning and scheduling in the ETO segment. Case study 1 was conducted with a Space products manufacturing organization in Gothenburg, Sweden; Case study 2 was performed with a high-end luxury textile manufacturing organization in Pollone, Italy. The total duration and project plan for both case studies had to be redesigned from the initial due to the COVID-19 pandemic.

As in literature study 1, the Scopus database was used for literature study 2. Two sets of keywords were used for the literature search with necessary Boolean operators. Five inclusion criteria were used to find the relevant papers from the available literature. After the final inclusion criteria, fourteen papers were selected. Six other papers were included in the literature study by backward snowballing. Hence, the literature study included 20 papers. The solutions identified from the literature were classified into two categories - solutions from a strategy perspective and solutions from an operational perspective. The classification was based on the literature review paper from Gosling and Naim [43]. Table 4 below shows the categorization of results from the literature study 2.

Table 4. Categorization of findings from the literature (Mathew et al., 2023)

Solutions from a strategy perspective	**Papers**
Supply chain integration	(Nambiar, 2016), (Brachmann & Kolisch, 2021), (Q. Chen et al., 2022)

Vertical integration	(Nambiar, 2016), (Sordan et al., 2022)
Lean manufacturing	(Wandt et al., 2012), (Nambiar, 2016), (Brachmann & Kolisch, 2021), (Sordan et al., 2022), (Vinci-Carlavan & Alejandro Rossit, 2022)
Agile manufacturing	(Tu, 1997b), (Dallasega et al., 2019), (Q. Chen et al., 2022), (Sordan et al., 2022)
Concurrent ETO operational framework	(C. S. Chen, 2006)
Quick response manufacturing	(W. Wang et al., 2021)
Solutions from an operational perspective	**Papers**
Simulation based solutions	(Tu, 1997b), (Wandt et al., 2012), (Dallasega et al., 2019), (Sordan et al., 2022)
Digital twins	(Padovano et al., 2021), (Sordan et al., 2022)
Collaborative planning system	(Gansterer et al., 2014)
Advanced planning and scheduling systems	(Alfnes & Hvolby, 2019), (Neumann et al., 2022)
Data analytics	(Management Association, 2016), (Zadeh et al., 2020)

For case study 1, the main aim was to understand and analyze the manufacturing organization's current production planning and scheduling process, identify improvement areas, and apply digital tools to improve production planning and scheduling process efficiency. The case study was conducted exploratively as the manufacturing organization needed guidance on enhancing its production planning and scheduling process. The case study used different procedures to collect production planning and scheduling data, and the data collection methods included supervised factory visits and qualitative interviews. Supervised onsite factory visits were done multiple times at the manufacturing facility. Field notes were gathered during the onsite factory visits. Onsite factory visits also helped to identify the right people for interviews. The interviews were conducted in a semi-structured format. Since the case study is explorative, the material analysis of the interview started right after the first interview. As mentioned earlier in the methodology chapter (section 3.3), the following interview discussion is affected by the results from the first interview. Production planning and scheduling is a collaborative process in the case study organization (typical to

ETO manufacturing). Hence, interviews were conducted with personnel from organizational functions such as planning, production, purchasing, component engineering and project management. The data collected from field notes (factory visits) and interviews were analyzed and verified with company personnel.

The data analysis identified the frequent requirement to replan shop orders as the primary concern in case study 1. Discussions were held with the relevant stakeholders at the manufacturing firm for further root cause analysis of the replanning issue and solution development. In case study 1, the replanning of shop orders was primarily due to material shortages. However, material shortages were caused by two causes: an internal issue within the company material planning process and one external issue related to suppliers. In the case company, each customer order is considered a project (typical to ETO manufacturing); each has its project-specific components. The lead-time uncertainty of project-specific components was the external issue that led to material shortages. In an engineer-to-order environment, each project is highly customized; therefore, it is difficult to maintain a proper lead-time history for project-specific components. Apart from that, it is also challenging to forecast customer orders in an ETO environment effectively. Hence, it was decided to consider the internal rather than the external issue for the case study. The internal issue was that the purchasing team needed to order the components in reference to the shop-order requisition dates in the ERP system. There was no link between the part arrival date and the actual requirement of the part on the shop floor. Due to this, if there is a delay in material, the production planning team will not know about that until the shop-order release date, which is close to the production starting date on the shop floor. This misalignment between component procurement and shop order planning caused frequent replanning and rescheduling of shop orders. Hence, the developed solution should help properly coordinate component and shop-order planning.

A comprehensive visual mapping of the components from the purchase date to their actual need date on the shop floor for each product based on its hierarchical structure was considered as a solution in the case study. A pilot solution model was developed using a data analytics software platform called Qlik Sense. Data sets in Excel files consisting of declared parts lists, purchase order lines, and shop-order requisition lines were given as input to the model. The model analyses the input files, and the output consists of a scatter plot with a single X-axis and a dual Y-axis. All the components mutually present from the declared parts list and the purchase order lines are plotted on the X-axis against their subsequent purchase order receipt dates on the Y-axis. The Y-axis also indicates the start date of the shop order requisitions.

Figure 7 below shows the conceptual diagram of the material scatter plot results for a specific product unit. The left side of Fig. 1 represents the area in the Qliksense software dashboard where the users can select a particular part description of a product unit, such as AO1 TOP ASSY, in the diagram. Then a material scatter plot will be displayed with all the components included in the AO1 TOP ASSY while connecting each component's shop order requisition dates with planned receipt dates from purchase order lines. The dots represent the components' planned receipt date in the scatter plot. All the components (dots) displayed on the scatterplot with black colour are late arriving. Visualizing late-arriving components will help the production planners know what parts could cause replanning or delays. This knowledge will help the planning team take a proactive approach to either arrange the timely delivery of material by coordinating with the concerned purchase team and suppliers or perform an early replanning of production orders to avoid the stress in the shop due to last-minute rescheduling. The developed solution was verified and validated with the case company for further implementation.

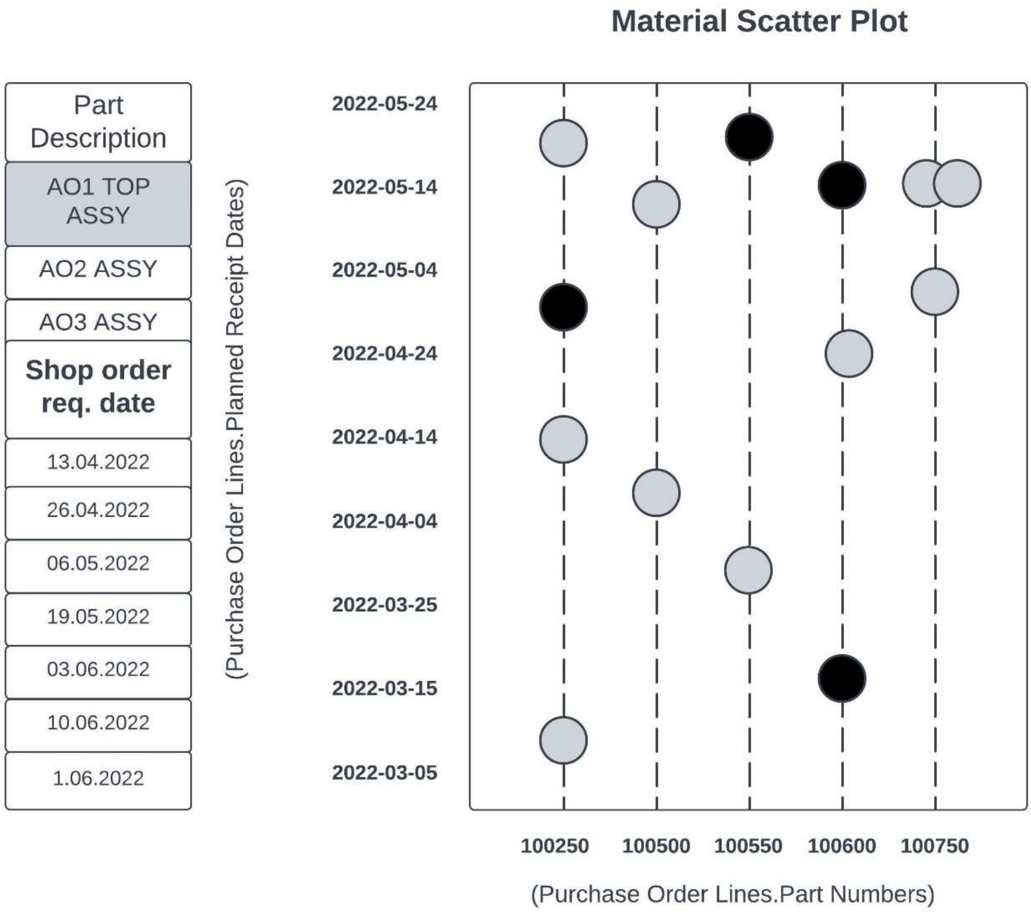

Figure 7. Material scatter plot conceptual diagram (Mathew et al., 2023)

For case study 2, the main aim was to improve the production planning and scheduling process of the weaving process in the case company with the help of digitalization. Case study 2 consisted of three project partners – the ETO manufacturing organization from Italy, the Chalmers University of Technology from Sweden, and another research organization called the Centre for Research and Technology (CERTH). The manufacturing organization is a high-end (luxury fabric producer. For the manufacturing organization, the efficiency of their weaving process is critical in maintaining the required productivity and meeting customer deadlines. The highly customized orders are fed into the weaving machines based on several factors like the complexity of the design, material attributes of the yarn, weaving machine (also known as loom machine) parameters, and weaving machine preparation time or setup time based on the design and material of the previous yarn type processed in that specific loom machine. The current ERP system checks for raw material and resource availability and generates the production schedules of the weaving process based on customer deadlines. However, the production schedule is frequently replanned or rescheduled due to unplanned or new orders (high-priority orders, sampling orders, prototyping orders). The current ERP system was incapable of handling these spontaneous orders. In addition, the ERP system did not consider the probability of unexpected events like loom machine failures, operator issues (delays and errors), and broken yarns while generating the production schedules for the weaving process. The manufacturing organization needed support in developing a planning tool that produces production schedules for the weaving process by considering all the complex parameters (design and material), unplanned orders, and unexpected production events.

Different data collection procedures were used to familiarize and understand the ongoing production planning and scheduling process. Field notes, interviews and direct observations were used as the primary methods for data collection in case study 2. However, manufacturing site proximity and the pandemic situation in Italy became crucial factors in deciding the number of onsite visits and interviews conducted. The COVID-19 pandemic in Italy and the distance of the manufacturing site from Sweden prevented conducting multiple onsite factory visits. Hence, supervised factory visits were conducted continuously at the case company for two days, during which the field notes were gathered, and two interviews were conducted, one with production planning personnel and one with production personnel at the weaving operation, to understand the case company's production planning and scheduling process in a detailed manner.

The solution development was divided into two parts - a primary planning optimization tool (developed by CERTH) and a secondary planning validation tool (developed by Chalmers). The primary tool will consider the complex parameters (design and material) and the incoming unplanned orders and generate an optimized schedule for the weaving process. The output from the planning optimization tool (primary tool) is fed to the planning validation tool (secondary tool). Visual Components simulation software was used to develop a pilot version of the solution model (planning validation tool). The data collected from the factory visits and the onsite meetings were used to build a digital replica of the weaving operation in the simulation software. Figure 9 below shows the framework of the developed solution for the planning validation tool.

The planning validation tool will simulate the production schedule considering production disturbances (planned maintenance and unexpected machine breakdowns). Table 2 above shows the variation between the planned and actual time for order completion due to disturbances. The simulation model developed was verified and validated with the case company. The planning validation tool results will help the weaving process production team make better decisions regarding implementing the best production schedule that would not cause delivery concerns and, at the same time, improve overall weaving process efficiency.

Table 5. Variation between planned & actual time for order completion (Mathew et al., 2023)

Loom machines	L1	L2	V6	P35	P36
Simulation Hours	200	200	200	200	200
Total fabric pieces	2614	3437	2739	2188	5038
Planned Time (hours)	67.5	91.2	55.6	68.4	179.9
Actual Time (hours)	69.5	93.1	57.0	71.4	183.6
Variation (hours)	**1.9**	**1.8**	**1.3**	**2.9**	**3.6**

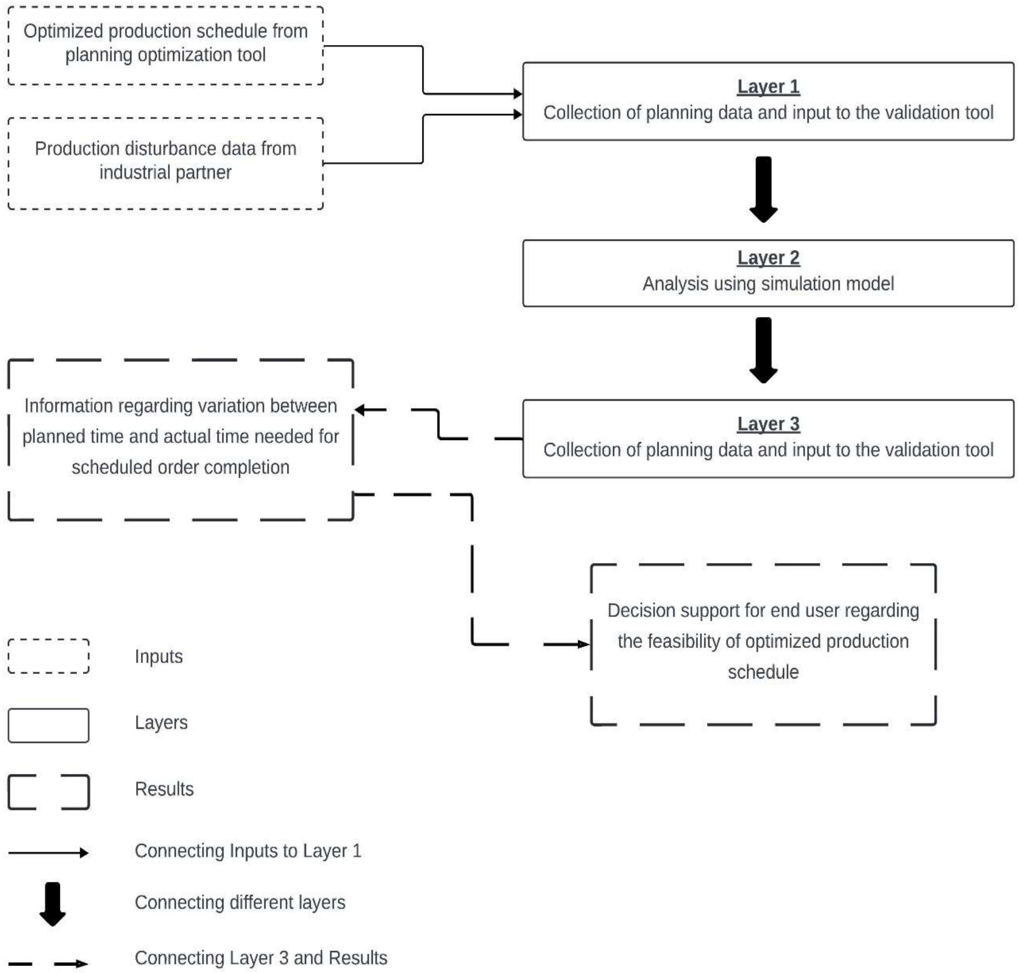

Figure 8. Planning validation tool framework (redrawn from (Mathew et al., 2023))

4.3 Contributions to RQ1 and RQ2

Research question 1 explores the challenges of performing production planning and scheduling operations in manufacturing companies that follow an ETO strategy. The thesis results provide information regarding the challenges and categorize them. The categorization of challenges into these four different perspectives helps to understand better the root causes behind these challenges, what actions are required to overcome the challenges, what has been done to mitigate these challenges so far, and how these challenges are connected. More details about the challenges and the categorization are provided in Paper 1. Thus, considering research question 1, the thesis results emphasize that due to demand volatility, uncertainty, and complexity in product structure, ETO manufacturing needs flexibility and resilience in adapting production plans or production schedules to avoid delivery concerns and financial penalties. Hence, replanning or rescheduling of production plans or production schedules is vital and, at the same time, a significant concern in ETO manufacturing. The thesis results also show that most of the challenges lead to the requirement of replanning or rescheduling, or the process of replanning or rescheduling to attain flexibility and resilience in ETO manufacturing leads to more challenges.

In an ETO manufacturing organization, production planning and scheduling is a highly collaborative activity that involves many stakeholders from various organizational functions, such as design, engineering, purchasing, planning, production, and logistics. Consequently, replanning or rescheduling is much more arduous and complex from a human resources perspective. Henceforth this thesis would like to highlight the need for and the importance of the right tools, technology, and facility for the production planning team not only to replan and reschedule rapidly but also to communicate and visualize the updated production plans or schedules to all stakeholders involved in the production planning and scheduling process. Therefore, from the research question 1 perspective, the thesis contributes by identifying and categorizing production planning and scheduling challenges in ETO manufacturing and emphasizes that manufacturing companies following an ETO strategy need support in replanning or rescheduling activity to achieve efficiency in production planning and scheduling operations.

Research question 2 explores the possibility of digitalization to support production planning and scheduling operations in manufacturing companies that follow an ETO strategy. The thesis results accentuate that integration from an organizational perspective (horizontally and vertically) and integration from a technical perspective (between planning tools and systems) is crucial in ETO manufacturing to achieve collaborative production planning and scheduling to facilitate efficient replanning and rescheduling. More information regarding the need for horizontal, vertical and systems integration is provided in Paper 2. The thesis case study results show that digital tools like simulation and data analytics or combining these digital tools could help achieve collaborative planning in ETO manufacturing and facilitate replanning and rescheduling. The literature study 2 results from the thesis indicate that simulation-related approaches have been the most proposed method for improving production planning and scheduling from a research perspective, and digital twins could be a future direction in improving production planning and scheduling in ETO manufacturing. Finally, with the support of both empirical and theoretical research, the thesis results provide strong arguments that digitalization could facilitate replanning and rescheduling in ETO manufacturing; however, more industry-oriented case studies are required to attain maturity and clarity in deciding what digital technology and critical systems are needed to achieve the full advantages of digitalization.

5

Discussion

The first two sections of the discussion chapter are about answering research question 1 and research question 2. Later, sections contain reflections on the contribution of this thesis towards industry and academics, an evaluation of the methodology, research design and methods used in the thesis, and finally, a review of the future research scope of the thesis.

5.1 Challenges in ETO production planning and scheduling

From the two research questions in the thesis, research question 1 explores and identifies the main challenges for performing production planning and scheduling operations in manufacturing companies that follow an engineer-to-order manufacturing strategy. Research question 1 is given below.

RQ1: What are the main challenges for performing production planning and scheduling in manufacturing companies with an ETO strategy?

From a broader point of view, the biggest challenges that affect production planning and scheduling operations include the volatility in the production volume or customer demands (Birkie & Trucco, 2016), (Johnsen & Hvam, 2019), the high level of customization in the product structure (Vaagen et al., 2017), (Varl et al., 2020), the high level of customer integration that leads to late changes in the product design or structure (Viana et al., 2013), (Mello et al., 2015), and the need for the high level of flexibility regarding multiple aspects like workforce, suppliers, manufacturing resources, and assembly procedures (Huang et al., 2015). All these challenges increase the complexity of ETO production planning and scheduling (Zach & Olsen, 2011), (Nam et al., 2018), (Mei et al., 2021). More details about the categories, the challenges associated with each category, and how they affect ETO manufacturing are presented in Paper 1. Similar potential issues were observed during the case studies conducted with two manufacturing organizations following the ETO manufacturing strategy. The challenges faced by case study manufacturing organizations are described in detail in Paper 2.

These challenges could lead to problems like overutilizing or underutilizing the manufacturing resources, causing late deliveries that result in penalties; otherwise, early completion of customer orders resulting in holding costs and, finally, increased manufacturing costs. Therefore, the manufacturing companies in the ETO segment will have to replan or reschedule their production plans or schedule to overcome these challenges. The results from Paper 1 corroborate these findings. Both case studies in Paper 2 performed replanning and rescheduling to overcome production planning and scheduling difficulties. They sought more support to improve the efficiency of the replanning and rescheduling process. Hence, from a production system perspective, replanning or rescheduling and thereby adapting the production plans could be a key determining factor in improving manufacturing productivity and efficiency and reducing manufacturing expenses in the ETO segment (Jünge et al., 2023).

Another important observation in the thesis is that these primary challenges in the ETO segment led to more secondary challenges in the production planning and scheduling environment. The results from Paper 1 show that either the challenges led to the need for replanning or rescheduling the production plans and schedules, or the process of replanning or rescheduling led to more challenges. The uncertainty in the ETO segment causes the frequent requirement of replanning and rescheduling, making the whole production planning and control arduous for planning personnel (Micale et al., 2021). More details about the production planning and scheduling challenges from a human resource perspective are provided in Paper 1.

Therefore, the people involved in the production planning and scheduling in ETO manufacturing need more efficient technology support and planning tools for continuous planning and replanning. In both case studies in paper 2, the common requirement was that the digital solutions should be capable of working alongside the current ERP system of the company. For planning and scheduling tools to be effective in an ETO environment, they should be compatible with the company's current ERP system (Micale et al., 2021). Apart from that, the planning tool must be able to access information on the current production status, as this is important in the ETO environment to effectively replan or reschedule based on production disturbances (Jünge et al., 2023). More descriptions of the production planning and scheduling challenges from a planning tool and technology perspective are provided in Paper 1. Apart from that, the production planning and scheduling activities in the ETO environment are performed in a highly collaborative environment where constant communication is needed between various functions like design, engineering, planning, purchasing, production, and logistics (Carneiro et al., 2014). The need for effective information sharing, communication, and collaboration (Björngrim et al., 2012) requires the planning tools to provide continuous updates in the planning information (replanned or rescheduled) to all teams or production personnel involved in the planning process.

Hence, due to the highly uncertain, complex, and volatile nature of the ETO segment, production planning and scheduling becomes a complex activity with primary and secondary challenges. These challenges cause replanning and rescheduling of production plans or schedules to be identified as an unavoidable activity in the ETO segment, and both Paper 1 and Paper 2 indicate that manufacturing companies in the ETO segment need further support in carrying out the replanning and rescheduling operations in an efficient manner. Based on the results from Paper 1 and Paper 2, for flexible and resilient production planning and scheduling, the planning personnel needs a collaborative planning system with tools and technology that updates information on current production status, facilitates planning and replanning activities and at the same time updates and communicates the replans or rescheduled information to all stakeholders involved in the process.

5.2 Digitalization for ETO production planning and scheduling

Research question 2 explores how digitalization or digital technologies help in improving production planning and scheduling operations for manufacturing companies with an ETO strategy. Research question 2 is given below.

RQ2: How do digitalization or digital technologies help in improving production planning and scheduling operations for manufacturing companies with an ETO strategy?

Regardless of their manufacturing strategy, many organizations view digitalization as an enabler for achieving competitiveness (Ferreira et al., 2019) and staying agile in the current global rapid change and growth (Thun et al., 2022). From a broader perspective, digitalization is redesigning current operations with new perspectives enabled by digital tools and technologies (Parviainen et al., 2022). Therefore, Industry 4.0 and the corresponding technological advancements (digital tools) have been employed to improve production planning and control in the highly customized ETO environment (Zhang et al., 2019), (Weng et al., 2020). Production planning and control has been the most popular topic of research in ETO manufacturing in the last decade due to its inherent complexity (Gössinger & Plitt, 2019). Virtual manufacturing tools like simulation modelling and digital twins have been explored in many research studies to reduce the challenges in production planning and scheduling in the ETO segment (Steinhauer & Soyka, 2012), (Back et al., 2016), (Urbina Coronado et al., 2018), (Arkouli et al., 2021). The application of big data analytics is also explored for effective data collection and analysis and sharing and visualization of information to all the relevant stakeholders involved in production planning and scheduling (Kozjek et al., 2020).

In paper 2, digital tools were applied in both case studies to facilitate replanning or rescheduling. In case study 1, a data analytics platform was used to support replanning, and in case study 2, the solution was developed using a combination of a data analytics tool and simulation software to support rescheduling. Even though these solutions are pilot models using digital tools, both solutions have been verified by the respective case companies, highlighting that digital tools or digitalization could help improve production and scheduling in manufacturing companies that follow an ETO strategy. Therefore, applying digital tools could enhance the production planning systems' flexibility and resilience towards uncertainties. Workflow resilience and flexibility are critical aspects of ETO manufacturing (Fortes et al., 2023).

Another important observation from the thesis is the need for a collaborative planning system for effective replanning and rescheduling in ETO manufacturing and how digitalization helps develop a collaborative planning system. Paper 1 emphasizes collaborative planning as a crucial requirement and challenge in ETO manufacturing. Literature Study 2 and case study findings from Paper 2 support the need for a collaborative planning system in the ETO segment. Due to the complex nature, continued communication and coordination between various functions (design, component engineering, purchasing, planning, production, and logistics) internally within the organization and also from an external point of view with suppliers and customers is essential for adequate production planning and scheduling in the ETO segment (Viana et al., 2013), (Carneiro et al., 2014), (Jünge et al., 2023). Therefore, horizontal and vertical integration from an organizational perspective (Johansen & Rolstadås, 2017) and system integration (integration between different planning tools and systems in the organization) (Foehr et al., 2015) from a technology perspective is necessary for efficient production planning and scheduling for manufacturing companies that follow an ETO strategy. Paper 2 results support the need for vertical, horizontal and system integration in ETO manufacturing. The benefits of employing digital tools in production planning and scheduling include increased transparency and agility of manufacturing operations, proactive workflow optimization, fast and effective knowledge sharing, and the availability of real-time information to all involved in production planning and control (Leyer et al., 2019). In both case studies from Paper 2, the pilot solution models developed by the application of digital tools like data analytics and simulation modelling have shown immense potential in achieving proactive optimization of workflows, increase in knowledge sharing and transparency, more agility in reacting towards uncertainties and production disturbances and not the least overall more collaborative production planning and scheduling. Therefore, this thesis provides strong arguments that applying digital tools could facilitate the development of a collaborative planning system required for efficient replanning and rescheduling for manufacturing companies in the ETO segment.

However, an important aspect to consider is that the digital solutions described in Paper 2 are case-specific pilot versions, and implementing these digital solutions in the case companies has not been part of the studies. Only a small body of literature has effectively addressed digitalization in ETO manufacturing companies with empirical-oriented research and real-world cases (Carvalho et al., 2015), (Salento, 2018). More industry-oriented case studies are required to validate which digital tools are most effective for production planning and scheduling operations in ETO manufacturing and how these digital solutions could be successfully integrated and implemented with the existing production systems in ETO manufacturing organizations (Cannas & Gosling, 2021). There can be many technology-related issues like software problems, compatibility issues with other technical systems, delayed system reactions to inputs leading to interruptions in production, low situation awareness, rework and additional time requirements, and negative multitasking, which leads to poor acceptance of the applied digital solutions among end users (Körner et al., 2019). Hence, the application of digitalization in production planning and scheduling in ETO manufacturing should be in a manner that is useful and relevant for end-users and especially with the emergence of Industry 5.0, there is a need for deeper understanding regarding development and proper implementation of digitalization and to understand the consequences of interfaces between human, digital technology, and organizations (Thun et al., 2022).

5.3 Contribution to Industry and Academia

This thesis has focused on production planning and scheduling in the ETO segment. From an academic perspective, this thesis has shown the experts the existing challenges with production planning and scheduling in the ETO or customer-driven manufacturing segment. More details about the various challenges are provided in Paper 1. The classification of challenges provided in Paper 1 could help researchers easily understand how the challenges are connected and what research areas need further attention from an academic perspective. Regarding the impact of digitalization in ETO production planning and scheduling, this thesis has provided empirical case studies showing the possibility of using digital tools to facilitate replanning and rescheduling in the ETO operational planning area and thereby contributing real-world case study examples to the literature addressing digitalization in ETO manufacturing. The thesis results from Paper 2 indicate the significance of a collaborative planning system in ETO manufacturing, leading to many future research opportunities connecting digitalization and ETO production planning and scheduling.

From an industrial perspective, the thesis provides information regarding the importance of applying modern technology solutions (digital tools) to solve issues regarding production planning and scheduling in the ETO segment. The case study results in this thesis show real-world examples to industrial practitioners of how digital tools could be utilized to mitigate production planning and scheduling from an operational perspective in the ETO segment. In addition, the literature study results give industrial practitioners more use cases on digital tool applications in improving production planning and control in the ETO segment. Even though the digital solutions developed are case-specific, industrial practitioners could adopt them according to their requirements and apply the modified solutions to facilitate production planning and scheduling in their respective manufacturing environments.

5.4 Evaluation of methodology, research design and methods

The quality of scientific research is associated with three factors- validity, reliability, and generalizability (Bell et al., 2022). In this thesis, the research idea has been to study production planning and scheduling challenges in production systems following an engineer-to-order manufacturing strategy and explore the possibility of mitigating the challenges using digital tools to improve production planning and scheduling efficiency. As a pragmatic researcher, I needed to understand the existing situation and challenges regarding production planning and scheduling in manufacturing companies that follow an ETO strategy before developing solutions or support systems. DRM has been chosen as the research methodology for this thesis as it matches the idea of exploring and understanding the research topic and then developing solutions. The first two stages (Research Clarification & DS-I) in DRM are about exploring and understanding the existing situation thoroughly, and the following two stages (PS & DS-II) are about developing the desired support to solve the problems in the existing situation and later evaluating the impact of the support or solution developed.

As stated in section 3.1 in the methodology chapter, a pragmatist researcher could choose different research methods based on the needs and requirements of the study under consideration. As mentioned in section 3.2, the DRM research approach allows the researcher to select suitable methods, or a combination of methods based on the requirements of the research problem and other interesting scenarios that could emerge while doing research. Therefore, in the research clarification stage in the DRM, a review-based study (literature study 1) was chosen as the appropriate method to explore the existing literature on the research topic as it could provide information to understand the challenges regarding production planning and scheduling in manufacturing companies that follow an ETO strategy. In the second stage, in the DRM, the idea is to further enhance the understanding of the research topic by continuing with more review-based studies or performing a comprehensive study including review-based and empirical studies. Hence, a comprehensive study was chosen as appropriate, encompassing a review-based study (literature study 2) and two empirical studies (case study 1 and case study 2) in this thesis. The review-based study was conducted to explore the existing literature and understand the application of digitalization or digital tools to mitigate the challenges regarding production planning and scheduling in manufacturing companies that follow an ETO strategy. The empirical studies were conducted to enhance the information obtained from the two review-based studies and understand more practically the needs and requirements for production planning and scheduling operations and how digital tools could be helpful from an industrial perspective. Studying the current production planning and scheduling operations in two manufacturing companies that follow an ETO strategy with industrial case studies made it possible to compare the findings from the literature with the current scenario in ETO manufacturing companies and thereby develop a clearer picture of the desired support needed to enable flexible and resilient production planning and scheduling in manufacturing companies that follow an ETO strategy.

The case study results are more convincing and accurate if the data is collected and analyzed from various sources (Yin, 2009). In this thesis, to ensure validity in the industrial case studies, the researcher has chosen multiple research methods and data collection techniques to perform the research collaboratively with the case company teams. Evidence from multiple data collection techniques, like interviews, direct observations, and field visit notes, were used in both case studies in paper 2. The data collected were verified with the case company team in each data collection phase, fostering a sense of inclusion and value for their expertise. This collaboration further corroborated the accuracy of the information gathered, ensuring the reliability of the thesis results and excluding misinterpretations and bias.

Regarding the generalizability of the results, both the literature studies have been conducted based on predefined research questions and inclusion criteria. Scientific data collection methods like interviews, field notes, and direct observations have been used in case studies. The literature study and case study methodologies have been detailed in Papers 1 and 2. Overall, the research topic has been approached from a theoretical and empirical perspective to answer the research questions.

5.5 Outlook on Future Research

The results from this thesis show that there are many challenges for production planning and scheduling in the ETO segment that need to be addressed, and digital tools could be used to mitigate these challenges. These results provide more opportunities for future research.

Based on DRM, the next two steps would be a Prescriptive Study (PS) and a Descriptive Study II (DS-II), developing the desired support for production planning and scheduling operations in ETO manufacturing companies based on understanding from the research clarification and DS-I stages and evaluating the developed support. Therefore, further research could lead to the development of a collaborative planning system for ETO companies that enables vertical and horizontal integration from an operational planning perspective, supporting effective replanning or rescheduling. More industrial case studies would be needed to validate the benefits and challenges associated with the developed collaborative planning system regarding ETO production planning and scheduling. Future research could also lead to developing frameworks or methodologies to effectively incorporate the application and implementation of digital tools in the current production planning and control framework in ETO manufacturing organizations.

6

Conclusion

The thesis aimed to investigate the challenges regarding production planning and scheduling in ETO manufacturing and explore the potential of digitalization in achieving flexible and resilient production planning and scheduling in engineer-to-order manufacturing. The Design Research Methodology approach was used to incorporate theoretical and empirical studies to accomplish the thesis aim.

The thesis results indicate that manufacturing organizations in the ETO segment continuously need help to mitigate the challenges associated with production planning and scheduling. The thesis identified and categorized the ETO production planning and scheduling challenges, and the categorization led to the conclusion that replanning or rescheduling production plans or schedules is unavoidable for ETO manufacturing companies due to highly customized product requirements and demand uncertainties. The results from literature study 2 and both case studies indicate that a highly collaborative integrated planning system is crucial for effective replanning and rescheduling in ETO manufacturing.

The thesis explored technical solutions and strategies applied to solve production planning and scheduling issues in ETO manufacturing from a broader perspective. The thesis shows that vertical and horizontal integration are essential to achieving a collaborative planning system that could support replanning and rescheduling. This is from an organizational perspective and mutually compatible and integrated planning tools and systems from a technological standpoint. The thesis studied how digitalization, or the application of digital tools, could help improve production planning and scheduling in manufacturing organizations that follow an ETO strategy. The thesis shows that using digital tools like simulation and data analytics could facilitate the ETO manufacturing companies to better replan or reschedule production plans or schedules, faster-smoother information sharing, and enhance collaboration between various functions. Thus, the thesis provides strong arguments that applying digital tools improves the flexibility and efficiency of production planning and scheduling operations in the ETO manufacturing segment.

7

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