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Evaluating the Potential Use of APS Systems for Production Scheduling

A conceptual framework of APS suitability with respect to optimization strategy and complexity in manufacturing

Master's thesis in Mechanical Engineering
Supervisor: Erlend Alfnes
Co-supervisor: Erik Gran
June 2023

Master's thesis

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ABSTRACT

The thesis delves into Advanced Planning and Scheduling (APS) systems related to production scheduling. The research is based on a literature review and two case studies. The study's goal is to pinpoint the factors that determine APS appropriateness and to present decision-makers with a summary of considerations for potential APS system adoption. The discovered benefits encompassed increased testing freedom, increased adaptability, enhanced visibility, the possibility for optimized production, and increased efficiency. However, limitations also emerged, including data vulnerability, expensiveness, and the requirement for training.

To contribute to the existing body of knowledge concerning the adoption of APS systems, a quantitative measurement model has been developed. This model focuses on evaluating the suitability of APS systems in relation to two parameters: manufacturing complexity, characterized by intricate product structures with multiple interconnected elements and relationships, and optimization strategy, which denotes the internal motivation within a company to implement tools aimed at maximizing performance. The model is grounded in the theory that suggests a positive fit between higher complexity and optimization strategy related to APS use, supported by generic APS theory, and theory surrounding the Job Shop Scheduling Problem (JSSP). The model serves as a guide for decision-makers in evaluating the appropriateness of APS for their business, only taking into account the complexity of manufacturing and optimization strategy.

Substituting conventional planning procedures with APS systems has the potential to bring significant benefits, including operational streamlining and knowledge acquisition within the industry. While implementation challenges may arise, diligent utilization can yield long-term benefits. Dynamic scheduling and customization capabilities were emphasized as valuable contributions. Future research could focus on studying different strategies and developing a comprehensive suitability measurement model encompassing parameters like e.g. manufacturing characteristics, economic aims, resources, or business types.

Keywords: advanced planning and scheduling (APS), production planning and control (PPC), production scheduling, manufacturing complexity, optimization.

SAMMENDRAG

Oppgaven går i dybden på Advanced Planning and Scheduling (APS) systemer knyttet mot produksjonsplanlegging. Forskningen er basert på et litteraturstudie og to case-studier. Målet med studien er å identifisere faktorer som bestemmer egnetheten av APS, og å presentere beslutningstakere med en oppsummering av vurderinger ved potensiell implementering av APS-systemer. De oppdagede fordelene inkluderer økt testfrihet, økt tilpasningsevne, forbedret oversikt, muligheten for optimalisert produksjon og økt effektivitet. Begrensninger har også blitt avdekket, inkludert sårbarhet vedrørende data, høy kostnad og behov for opplæring.

For å bidra til det eksisterende kunnskapsgrunnlaget om innføring av APS-systemer, har en kvantitativ egnethetsmodell blitt utviklet. Denne modellen fokuserer på å evaluere egnetheten av APS-systemer i forhold til to parametere: produksjonskompleksitet, som kjennetegner intrikate produktstrukturer med flere sammenkoblede elementer og relasjoner, og optimeringsstrategi, som angir den interne motivasjonen i et selskap for å implementere verktøy som sikter på å maksimere ytelse. Modellen er basert på teori som antyder en positiv sammenheng mellom høy kompleksitet og optimaliseringsstrategi knyttet til bruken av APS, støttet av generell APS-teori og teori omhandlende Job Shop Scheduling Problem (JSSP). Modellen fungerer som en veiledning for beslutningstakere i vurderingen av egnetheten til APS for deres virksomhet, og tar kun hensyn til produksjonskompleksitet og optimeringsstrategi.

Konklusjonen omhandler at et skifte fra konvensjonelle planleggingsmetoder til bruken av APS-systemer har potensial til å gi betydelige fordeler, inkludert effektivisering av operasjonene og kunnskapsoppbygging innen industrien. Selv om det kan oppstå implementeringsutfordringer, kan anvendt bruk av APS-systemer gi langsiktige fordeler. Dynamisk planlegging og god tilpasningsevne ble understreket som verdifulle bidrag. Fremtidig forskning kan fokusere på å studere ulike strategier og utvikle en omfattende egnethetsmodell som omfatter parametere som for eksempel produksjonskarakteristikker, økonomiske mål, ressurser eller bedriftstyper.

PREFACE

Before you lies the master's thesis *Evaluating the Potential Use of APS Systems for Production Scheduling*. It is written to fulfill the graduation requirements of the Mechanical Engineering program at the Norwegian University of Science and Technology in Trondheim. The thesis is written in the period January to June 2023.

Our personal motivation is driven by our profound interest in the field, and the fascination began to flourish during our specialization project in the autumn of 2022, further fueling our determination to explore the potential use of APS systems for production scheduling. The immense size of the field is a compelling factor that has truly motivated us.

We would like to thank our supervisors, Erlend Alfnes and Erik Gran, for your guidance and support throughout the process. Your knowledge of the field and your previous research helped us develop a deeper understanding and insight, and your guidance has helped us to refine our arguments and analysis. Your advice and patience made us believe that we could turn difficulties into challenges. We have learned so much from you, and we will carry the lessons we have learned into our future endeavors.

We are also grateful to each other. A thesis in this enormous field of study would have been impossible without the support and cooperativeness we have received from each other. We have experienced good and bad days together, including both deep frustration and a feeling of mastery. Through countless late nights and early mornings, we have bonded over our shared goal and have formed a strong sense of camaraderie that will stay with us long after we have completed this academic endeavor.

Trondheim, June, 2023
Oscar Aleksander Lysgård, Emil Gjærum Berge

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ABBREVIATIONS

- **APS** Advanced Planning and Scheduling
- **ATO** Assemble To Order
- **ATP** Available To Promise
- **CCA** Case Company A
- **CCB** Case Company B
- **CFJSSP** Classical Flexible Job Shop Scheduling Problem
- **COP** Customer Order Point
- **DIY** Do-It-Yourself
- **ERP** Enterprise Resource Planning
- **ETO** Engineer To Order
- **FJSSP** Flexible Job Shop Scheduling Problem
- **I4.0** Industry 4.0
- **JSSP** Job Shop Scheduling Problem
- **MTO** Make To Order
- **MTS** Make To Stock
- **MRP** Material Resource Planning
- **MES** Manufacturing Execution System
- **PPC** Production Planning and Control
- **RFID** Radio Frequency Identification
- **SMEs** Small to Medium Enterprises
- **SMM** Suitability Measurement Model
- **UI** User Interface

CHAPTER

ONE

INTRODUCTION

The introduction chapter establishes a foundation by defining key concepts and presenting a rationale for focusing on Advanced Planning and Scheduling (APS) systems in relation to production scheduling as the subject of investigation. The chapter serves to provide a comprehensive understanding of the research context and the motivations behind delving into APS systems. By investigating APS systems in the specific context of production scheduling, the study strives to contribute novel insights and generate new knowledge in the field. The significance of this research lies in its potential to contribute to the understanding of APS systems and their impact on production scheduling practices.

In recent years, Production Planning and Control (PPC) systems have been developed towards systems that integrate both materials and capacity requirements, such as Material Resource Planning II (MRP II). Further development has led to systems such as Enterprise Resource Planning (ERP) and APS systems, which have improved production scheduling [Hvolby and Steger-Jensen, 2010]. Thus, there is a noticeable trend shifting towards the adoption of more advanced systems to manage planning and scheduling activities.

Due to globalization and rising customer expectations, scheduling has a more crucial function than ever in modern society. Failure to meet production deadlines or delays brought on by unsatisfactory PPC could result in serious issues for a business [Farizal et al., 2021]. Production scheduling is one of the primary issues with PPC [Jeon and Kim, 2016], and this thesis is attempting to learn more about the subject. With the growing complexity of manufacturing environments and the increasing need for real-time decision-making [Silva et al., 2023, Nouinou et al., 2023], the adoption of APS systems has emerged as a promising solution. However, despite their potential benefits, the concerns and limitations of APS systems in the context of production scheduling remain subjects of investigation. By exploring the current state of the art of APS and production scheduling, reviewing the relevant literature, and presenting the findings of two case studies, the thesis seeks to contribute to the body of knowledge.

The chapter starts by stating the background and motivation of the study, before moving on to the project description. Furthermore, the research questions are presented, followed by the overall aim of the study. Important definitions and the scope of the study are also included. Lastly, the outline of the thesis is presented.

1.1 Background and motivation

Digitization has become an everyday word and is performed throughout most industries to stay competitive [Kraus et al., 2021]. Industry 4.0 (I4.0) is a concept that represents industrial companies' adjustments to the ever-digitized pressure to stay competitive. I4.0 has numerous systems, advanced technology, and techniques to take advantage of the benefits I4.0 provides. I4.0 offers solutions e.g. cloud computing, the internet of things, and digital twins, among numerous other technologies [Castelo-Branco et al., 2019, Ghobakhloo, 2020, Zheng et al., 2021, Bai et al., 2020, Masood and Sonntag, 2020]. Classical manufacturing planning methods are widely used in today's manufacturing despite the pressure of turning to I4.0 technology. MRP is a material planning method that practices a master production schedule and bill of materials to determine material needs and replenishment timing [Moon and Phatak, 2005]. The difference between MRP and MRP II is that MRP II has the capability to integrate other resources than materials [Mattsson, 2004]. MRP II is one of the most used in PPC, and is considered suitable in certain manufacturers [Thürer et al., 2022]. However, it has been known for a long time that there is a lack of fit between the functionalities and the requirements in the e.g. ETO context [Bhalla et al., 2022], for instance, the lack of consideration for capacity [Jodlbauer and Strasser, 2019]. The planning system perspective is addressed in several papers, and APS is proposed e.g. in an ETO shipbuilding context in [Nam et al., 2018]. As stated by [Salur and Kattar, 2021, Allaoui et al., 2019], the adoption of APS systems that incorporate optimization can lead businesses to gain a competitive advantage in the marketplace and improve their bottom line. An APS system is an integrated planning system where the supply chain is targeted with emphasis on the processes involved in accordance with constraint-based or optimized planning [Steger-Jensen et al., 2019, Nam et al., 2018]. ETO and MTO manufacturers, which in accordance, either have a one-of-a-kind production nature, with little to no previous data on projects, or a product that is not beneficial to keep in larger stocks, both have similar challenges in manufacturing logistics at the small to medium enterprise range (SMEs) [Strandhagen et al., 2019, Zennaro et al., 2019, Neumann et al., 2022]. The main difference between the different production strategies MTS, MTO, ATO, and ETO is the location of the COP [Zennaro et al., 2019]. Literature regarding the challenges in the scheduling part of PPC in different manufacturing environments is scarce and poorly suited to modern manufacturers.

The discrete manufacturing sector, including the case firms in this study, often has several complicated manufacturing procedures that are evolving along with industry standards. These intricate manufacturing procedures can include complex machining procedures or many steps on a single product. The manufacturing sector faces hurdles as a result of the ongoing development of industrial strategies like I4.0, which forces companies to constantly seek out more expensive but promisingly better technology [Liu et al., 2022b, Albukhitan, 2020, Björkdahl, 2020, Wang et al., 2021a, Chansombat et al., 2019]. Implementing I4.0 technology is a huge focus [Li et al., 2022], but little focus has been on the use of systems to optimize production in more complicated manufacturing environments. I4.0 manufacturing systems are powered by advanced technologies that are known as I4.0 concepts [Ghaleb et al., 2020]. Classical manufacturing planning, such as backward MRP planning is fairly simple, with straightforward and rigid procedures that lack optimization in most cases [Gyenge et al., 2021]. In an attempt to utilize I4.0 technologies in complex manufacturing, APS systems provide the abilities needed to combat some of the largest challenges with classical manufacturing planning.

Studying production scheduling holds significant motivation as it plays a crucial role in handling manufacturing operations and achieving operational efficiency [Romero-Silva et al., 2015]. By studying production scheduling, one can gain insights into various scheduling techniques tailored to specific manufacturing environments. Additionally, understanding the challenges and opportunities in production scheduling can empower businesses to respond swiftly to changing market demands, improve production planning accuracy, and maintain a competitive edge in the dynamic landscape of modern manufacturing.

The scarcity of literature focusing specifically on the use of APS systems for production scheduling, combined with industrial demand for solutions in the field, serves as the primary motivation for the thesis. Investigating the challenges and opportunities of implementing APS systems to support production scheduling can provide valuable insights for companies and contribute to filling the existing research gap.

1.2 Project description

The thesis aims to delineate the essential considerations and assessments required for the successful use of APS systems to support the work of production scheduling within a manufacturing company. This includes the categorization of APS systems, concerning the degree of optimization, as well as mapping the different applications APS offers in relation to production scheduling. It also aims to evaluate how the complexity in manufacturing and optimization strategy affects the degree of suitability for APS use. A suitability measurement model (SMM) with respect to complexity and optimization strategy is developed to assist managers who want to look into and consider whether an APS system is appropriate for their business. The decision to focus on optimization and complexity is because of the lack of research in this field, and the issue of solving complex combinatorial optimization, which can be easily formulated e.g. if n jobs, are to be performed on m machines, there are potential $(n!)^m$ possible sequences [Pongcharoen et al., 2004a]. A crucial area is where one can expect to find differences between an APS solution compared to ERP and standard backward MRP planning. Relevant constraints need to be taken into account. How APS creates an operational plan to meet the ERP plan. The aspect of uncertainty and data availability, and how ERP and APS consider this. The importance of purposeful changes to product structures and data quality. How ERP and the planning process must be changed in order to use an APS system successfully. These main elements form the foundation of the study and connect the different parts and chapters of the thesis.

The study concentrates on production scheduling, with specific emphasis placed on certain aspects within the term. Job shop scheduling, process planning, and job planning are all essential components of production scheduling, and these terms are described in section 1.6. Notably, the study highlights the significance of job shop scheduling, particularly because of its relevance to addressing the Job Shop Scheduling Problem (JSSP), which plays a crucial role in the research findings. The increasing complexity of modern production systems has posed substantial challenges in achieving efficient coordination of shop floor activities, necessitating a heightened emphasis on job shop scheduling. By exploring APS in relation to job planning, process planning, and job shop scheduling, the hope is to identify the applications of an APS system that can improve the process of production scheduling.

1.3 Research questions

For the study, the objective was to map out which considerations a decision-maker should be aware of when considering APS implementation to support the decision-making related to the scheduling of manufacturing. With this in mind, formulating research questions was vital to making the study tangible and precise. The work of formulating and narrowing down the study resulted in the following research questions:

RQ1: What are the applications of APS systems related to production scheduling?

RQ2: What are the limitations of APS systems related to production scheduling?

RQ3: How does the complexity in manufacturing and optimization strategy inform about the fit of APS use?

1.4 Overall aim

By investigating and answering the research questions, the thesis should be able to provide guidance to a decision-maker on important considerations respecting APS implementation to support production scheduling. There are two main objectives for the study:

1. To derive opportunities, application areas, and limitations, as well as research and application recommendations for managers in the future regarding APS implementation targeted at production scheduling.

2. To create a quantitative measurement of APS suitability with respect to optimization strategy and current complexity in manufacturing.

The choice of investigating APS systems in relation to optimization strategy and complexity is justified due to the lack of guidance tools regarding these parameters in the literature. The literature is deficient when it comes to precise measurement tools regarding APS implementation, and the second aim of this study should therefore supply the literature. The term *suitability* in the second overall aim, refers to the degree of compatibility or appropriateness between specific elements under consideration. As for the second aim, the elements under consideration are APS systems, the complexity of manufacturing, and the optimization strategy. Figure 1.1 shows how the research questions are utilized to address the overall aims.

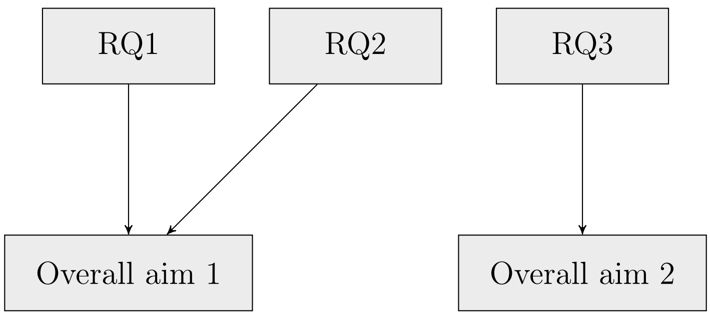

Figure 1.1: Approach to overall aims

1.5 Definitions

This section offers definitions of essential terms and concepts crucial to the research and consistently employed across the thesis. The purpose of this section is to clarify the meaning of the terms and concepts and ensure a shared understanding between the authors and the reader. By providing clear and concise definitions, this section aims to enhance the reader's comprehension of the research and to avoid any ambiguity or confusion.

APS

The term APS needs to be justified in order to make the study make sense. Below are some relevant descriptions:

An Advanced Planning and Scheduling system is defined as any computer program that uses advanced mathematical algorithms or logic to perform optimization and/or simulation on finite capacity scheduling, sourcing, capacity planning, resource planning, forecasting, demand planning, and others [Ivert, 2012].

(...)*any computer program that uses advanced mathematical algorithms or logic to perform optimization or simulation on finite capacity scheduling, sourcing, capital planning, resource planning, forecasting, demand management, and others. These techniques simultaneously consider a range of constraints and business rules to provide real-time planning and scheduling, decision support, available-to-promise, and capable-to-promise capabilities* [APICS, 2007].

The above quotations indicate that an APS system can contain several capabilities, and the definition can be wide. These definitions however match the majority of descriptions in the literature. There are no strict requirements for what is allowed to be included within the term; hence, the common denominator is that it involves using mathematical methods and simulations to solve planning problems. This is also what the definition of APS systems is based on in this study. In order to understand the functionalities of APS systems in the context of the study, the exact area of investigation needs to be clear. In this thesis, the field of production scheduling is of interest.

ERP

Businesses and organizations have, in recent decades, spent millions of dollars implementing and developing ERP systems [Ruivo et al., 2020]. An ERP system can be described as a system that automates all aspects of an organization's business processes [Ivert, 2009]. It uses one database that contains data for the software modules, such as manufacturing, distribution, finance, purchasing, warehousing, and project management [Berchet and Habchi, 2005]. ERP systems have been questioned and criticized for their limitations regarding planning and scheduling [David et al., 2006].

PPC, production scheduling, and job shop scheduling

Production Planning and Control is a broad term with many available definitions and interpretations. Production planning and control refers to the process of strategically organizing and coordinating all activities related to the production of goods or services within a company. This definition has many similarities with the characterization of PPC in [Bueno et al., 2020]. PPC must always adapt to changing tactical and strategic contexts, intricate consumer demands, and fresh supply chain opportunities [Yin et al., 2018].

Production scheduling is intricately intertwined with PPC, as it serves as a vital component within the broader framework of coordinating and planning manufacturing operations. While PPC encompasses the strategic organization and coordination of all activities related to the manufacturing of goods, production scheduling delves into the detailed execution by determining the precise timing, sequencing, and allocation of resources for individual tasks [Jacobs et al., 2014]. In order to accomplish the production tasks, it is crucial to meticulously plan so that the necessary equipment, materials, utilities, personnel, and other resources are readily available at the required times [Harjunkoski et al., 2014].

The job shop is defined as the part of an organization where production and manufacturing are carried out. [Waschneck et al., 2018] defines it as *...an elementary type of manufacturing, where similar production devices are grouped in closed units.* A shop floor where jobs are processed by machines is defined in this study as a job shop. Each job implements a specific number of operations. The processing time is defined, and each operation has to be handled on a dedicated machine [Mattfeld, 2013]. Hence, job shop scheduling is the process of employing a schedule to use the resources on the shop floor effectively [Jeon and Kim, 2016]. Job shop scheduling and production scheduling share common ground, but job shop scheduling is arguably even more restricted.

Figure 1.2 visualizes how the three terms are related to each other and how they are treated in this thesis. Job shop scheduling occupies a position of utmost specificity as it concentrates exclusively on the streamlining of the shop floor activities. Further, production scheduling encompasses a slightly broader scope, as it extends beyond the sole pursuit of streamlining processes by possibly incorporating other multifaceted measurement parameters to ensure successful production. PPC encompasses both production scheduling and job shop scheduling, as it encapsulates the process of strategically organizing and coordinating all activities related to the production of goods or services.

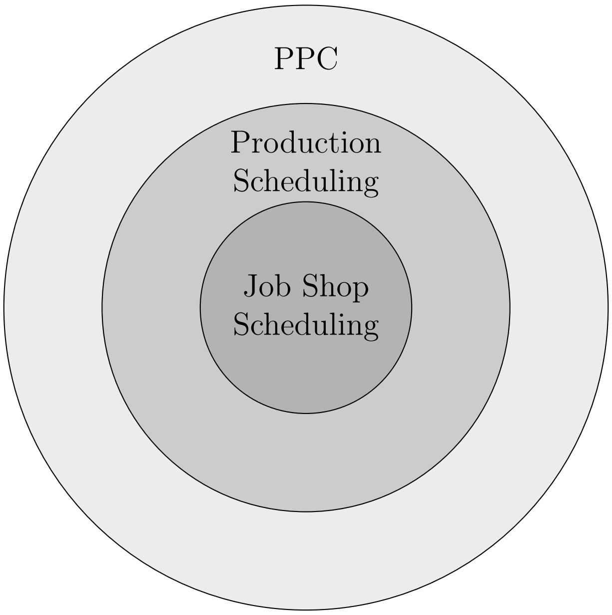

Figure 1.2: PPC, Production Scheduling, and Job Shop Scheduling

Optimization and optimization strategy

Optimized plans are generated based on objectives and constraints [Hvolby and Steger-Jensen, 2010]. The term is described in various ways in the literature, and defining it for this specific study was a hard task. [Altendorfer and Minner, 2011], [Tang et al., 2007], [Köchel and Nieländer, 2005], [Li et al., 2009] and [Almeder et al., 2009] are examples of previous related work regarding optimization towards production planning. The common denominator in these papers is that there is a mathematical algorithm for optimization of production planning in the scenarios the research deals with. [Ivert, 2009] refers to optimization as the possibility to use models to find the most feasible solution regarding some predefined criteria.

Due to the large variations and variants of definitions for optimization, it needs to be defined in an easy and understandable way for this study. The focus of this thesis is not to deep dive into the field of optimization and study different algorithms and mathematical solutions, and therefore the definition of optimization resulted in a general and broad definition that can be justified for the majority of the target group. With this mentioned, optimization is defined in this thesis as planning, including chosen decision variables and penalty factors, with the goal of streamlining and utilizing resources in the best possible way. This is also the essence of the majority of related work concerning optimization. It is also important to emphasize that when optimization is enabled in production planning, it is performed by IT systems and not by human judgments. Humans set the constraints and what to put emphasis on for the system, and the system makes an optimized plan given these constraints.

Optimization strategy, in the context of this study, refers to the internal motivation within the company to enhance the efficiency, effectiveness, and overall performance of its processes related to production scheduling. It involves the motivation of implementing tools aimed at maximizing output, minimizing costs, and streamlining operations to achieve optimal results. The motivation behind employing an optimization strategy lies in the company's desire to improve its competitive position, increase profitability, and meet customer demands more effectively. By embracing a clear optimization strategy, businesses can optimize their production planning processes to achieve greater results.

Complexity

In the context of this study, complexity refers to complex production, which is characterized by product structures with multiple interconnected elements and relationships [Danilovic and Browning, 2007]. An example for this study would be the relationship between the component elements, the production processes for these components, and the people planning for these processes.

Dynamic scheduling

Refers to the flexibility of making changes to a production schedule. In the majority of real-world settings, scheduling is a reactive process that is constantly forced to reevaluate and revise established schedules due to a range of unpredictable interruptions that are almost always present [Ouelhadj and Petrovic, 2009].

1.6 Scope of the study

The study is limited to the scheduling of manufacturing activities, referred to as production scheduling. This delimitation excludes economic considerations regarding software prices and the potential need for a new workforce. The study is also limited to in-house operations. Therefore, the level of outsourcing, delivery times from suppliers, and other external parameters are excluded from the scope. It is narrowed down to short-term scheduling, the decision-making process of how and when the production of each component or assembly should be carried out. Included in the scope are some of the known problems related to production scheduling, obtained from [Jeon and Kim, 2016]. Research on previous articles and periodicals shows that it is relevant to study these specific areas more thoroughly in relation to APS systems.

Area	Description
Job planning	Consider the job schedule, which specifies the times for beginning and ending each task to be completed at the shop floor [Jeon and Kim, 2016].
Process planning	The selection of the process by which the product is to be manufactured competitively. This includes the sequence of jobs and the machine routing [Jeon and Kim, 2016].
Job shop scheduling	The process of employing a schedule to use resources effectively [Jeon and Kim, 2016].

Table 1.1: Areas inside scope

Job planning and process planning and job shop scheduling are all aspects of production scheduling that are included in the scope. The partition helps to contribute to a broader and better understanding of the whole process regarding production scheduling. As mentioned in section 1.2, the study emphasizes the significance of job shop scheduling, but it also acknowledges the importance of addressing the other aspects of production scheduling to ensure comprehensive coverage of the subject matter.

All manufacturing environments are included in the scope. Everything from MTS to ETO. However, the research and experience indicate that it is more natural to direct attention toward the more complex environments, as ETO and MTO environments are more unique and face more concerns touching the aspect of scheduling. [Micale et al., 2021], [Ghiyasinasab et al., 2021], and [Jiang et al., 2019] are examples that accentuate the scheduling problems in ETO and MTO environments and highlight that scheduling issues arise when the manufacturing load and variation become more unpredictable and tailored.

1.7 Thesis outline

Chapter 2 (Methods) presents the methods and methodology used in the research. It presents how the different research questions are approached as well as describes how the literature review and the case studies are performed. Finally, it visualizes the three-step approach for the development of the APS suitability measurement model.

Chapter 3 (Theory) provides a comprehensive exposition of the pertinent theoretical framework serving as the foundation for the subsequent research findings. It addresses the theory relating to production scheduling, I4.0 in connection to production scheduling, as well as a more general theory of APS' functionalities, limitations, and concerns. Additionally, the theory underlying JSSP and the issue it creates are presented. Complexity and optimization theory are presented in relation to APS, and lastly, the theoretical application for the research is shown. This chapter lays the foundation for the results of the study.

Chapter 4 (Results) summarizes the findings and presents the results of both the literature-, and the case study. It categorizes APS systems as well as their applications. The results from the case study are presented. At last, the developed suitability measurement model is presented, together with the case companies' responses to the questionnaire that is part of the model.

Chapter 5 (Discussion) discusses the results presented in the previous chapter. This chapter is supposed to answer the research questions in a qualified and proper way. Practical use of APS systems, benefits, and limitations are discussed. It justifies the statements created for the SMM and discusses the model in general. At last, a review of methods and bias, and the study's contribution to the field of research are presented.

Chapter 6 (Conclusion) presents the conclusions of the study as well as suggests areas for further research on the topic. It offers a comprehensive summary of the research, including the key insights and outcomes derived from the study.

CHAPTER

TWO

METHODS

This chapter presents the methodology used to conduct the research and achieve the research objectives of this study. In this chapter, the research approach is presented in detail. The aim of this study was to derive opportunities, application areas, and limitations, as well as research and application recommendations for managers in the future regarding APS implementation targeted at production scheduling, and to create a quantitative measurement of APS suitability with respect to optimization strategy and current complexity in manufacturing. To achieve this aim, a mixed-method approach was employed. The choice of methodology was based on the research questions, the type of data required, and the availability of resources.

The chapter begins with an overview of the research approach. Next, the literature review process is described in detail, which includes the main targets of the literature study and the keyword search. The chapter then moves on to the case study process, which includes the interview targets and the qualitative techniques used to interpret the results. Lastly, the chapter presents the procedure for developing the APS suitability measurement model and the quantitative contribution to the results of the study. Overall, this chapter provides a detailed account of the methodology used in this study and highlights the rigor and systematic approach taken to achieve the research objectives.

2.1 Research approach

The research is based on a literature review and a multiple case study. The research questions were approached in a proper way, where their naturalness and availability of information from the case studies are considered. Table 2.1 shows how the research questions were approached.

	Research question	**Approach**
RQ1:	What are the applications of APS systems related to production scheduling?	Literature review and case study
RQ2:	What are the limitations of APS systems related to production scheduling?	Literature review and case study
RQ3:	How does the complexity in manufacturing and optimization strategy inform about the fit of APS use?	Literature review and case study

Table 2.1: Approach to research questions

All of the research questions are addressed by both the literature review and the case study. *RQ3* is mainly answered through the literature review, but the case studies were important to validate the theory. The reasoning for this is the difficulty of gaining sufficient knowledge regarding this question mainly through a case study because it needs to be addressed through comprehensive research of previously written papers. It is also the most difficult question to formulate for an interview object. The correlation between optimization strategy and complexity is previously poorly studied in relation to APS suitability, and it is, therefore, natural to approach that research question mainly through theory.

2.2 Literature review

With the intention of gaining better insight and understanding of APS applications in relation to production scheduling, the study is naturally based on a research literature review. A research literature review is *...a systematic, explicit, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners* [Fink, 2019]. In other words, this definition means that the research on other people's work is done in a way that can be replicated, and in a systematic and justified way. The literature review showed that previous studies carried out within the field of research are either antiquated considering the constant development of new technologies and solutions, or they do not cover the same affair. It also demonstrated that there has been little focus in the past on scoping for production scheduling.

No particular scientific journals have been prioritized. Search databases such as Scopus, Google Scholar, and Science Direct were used to find relevant studies, papers, and articles. It was a priority to gain a wide insight into the problem scope and the relevance of the study, and that is why the literature study was not subject to strict guidelines as to which search engine or scientific journal to be used. According to [Wohlin, 2014], not limiting the search to any scientific journals is a good alternative to avoid bias in favor of any specific publisher. The start-up period was used exclusively for the work with the literature study, something that gave reassurance that the background investigation was done properly. Due to a large number of previous studies and knowledge within similar areas as this study, it was important to highlight and choose a quite wide spectrum of literature, to develop knowledge and see connections. There were three main targets of the literature study:

1. To identify the main applications of APS systems related to production scheduling. This includes the categorization of APS systems concerning the degree of optimization and autonomy, how APS creates a plan compared to ERP, how it deals with uncertainty and data availability, etc. The objective was to develop an understanding of the range of applications that APS systems can encompass and to identify which applications or features are specifically designed for production scheduling purposes. This target directly justifies the use of this method hence it correlates with *RQ1*.

2. To identify the main concerns related to the scheduling part of PPC on a shop floor level. This second target of investigation provided knowledge on a general basis regarding the typical scheduling challenges manufacturing companies have to deal with on a shop floor level. This was important to map out the most extensive challenges and to further be able to connect them with APS functionalities in this thesis. Due to the overall aim of the thesis, this target was important to gain enough depth of knowledge regarding production scheduling.

3. To gain comprehensive insights into the existing body of research pertaining to the integration of APS systems for PPC, and potentially encompassing production scheduling as well. To ensure the relevance and utility of this thesis, research on similar papers and studies was necessary. It gave a more pointed insight into the field, after the two more wide targets listed previously.

Most preferences were given to articles published after 2015 to ensure that the references used in this study were up to date. Empiricism suggests that the research on the topic is fast-moving and constantly evolving, justifying the use of newer articles. Some older references were included, often as a reference to a term description or timeless definitions. Peer-reviewed articles were also considered more relevant, because of the documentation of reasonable quality and credibility as suggested by [Haddaway et al., 2020].

2.2.1 Keyword search

Figure 8.1 can be seen in the appendices and presents the main keywords used in the literature search. The conceptual block includes the keywords that concern the concept of the study. The contextual block contains keywords that were used together with the conceptual keywords to narrow down the scope. The conceptual block II contains keywords that were used together with all the other keywords to further narrow the search. Search terms had run in separate or with limited combinations that considered the requirements, or limitations.

Database searches on the chosen keywords yielded hundreds of publications, hence there is a growing list of literature concerning the area of research. However, the literature study emphasized that the immediate area studied in this thesis has attracted little attention in recent times. Despite the keyword searches' discovery of relevant articles, backward snowballing was introduced to address specific topics within some of the articles. Snowballing is reviewed to be efficient when the keyword search includes general terms [Mourão et al., 2020], as some of the keywords in this search are.

2.3 Case study

To investigate the chosen area of interest in this paper, a qualitative, multiple, case study has been carried out. A qualitative case study is a research methodology that contributes to the exploration of a phenomenon within a particular area of interest through various data sources [Rashid et al., 2019]. The case study methodology was particularly well-suited to this study, as it allowed for an in-depth exploration of the phenomenon within the specific context of the study. The case study approach allowed for a detailed examination of the experiences, perspectives, and practices of businesses within the study context. The qualitative, multiple, case study approach provides a rich and nuanced understanding of the phenomenon under investigation and enables the identification of new insights and opportunities for future research.

The target was to examine a company currently using an APS system to support its production scheduling and a company currently not using it. Then it would be possible to compare the two businesses and examine their current issues related to their production. The comparison between two companies, one using an APS system for production scheduling and the other not using it, provides a unique opportunity to gain insights into the effectiveness of the technology. By examining the production processes of both companies, identification of the key differences in their production planning, scheduling, and execution is possible. Furthermore, the study can help to identify the current issues faced by each company and explore whether these issues are linked to their production planning. The target was to explore if their concerns in the production are linked to their production planning, and if the APS system contributes to other/fewer issues in the manufacturing. The case study should contribute to a better understanding of the role of APS systems in production scheduling.

2.3.1 Interview

To gather relevant information and insight from the case companies, a comprehensive interview was performed to map their experiences and challenges regarding the planning of their production. The information that was interesting to examine for this study is broad, so it would therefore be difficult to extract using quantitative methods. The interview was performed with the head of planning at the case companies. The interview gave a good insight into the topics and aspects covering the study. The main targets of the interviews were to:

- understand the layout of their manufacturing process
- map the manufacturing challenges they are facing
- gain knowledge and insight into their current planning tool
- understand how their production strategy is connected to the production management
- establish the challenges related to their production scheduling
- pick up their considerations regarding the implementation of an APS system/why they have implemented an APS system
- familiarize how they use an APS system in relation to the planning strategy (if using APS)

The questions used for the interviews were based on scientific literature regarding PPC, production scheduling, and APS functionalities. The insight gained through the interviews was used to identify how real-life companies evaluate and match their strategy with appropriate management tools. The level of knowledge the interview subject had regarding the area was unknown beforehand, but most of the questions were expected to be answered sufficiently for it to be satisfying input to this study. It is important to highlight that the quality of the interview subject and interview guide fundamentally influences the results of the case study [Kallio et al., 2016]. Some questions were also added by the supervisors of this thesis, as they attended the interviews.

2.4 Measurement of suitability

As part of the thesis results, a more precise measurement of suitability was desired. To include a quantitative result for the study was essential due to the ambition regarding categorization and viewing patterns in the data. Therefore, a suitability measurement model (SMM) was created. The model consists of a questionnaire that gives a mean score between the optimization strategy and a manufacturer's complexity in manufacturing. The structure of the SMM is highly influenced by maturity models. As the aim of maturity models are to measure the relationship between maturity and performance [Jünge et al., 2019, Bititci et al., 2015], it was deemed unfitting to use the same term, as the aim of using this method is to measure suitability. The structure of the SMM was inspired by the maturity model in [Schumacher et al., 2016], where the maturity model was developed for the maturity of manufacturing enterprises. The questionnaire is structured into different dimensions, which will consist of the most prominent and crucial aspects of the suitability evaluation. The approach from the questionnaire to the representation of the collected data is shown in Figure 2.1.

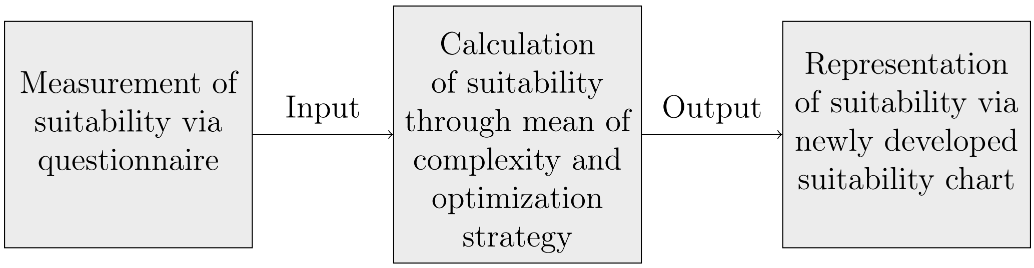

Figure 2.1: SMM Approach

2.4.1 Questionnaire

Evaluation of suitability through the questioned items is conducted by using a standardized questionnaire consisting of a number of closed-ended statements per dimension. Each question requires an answer reaching from *1 - strongly disagree*, to *5 - agree completely*. It is important that the questions are simple and easy to understand for the respondent to make the results reliable and usable [Ivert, 2009]. The questionnaire was based on the literature review and previous interviews with the case companies. The layout of the questionnaire is shown in Figure 2.2. Through empiricism, it is found vital for the results of the questionnaire, that the respondent has sufficient knowledge of the topic. Therefore, the questionnaire is sent out with a brief introduction to all the terms and statements used in the questionnaire.

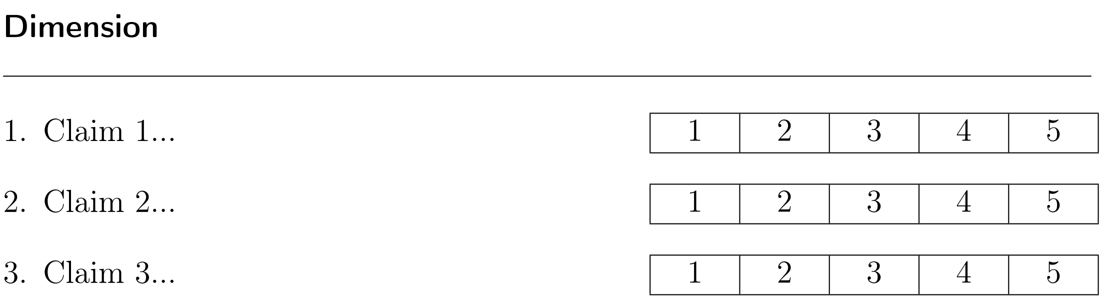

Figure 2.2: SMM questionnaire layout

The two chosen dimensions for the questionnaire, and hence the SMM are the complexity in manufacturing and optimization strategy. These dimensions demand differently formulated questions. The claims surrounding the complexity dimension are formulated AS-IS, how the manufacturing company is considering their production today. The optimization dimension calls for more TO-BE-aimed claims. This is because the questionnaire wants to address the possible development of the company's optimization strategy. The statements' outcomes are depicted in Figure 8.2 and Figure 8.3 in the appendices.

CHAPTER

THREE

THEORY

In this chapter, the focus is on presenting the insights and knowledge gathered from the literature review. The field of PPC and production scheduling encompasses a significant amount of theory, which can make it challenging to navigate and extract the most relevant information. Therefore, this chapter aims to provide a selection of pertinent and easily understandable theories that can aid in addressing the research questions and accomplishing the study's objectives.

The overarching aim is to explore and analyze a range of theories and ideas that are applicable to the contemporary manufacturing challenges of today. By doing so, the chapter will contribute to the understanding of the issues faced in the production scheduling part of PPC and provide a foundation for the results. The selected theories will be presented in a coherent and concise manner to enhance their accessibility and usefulness to both researchers and practitioners.

Firstly, an examination of production scheduling and I4.0 in relation to this is presented, which provides a framework for understanding the foundation of the study. Additionally, the chapter will delve into the theory of APS systems, including the functionalities, limitations, and concerns. Then, the JSSP is introduced, which is a widely known term revolving around sequencing and processing time of job tasks. Finally, the theory concerning complexity and optimization is explained, before an explanation of how the theory is applied related to the two main targets of the thesis. By examining these theories and concepts, a deeper understanding of the challenges facing modern manufacturing businesses and how APS systems can be leveraged to overcome them will be developed.

3.1 Production scheduling

Scheduling, as a fundamental decision-making process in the realm of manufacturing, plays a crucial role in effectively allocating resources to tasks within a defined sequence and over a specific time frame [Parente et al., 2020]. By harnessing production data, scheduling aims to strategically plan operational activities that not only meet the requirements of a manufacturing company but also fulfill its delivery agreements [Parente et al., 2020]. In the context of short-term scheduling, the focus lies on managing jobs that encompass operation chains characterized by varying machine sequences and distinct processing times. The challenge arises in efficiently orchestrating these operations across machines equipped with additional processing power while taking into consideration various essential criteria. These criteria encompass factors such as lead times, make-span (i.e., the total time required to complete a set of operations), and due dates [Dolgui et al., 2019]. By carefully evaluating these parameters and leveraging scheduling techniques, manufacturers can optimize their production processes, improve operational efficiency, and ensure timely order fulfillment, ultimately enhancing customer satisfaction and maintaining a competitive edge within the industry.

3.1.1 I4.0 in relation to production scheduling

The integration of Industry 4.0 technologies into production scheduling can have a significant impact on the effectiveness of production processes. Real-time monitoring of physical processes can enable production planners to make more informed decisions [Ghaleb et al., 2020]. I4.0 was envisioned to leverage an array of technologies to develop better solutions for production, capable of real-time monitoring of physical processes, and making processes interact with each other to improve production. One of the key benefits of I4.0 for production scheduling is the ability to create a more flexible and agile production environment. With real-time data and analytics, production planners can adjust schedules and production plans on the fly, based on changes in demand or resource availability. This can help to reduce bottlenecks, minimize downtime, and optimize the use of resources [Parente et al., 2020]. The intersection between I4.0 and production scheduling is a promising area of research, with the potential to drive significant improvements in manufacturing processes [Ivanov et al., 2016].

3.2 Advanced Planning and Scheduling systems

Previous literature about APS systems emphasizes that APS systems support both constraint-based planning and optimization. In constraint-based planning, no optimization objectives or criteria are treated. Only the predefined decisions on planning options are considered; business rules and constraints. On the other hand, the optimized plan is often based on economics, which makes the plan optimal seen from a financial perspective [Steger-Jensen et al., 2019]. The importance of categorizing APS systems became clear after talking with one of the case companies in this thesis. The categorization is a part of the results chapter.

APS systems are based on planning engines or algorithms. The approach the APS systems typically consist of is optimization techniques, heuristic searching algorithms, or simulation [Wang et al., 2021b]. APS plans can be altered in real-time based on the production, and environment, allowing companies to respond quickly to unexpected events or customer demand [Oluyisola et al., 2022].

The characteristics of an APS system are poorly defined in most literature. The literature frequently mentions APS systems and poses an APS-related challenge for a solution, but it rarely clarifies what exactly an APS system is. The main characteristics of an APS system have previously been mentioned: constraint-based and optimization. More in-depth about the characteristics are found in the literature. [Wang et al., 2021b] parts APS into four layers: the user layer, the application layer, the service layer, and the resource layer. The content of each layer is what can very well characterize an APS system. The system's user interface (UI) is in the user layer. The information and plans the systems produce are available to the planner, purchasers, sales staff, and shop floor operators. Changes are updated in the UI, and newly updated plans are delivered back to the users. For the second layer, the functions of the system come into play. Functions available at this layer vary depending on the manufacturer of the system, but this layer could typically consist of order management, visualized capacity, intelligent scheduling, and more. The service layer consists of the scheduling engine responsible for the simulations and the monitoring of the shop floor progress in relation to plans. The last layer contains virtual and physical resources, where virtual resources are mainly information stored in e.g. ERP systems or MES, and physical resources are e.g. computing hardware and sensors [Missbauer and Uzsoy, 2022, Stüve et al., 2020, Nadj et al., 2020].

In the introduction, APS was defined using the definition from [APICS, 2007]. The definition states that APS provides decision support, which has not been defined up to this moment. Decision support refers to the provision of tools that assist individuals or organizations in making informed and effective decisions [Sanders and Premus, 2005]. In the context of APS systems, decision support involves utilizing software to provide decision-makers with real-time data, predictive analytics, and optimization capabilities to support their planning and decision-making processes. As for another term supported by [Ivert, 2009], APS provides planning efficiency. Planning efficiency is defined in [Estlin and Mooney, 1997] as a benefit that provides domain-specific control rules that enable planners to find solutions more quickly. It involves automating and streamlining planning processes, reducing manual intervention, minimizing disruptions, and improving overall planning effectiveness [Dang and Barnes, 2012]. To state it easily, it refers to lower time consumption in the work of planning and scheduling. These two terms become important later on in the result section for categorizing the most important benefits of using APS.

3.2.1 APS functionalities

The overall goal of utilizing an APS system is to improve the decision-making process [Li et al., 2022]. To improve the decision-making process, APS systems contain several functionalities to cover the different aspects of a complex manufacturing process. Some of the functionalities are briefly mentioned in section 3.2 and will be further elaborated on in this subsection.

A feature in APS is the ability to simulate different planning scenarios [Hvolby and Steger-Jensen, 2010]. Simulation is used to verify operational problems and to validate the production planning [Jeon and Kim, 2016]. This gives the planner the opportunity to predict how the production plan will look beforehand, without having to try it out and possibly experience unseen failures or inaccuracies. The incorporation of simulation into an APS system is a vital capability that significantly enhances the system's dynamic scheduling performance [Liu et al., 2019].

[Kapulin and Russkikh, 2020] divides APS systems functionalities into three subsystems. The three subsystems are execution control, capacity estimation, and scheduling. The essence of these subsystems is what is considered the typical functionalities of an APS system. The execution control subgroup is distilled down into monitoring the production activities and enables the system to have complete control of the production which is active. The capacity control subgroup is used to estimate the optimal workload for the different processes and to automatically generate optimized plans in an APS system containing the optimization characteristic. The scheduling control subsystem uses the capacity control subsystem assessment on the capacity and solves two tasks, order prioritization, and sequence. [Kunath and Winkler, 2019] sites that the three subsystems are also found to be the main functionalities. Simulation-based planning could in most literature be described as the most prominent function obtained through the usage of an APS system [Park et al., 2021, Mousavi et al., 2019, Lee and Shin, 2015]. Complexity and dynamic environments in today's manufacturing processes highlight the necessity of simulations to map the manufacturing processes [Zhang et al., 2022]. The simulations that APS performs, using multiple constraints, give an output of plans and schedules, decision support, available-to-promise, and capable-to-promise [Kemen and Musa, 2020].
[Kjellsdotter Ivert and Jonsson, 2010] highlights the user-facing data's streamlined aesthetics and the plans' simplification.

Simulations in APS are based on hard and soft constraints. Hard constraints are constraints that limit the simulations to work within these and soft constraints can be overruled if necessary according to the goals of the production. Using mathematical algorithms and logic, these constraints are the guidelines for creating feasible plans [Hvolby and Steger-Jensen, 2010]. The simulations' plans and schedules lay the foundation, typically consisting of projected order completions, resource schedules, and a sequenced schedule. Essentially, simulations aid in the complex planning situations that today's manufacturers come across [de Paula Ferreira et al., 2020]. As mentioned earlier in this thesis, APS systems usually come as an add-on to an ERP system, meaning that the simulation input is fed from the ERP system into the APS system, and the outcome is fed directly back to the ERP system giving a closed loop between the two systems [Sobottka et al., 2020].

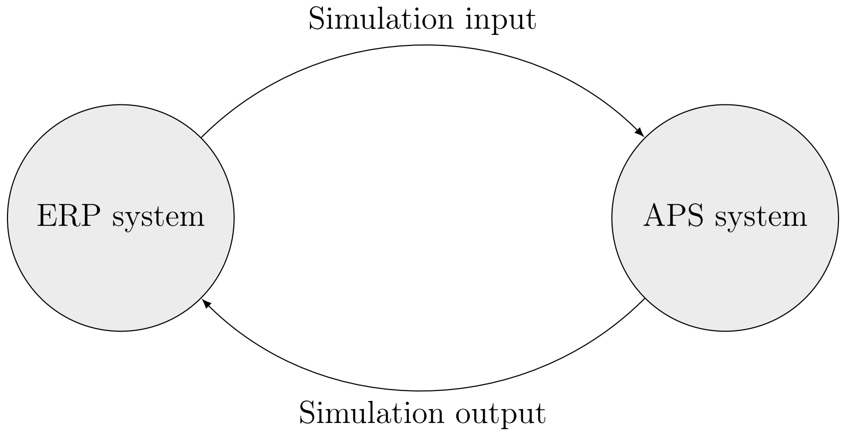

Figure 3.1: ERP - APS information flow

Figure 3.1 very simply illustrates the information flow between the ERP system and the APS system. The simulation input (basic data) is fed into the APS system, and the production plan created through simulations is fed back. The figure is added due to the visual understanding it creates of the information flow between the two systems. The information flow between the two systems is mostly the same in every APS variation, which is natural given that APS is either described as an add-on or an integral component of an ERP system in nearly all literature. Similarities also occur when talking about the implementation of ERP and APS. The dependencies APS has regarding ERP make implementing ERP and APS one of the most important implementation challenges [Lupeikiene et al., 2014]. Therefore, challenges in the implementation of ERP are suggested to be similar for APS. These challenges in the implementation of ERP are management support (in terms of a unifying strategy), data collection, extensive project, DIY project, man-hour intensive, not priority number one (in terms of ongoing projects), involving all departments, and changing the way of working. For a successful implementation, it is considered important to have a project champion, a business plan and vision, top management support, effective communication, business project re-engineering (BPR), software development, testing, and troubleshooting, and finally monitoring and evaluation of performance [Sagegg and Alfnes, 2020].

A list of the literature citations where the most common APS features first appeared is provided in Table 3.1. Citations that are already mentioned in the thesis are not listed. It is included to provide a sense of the general consensus regarding the functionalities of an APS system.

Functionality	Citation
Simulation	[Tan et al., 2019] [Wang et al., 2022b] [Mousavi et al., 2022] [Liu et al., 2022a] [Yazdani and Daim, 2022] [Lee et al., 2022] [Leu and Liu, 2022]
Capacity planning	[Leu and Liu, 2022] [Chen et al., 2013] [Neumann et al., 2022] [Wolfshorndl et al., 2020]
Sequencing	[Wang et al., 2021c] [Wolfshorndl et al., 2020] [Zheng et al., 2020] [Alfnes and Hvolby, 2019]
Order prioritization	[Lü et al., 2021] [Alfnes and Hvolby, 2019] [Piengang et al., 2019] [Moghaddam and Saitou, 2019]
ATP/CTP	[Shen et al., 2006] [Lü et al., 2021] [Moon et al., 2004] [Wolfshorndl et al., 2020]

Table 3.1: APS functionalities

3.2.2 APS limitations and concerns

APS systems come with some concerns and limitations that need to be accounted for. Several concerns regarding choice complicatedness, decision complexity, level of aggregation, data availability and quality, uncertainty, and variations are declared in [Alfnes and Hvolby, 2019].

Decision complicatedness and complexity is a concern backed by [Piengang et al., 2019, Li et al., 2022], whereas the proposed solution in [Piengang et al., 2019] is to put the complex multi-criteria decision-making problem into a hierarchy. [Kapulin and Russkikh, 2020] connects the complex decision process that APS requires with the concern regarding data availability and quality.

In [Oluyisola et al., 2022] the data feasibility of real-time or near-real-time is discussed as something production planners commonly avoid but is suggested in [Jonsson et al., 2007] to be a requirement for APS. [Oluyisola et al., 2020] talks about how the slender data the enterprise planning systems such as ERP and APS collect affects production due to the other factors that influence production performance. Data availability has been mentioned as a problem, and the solutions often come in the form of RFID usage. However, RFID usage has varying results depending on what industry the manufacturer coincides with [Zhong et al., 2013]. Examples of data that should be feasible and updated are item information, resource information, operations information, and run parameters [Musselman et al., 2002]. All of these are grouped under the term basic data.

Level of aggregation is described as the simplification of problems through the definition of condensed data and decision variables as well as the differentiation of levels based on hierarchy and decision models, with the difference between levels being referred to as a level of aggregation. It, therefore, achieves a reduction of data requirements and model complexity. [Zoryk-Schalla et al., 2004]. The concern raised by [Alfnes and Hvolby, 2019] is the problem of automatic simplification when you essentially want a detailed schedule. Aggregation can however be beneficial depending on the level of optimization in the APS system.

The last concern identified by [Alfnes and Hvolby, 2019] was uncertainty and variations. APS systems are normally well-suited for manufacturers with high variation and fluctuating demand [Ivert and Jonsson, 2014]. However, as identified by [Alfnes and Hvolby, 2019], there are other factors that could affect a production target or a detailed schedule. Some of these factors could be interruptions due to defects, varying processing times, rush orders, maintenance stops, etc. The frequent update in the APS system these factors would require could as well create nervousness in the plans. The uncertainty and variations problem is a problem that is well known among researchers of APS systems, a few papers that mention the problem are [Piengang et al., 2019, Kapulin and Russkikh, 2020, Man et al., 2020, Zheng et al., 2022].

Investing in an APS system is expensive and can be time-consuming [Ivert, 2009, Oluyisola et al., 2022]. Therefore, it is important that the investment generates a profit for the company in the form of a more efficient schedule.

3.3 Job Shop Scheduling Problem

The JSSP is a widely known term, and the literature study states that it is difficult to generalize. The main essence of the problem is that each job in a job shop comprises a set of tasks that must be performed on a specified machine with a known processing time, in a given order. A common objective of that process is to minimize the makespan of the total jobs to be completed [Chaudhry and Khan, 2016]. In [Xiong et al., 2022a] the classical JSSP is defined as a job shop containing a number of machines $M = M_1, M_2, ..., M_m$, there are a number of jobs $J = J_1, J_2, ..., J_i, ..., J_j$, where each job, J_i, have a series of operations $O = O_i1, O_i2, ..., O_ij, ..., O_in_i$ which need to be sequenced in the most optimized order. It is stated as the most classical and important combinatorial optimization problem, which further fuels the desire to study the use of APS systems in JSSP environments. Figure 3.2 from [Destouet et al., 2023], visualizes a representation of the JSSP as a classical flexible JSSP (CFJSSP) and as a flexible JSSP (FJSSP). The illustration is on a generic level.

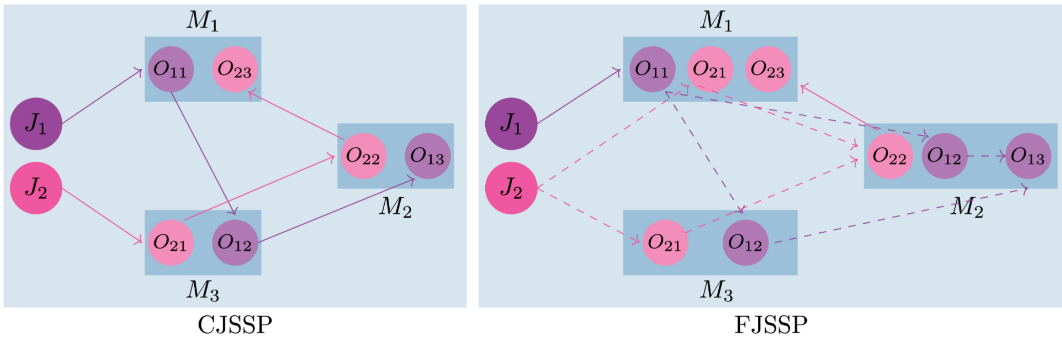

Figure 3.2: JSSP in CFJSSP and FJSSP

There are many ways to measure performance in the JSSP. It can be measured by time-based criteria, which take makespan, completion time, and tardiness into account. It can be measured by the number of completed jobs, which is considering the sum of tardy jobs, the percentage of tardy jobs, the number of jobs in stock, and the number of jobs in the process. Other criteria can be cost-based, revenue-based, and environment-based performance measurements [Xiong et al., 2022b]. However, because of the scope of this study, the time-, and job-number-based performance measurements are the ones considered important.

The broadest solution proposed by researchers is the use of various algorithms as optimization method. [Gao et al., 2020] proposed the use of a differential evolution algorithm as a basic optimization framework, with the advantage being an evolutionary strategy to carry out mutation operations. [Wang et al., 2022a] uses a hybrid adaptive differential evolution algorithm to transform a multi-objective fuzzy JSSP into a single-objective. In [Mohan et al., 2019a] several job shop scheduling techniques are reviewed, where simulation, genetic algorithms, and a combination of these two methods are reviewed. The combination of simulations and genetic algorithms is highly relevant in the context of APS. There have been multiple studies on this topic, e.g. [Chen et al., 2011, Pongcharoen et al., 2004b, Dellaert et al., 2000, Caraffa et al., 2001, Lee et al., 2002, Shen et al., 2006]. These studies are relatively old, especially in regard to the strategy of this paper's literature search, but they are exhibited to highlight the research done in the context of APS, genetic algorithms, and JSSP.

3.4 Complexity and optimization

Complexity in manufacturing and optimization strategy are important parameters to take into account when making decisions surrounding APS use. The theory states that the APS need should decrease when a clear optimization strategy is absent and the planning task complexity is low [Ivert, 2009]. Figure 3.3 is extracted from one of the papers discussed in [Ivert, 2009], and illustrates this. The model illustrates four quadrants representing different scenarios related to complexity and optimization in relation to each other.

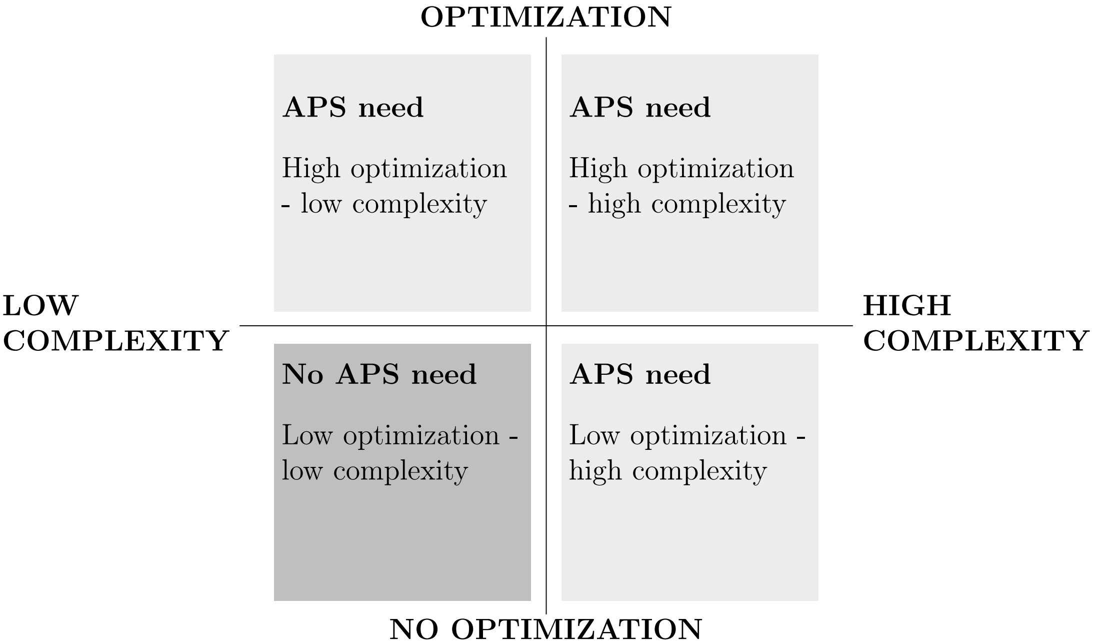

Figure 3.3: Optimization - complexity correlation

- Q1 represents a situation where both optimization and complexity are considered high.
- Q2 represents a situation where optimization is considered high, and the complexity is considered low.
- Q3 represents a situation where optimization and complexity are considered low.
- Q4 represents a situation where optimization is considered low, and complexity is considered high.

As observed, Q1, Q2, and Q4 are classified as *APS need*, which implies that there is a possibility of recommending an APS system in such cases. However, Q3 is labeled as *No APS need*, indicating that it is not advisable to suggest an APS system solely based on the requirement for optimization and the level of complexity. It may require further analysis and evaluation of other factors to determine the suitability of an APS system for Q3. Figure 3.3 is of importance for the second overall aim of the study, hence the development of the suitability measurement model provided in the results chapter.

3.5 Theoretical application

Within this subsection, the present study unveils the theoretical application that serves as the underpinning basis for each of the research objectives, establishing a solid foundation upon which to conduct analysis and interpretation. Specifically, the theory is rooted in an in-depth examination of APS functionalities, the limitations, and concerns associated with APS utilization, the intricate relationship between optimization and complexity, and, lastly, the domain of JSSP, all of which have been expounded upon in this chapter. Through the application of this visualization of how the theory is applied, the ultimate goal is to derive valuable insights and contribute to the advancement of both theory and practice within the realm of production scheduling.

By delineating the various topics presented throughout this chapter in Figure 3.4 and linking them back to the overall aims presented in section 1.4, a comprehensive understanding is provided to the reader regarding the impact of these different topics on the thesis' overarching goals established from the outset. This visual representation not only facilitates a clear comprehension of the relationships between the individual topics and the overall aims but also highlights the strategic alignment between the research objectives and the subsequent chapters. The inclusion of Figure 3.4 serves as a navigational tool, guiding the reader through the root of this thesis's theoretical application and ensuring that each topic's relevance and contribution to the thesis' overarching objectives are effectively communicated.

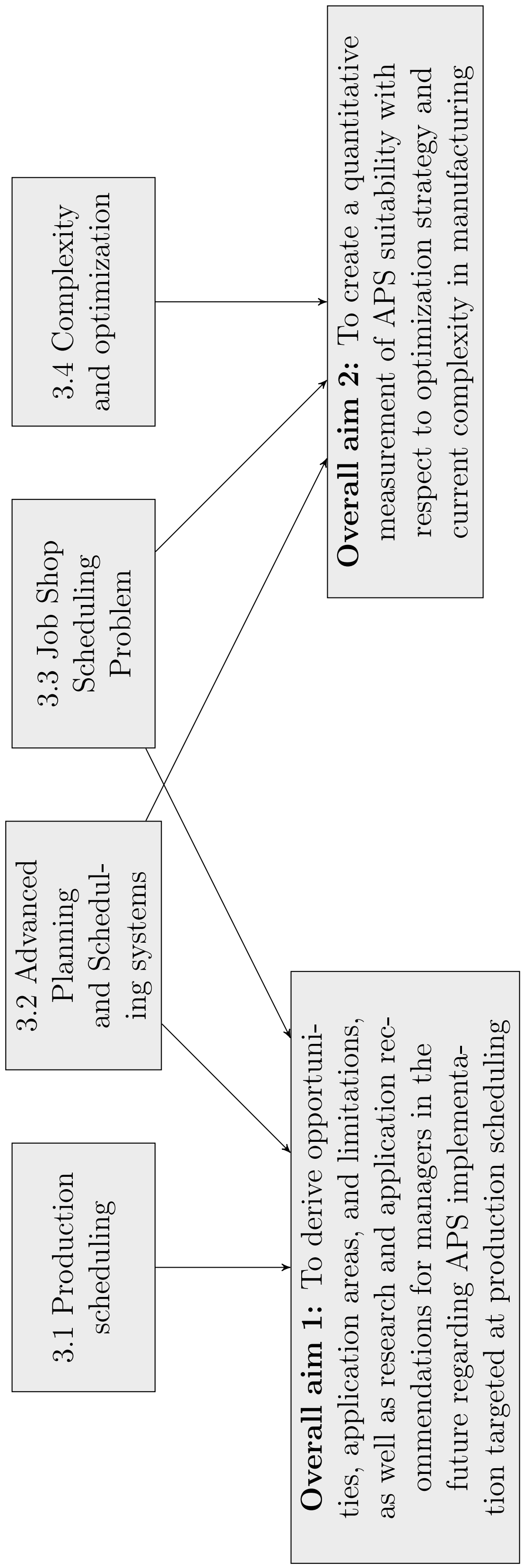

Figure 3.4: Theoretical application

CHAPTER FOUR

RESULTS

The results chapter is a pivotal section of this thesis as it provides a detailed presentation and analysis of the data collected during the research process. The chapter aims to offer a comprehensive overview of the research findings, which were obtained through various research methods and techniques presented in chapter 2. The primary objective of this chapter is to present a factual and precise depiction of the research discoveries. This account will serve to address the research inquiries and augment the existing knowledge base within the field. It is important to ensure that the results are impartial and based on solid evidence so that they can be considered reliable and useful for future research and practical applications. The chapter will aim to provide a comprehensive understanding of the research findings. All of the results from the case studies are obtained from the performed interviews.

Tables and categorizations play a crucial role in providing a clear and concise representation of the research findings. The categorization of APS systems and benefits under consideration is presented through tables, which offer a visual benefit in understanding the complex relationships between different variables. The use of tables helps in organizing large amounts of data and presenting it in a comprehensible format for the reader.

A basic categorization of APS systems is followed by a categorization of the benefits under consideration. To add context and showcase the findings from the interviews, the results from the case studies are also presented. The newly created suitability measurement model is then provided after the developed questionnaire. Finally, the case companies' questionnaire replies are shown.

4.1 Categorization of APS systems

The categorization of APS systems is crucial in facilitating a better understanding of their suitability for various PPC scenarios. By grouping APS systems according to their optimization level, researchers and practitioners can identify the system that is best suited to address their optimization strategy. APS systems are available in a variety of optimization levels, which can make it difficult to understand their specific functionalities and capabilities. Through empirical research and analysis, this section seeks to provide a general categorization of APS systems, as depicted in Figure 4.1.

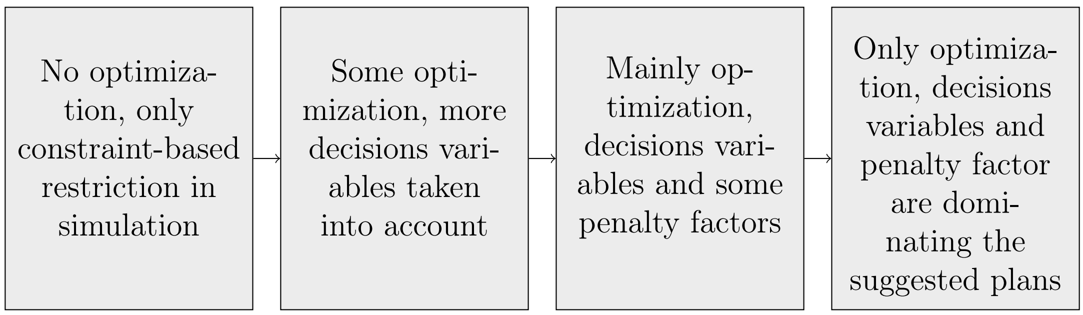

Figure 4.1: APS categorization

Looking at Figure 4.1, the three categories farthest to the right can be difficult to tell apart. To clarify, the difference in optimization between the three is mainly the depth of the data the system takes into consideration. The depth of the data refers to the comprehensive nature of the information gathered, encompassing the depth of priorities and constraints. It is important to note that the categorization of APS systems presented in this section is a generic one, which highlights that these systems can incorporate different levels of optimization. The categorization is not based on an empirical study of various APS systems but is instead an extraction from interviews and existing theory. As such, the categorization presented in this section is mainly based on the information gathered from CCB, which highlighted the presence of multiple levels of optimization in APS systems. While this categorization is based on limited information, it provides a framework for understanding the general optimization levels that an APS system can possess.

4.2 Categorization of benefits

In the theory chapter, APS functionalities are listed, but this section aims to sort the potential benefits into decision support benefits and planning efficiency benefits. The following table provides the potential benefits of APS systems related to production scheduling. The origin of the information in Table 4.1 are the citations in section 3.2 and in Table 3.1.

	Benefit	Category
1.	Ability to simulate different planning scenarios using multiple constraints	Decision support
2.	Makes it possible to identify unexpected events	
3.	Visual simplifying of the plans	
4.	The possibility to create optimized plans given chosen constraints and priorities	
5.	Automatically generate optimized plans	Planning efficiency
6.	Handles order prioritizing and sequence	
7.	Simplifies planning activities	
8.	Time-reducing planning activities	
9.	Workload estimation	

Table 4.1: Potential benefits of APS systems for production scheduling

As seen in Table 4.1, the different beneficial functionalities presented in the theory chapter are divided into two categories. The categories are defined in the last paragraph in section 3.2. The categorization makes it easier to visualize the potential benefits and refer to them. Aiding the understanding of what the different functionalities offer to important beneficial aspects of production scheduling.

4.3 Case study

The case studies were conducted with the aim of investigating and analyzing the real-world applicability of how production scheduling is performed with and without the use of APS systems. This section will delve into the specific findings obtained from each case study, highlighting the key insights and observations derived from the interviews. The results presented will provide a comprehensive understanding of the similarities and differences between the two companies.

4.3.1 CCA

The shop floor activities in CCA mainly consist of the machining of large propellers and thrusters for the maritime industry. Different-sized pallet machines are used for machining the parts in 5-axis. The components' turning, drilling, and further milling are performed in manual lathes. Because of the great variation in demand, CCA produces mainly according to orders and projects, with only service parts produced to inventory. A basic ERP system is used to determine the production plan, and this is the tool used to provide communication between the planners and the shop floor. The company uses standard backward MRP planning, which assumes infinite resource capacity. Lead times are estimated using past experiences and historical data. Their target is to constantly have queues in the machines. The tops and bottoms of the manufacturing are directly dependent on the orders received.

The main challenge presented by CCA is leveling of the production. Avoiding large tops and bottoms has proven to be a major challenge. The strategy of mainly producing everything on orders and projects is connected to this challenge. [Vinci Carlavan and Rossit, 2021] states that the leveling challenge is well known when producing on received orders, hence this challenge is related to the literature.

When it comes to flexibility in changing the production plan, standard backward MRP planning is inconvenient. If unforeseen obstacles arise, the production sequence has to be changed, and this was described as difficult with their current planning tool and strategy. However, the workers on the shop floor are allowed the authority to move parts internally between machines if they believe it would speed up production.

Another possible challenge CCA was aware of is that if the production has increased drastically, as they expect for the future, the current system will be difficult in addition to today's resources on planners. This is one of the reasons CCA is considering the implementation of a new system to improve planning for the shop floor activities. The ongoing decision in CCA is about cost/utility regarding the decision of whether a new system should be implemented as an add-on to the ERP system.

4.3.2 CCB

CCB mainly produces roof coverings on a large scale and has production facilities in Norway and two locations in Europe. The products are fairly straightforward in terms of actual production, interpreted from a single interview, but all variants go through at least two machines which complicate the planning process. Some products are more or less produced to stock, but there are some variants that are produced on demand in relationship with projects. The production facility in which the interviewee is mainly based in has three machines that do the production. Planning for these three machines, with the APS system, is uttered as very streamlined. The APS system that is in use, uses basic data for every product in its simulations on the schedule.

Regarding the production strategy in CCB, they produce some goods to stock, and some on order. The products are classified as A, B, C, or D products which are MTS and more towards ETO respectively. B and C products are in an out-phasing at CCB. The goods produced to stock are based on a fairly evenly demand and past experiences. In contrast to CCA, CCB has completed the implementation of an APS system as an add-on to their ERP system, to support production planning. The assessments done when deciding the implementation of such a system were that the efficiency would increase, and the planning would more easily be up-to-date. The planner would be able to increase the planning horizon and make overall plans in regards to e.g. capacity more accurately. CCB also wanted to pursue opportunities they may not have uncovered. The utility of extending the current system was also something CCB wanted to explore. At present, the APS system is used on a quite simple level, but it provides an easier capacity calculation and placement on production plans against available capacity and resources. The planning is performed in the ERP system at first before the plans are transferred to the APS system where a finer and more accurate plan is proposed to the planner. The APS system provides automatic suggestions for what to produce when there is a gap in production. CCB described their APS use as a "pick and drop" solution, where the system simulates the consequences when changes are made to the plan. In that way, the APS system streamlines updates to the plans. CCB pointed out that the APS system is used mainly as a simulation- and adjustment tool. The ability to simulate "what-if" scenarios allows planners to model potential outcomes that they believe are necessary, which is the key advantage outlined by CCB.

CCB's interview object points out several aspects revolving around the use of the APS system they use today. Some of the talking points throughout the interview focused on the drawbacks and issues with the APS system, which was a crucial aspect of it given the goals of this thesis. The literature demonstrates that CCB likewise highlights the value of high-quality fundamental data as the foundation for APS systems' calculations. The capacity is usually set lower at CCB's basic data due to the fear of inaccurate data on the capacity. The capacity contains several parameters such as percentage up-time, and available time, which all accumulate to a difficult situation for the planners at CCB because of the lack of control over the cost price with regards to the capacity aspect. Service on machines and dismissal due to the quality of the parts are also a parameter that is tracked and used in the percentage up-time. The basic data at CCB are usually a continuous revision because the data never becomes accurate enough. Lastly, the requirement of training on the system to be fully utilized is emphasized.

4.3.3 Comparison

This section summarizes subsection 4.3.1 and subsection 4.3.2 by showing the main differences between the companies related to job planning, process planning, and job shop scheduling. It is once again repeated that CCA does not use an APS system, while CCB is.

Area	**Case Company A**	**Case Company B**
Job planning	Performed and set manually in the ERP system. Lead times are estimated using past experiences and historical data.	The start- and end time of each task is worked out with the help of the "pick and drop" method and simulation in the APS system.
Process planning	Sequence and machine routing are chosen and set in the ERP system.	Through simulation and dynamic scheduling, the APS system contributes to the determination of the sequencing and machine routing.
Job shop scheduling	Performed manually in the ERP system. The workers on the shop floor are allowed the authority to move parts internally between machines if they believe it would speed up production.	Through simulation and dynamic scheduling, the APS system contributes to the work of creating a plan that utilizes resources effectively. The schedule is carried out as intended by the planners.

Table 4.2: Comparison of the case companies

4.4 Questionnaire

The questionnaire, which the SMM utilizes to extract the results, is based on the theory acquired through the literature search and the interviews. It became clear that APS has good applicability in most production scheduling environments, but due to the high cost of acquiring most APS systems, suitability with respect to optimization strategy and complexity is a differentiating factor that could determine whether a manufacturer will have good net utility value using an APS system.

4.4.1 Optimization strategy statements

The ten statements concerning the optimization strategy in the created questionnaire are introduced in this subsection. The supporting evidence for each claim is provided in section 5.4.

	Statement	Source
1.	You see the potential benefits of the ability to simulate the production plan before the release	CCB [APICS, 2007] [Kwahk and Lee, 2008]
2.	You think you have unrealized potential regarding the quality of your production schedule	CCA [Kwahk and Lee, 2008] [Boyer and Sovilla, 2003]
3.	You often experience inaccuracies in the production plan that leads to unwanted free time in the machines	CCA [Rinciog et al., 2020] [Chen et al., 2020]
4.	You often experience inaccuracies in the production plan that leads to overloaded tasks on the machines	CCA [Ivert, 2012] [Rinciog et al., 2020] [Chen et al., 2020]
5.	You have a clear understanding of what constraints and penalty factors you would want to utilize in the possible simulations	[Mettler et al., 2016] [Eid et al., 2021] [Sedlaczek and Eberhard, 2006]
6.	Basic data for the production processes in the production exist	CCB [Oluyisola et al., 2020] [Wang et al., 2021c]
7.	The basic data of your production processes are stable and rarely change	[Alfnes and Hvolby, 2019] [Ivert and Jonsson, 2014]
8.	Service of machines and errors in machinery are fairly predictable	CCA [La Fata and Passannanti, 2017] [Bohlin and Wa¨ rja, 2010]
9.	Guidelines/constraints of how the production planning is done are set at a holistic level among planners	CCA CCB [Zhai et al., 2019]
10.	Guidelines of priorities in the scheduling are set at a holistic level among the planners	CCA [Stanitsas et al., 2021] [Yang et al., 2020]

Table 4.3: optimization strategy statements

4.4.2 Complexity statements

The ten statements describing the complexity of the manufacturing in the created questionnaire are introduced in this subsection. The supporting evidence for each claim is provided in section 5.4.

	Statement	Source
1.	Your current product structure is complex, meaning the finished product consists of several parts	CCA [Destouet et al., 2023] [Xiong et al., 2022b]
2.	Many of your products are made one-of-a-kind (tailored especially for the customer/project)	CCA [Li et al., 2022] [Chansombat et al., 2019]
3.	A small error/inaccuracy in one of the production steps causes delays or other significant unwanted consequences	CCA [Wang et al., 2022a] [Barni et al., 2020]
4.	You spend many human working hours to generate the production schedule due to the need of calculating many variables and important interactions	CCA CCB [Zhang et al., 2020] [Mohan et al., 2019b]
5.	The products you produce have a high variance in processing-time	CCA [Caldeira and Gnanavelbabu, 2021] [Amaro et al., 2022] [Alkhateeb et al., 2022]
6.	Every part needs to pass through several machines in the manufacturing process	CCA [Destouet et al., 2023] [Xiong et al., 2022b]
7.	You have several activities processing simultaneously at your job shop	CCA CCB [Zhang et al., 2022] [Liu et al., 2020] [Zhang et al., 2021]

Continued on next page

Table 4.4 – continued from previous page

	Statement	Source
8.	There is a choice in material selection for each part	CCA [Min et al., 2019] [Cheng et al., 2020]
9.	Machines used in the shop floor activities need to be manually operated or need programming before each use	CCA [Rauch et al., 2020]
10.	Shop floor workers follow schedules slavishly	[Wiers, 2009]

Table 4.4: Complexity statements

4.5 Suitability Measurement Model

This section introduces the developed APS suitability measurement model. It is developed to contribute to answering *RQ3*. In terms of complexity and the requirement or need for optimization, the model indicates which environments are suitable for the implementation of APS systems.

Figure 3.3 indicates which situations could fit with the idea of implementing an APS system, but it is not very measurable and does not contain any measurability values. The idea was to further develop a model that uses the questionnaire attached in the appendices (Figure 8.2 and Figure 8.3) as a base to provide a measurable result for suitability. The result of this is Figure 4.2 as seen below. It contains the same parameters as Figure 3.3, but with values from 2 to 10 to contribute to a quantitative result.

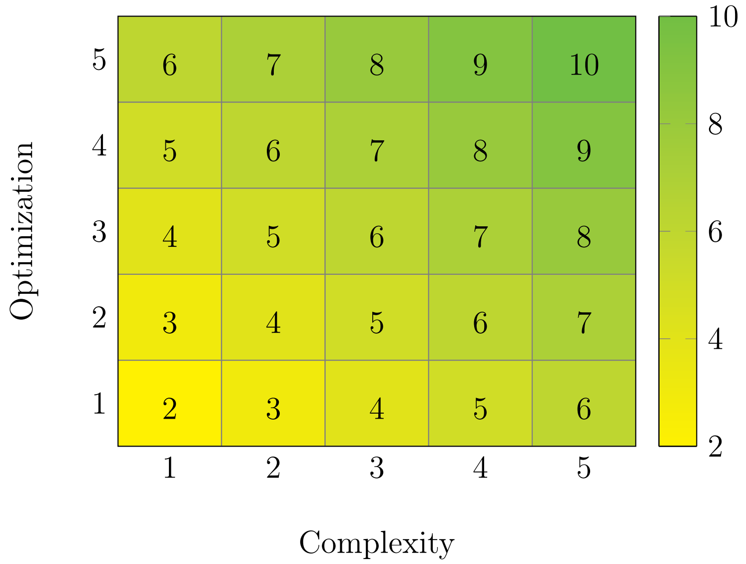

Figure 4.2: Suitability Measurement Model

The questionnaire is structured in a way so that each question requires an answer reaching from 1 - “strongly disagree”, to 5 - “agree completely”. These values are transferred to Figure 4.2. The average answer value from the two dimensions in the questionnaire results in a value from the figure. For instance, if the mean complexity value is 3 and the mean optimization value is 4, one can read the suitability value straight from the figure and get the number 7.

Value	Description
2-4	From the two parameters emphasized, an APS system can not be recommended.
5-8	APS can be beneficial, but complexity and desired optimization level should not be the foundation of the decision. Other parameters such as strategy should be further investigated.
8-10	High complexity in the production and a highly desired level of optimization fits with the implementation of an APS system. If other consideration parameters do not contradict with APS use, the implementation should be highly considered.

Table 4.5: SMM value guide

As described in section 4.1, APS systems can contain different levels of optimization. Therefore, it is important to emphasize that the SMM states that an APS system will be more suitable when the optimization strategy is higher, and the manufacturing is of a more complex nature. An APS system could improve production scheduling even without optimization at all, but the necessity of such a system increases when optimization is demanded.

4.5.1 Response to statements

The SMM was validated by letting the case companies that previously had been investigated, respond to the questionnaire. This section only presents the results of the validation, and it is further discussed in subsection 5.5.1.

Optimization statement	CCA	CCB
1.	4	4
2.	4	3
3.	3	4
4.	4	2
5.	4	1
6.	3	5
7.	3	3
8.	2	4
9.	4	4
10.	3	4
Mean Value	**3**	**$3.4 \approx 3$**

Table 4.6: Response to optimization strategy statements

Complexity statement	CCA	CCB
1.	5	5
2.	4	4
3.	2	4
4.	3	3
5.	4	5
6.	3	5
7.	5	4
8.	2	4
9.	3	5
10.	2	4
Mean value	**4.5 $\approx$ 5**	**4.3 $\approx$ 4**

Table 4.7: Response to complexity statements

CCA's response to the questionnaire, shown in Table 4.6 and Table 4.7, resulted in the mean values 3.0 and 4.5 respectively. CCB's response resulted in a mean value for optimization strategy and complexity of 3.4 and 4.3.

CHAPTER

FIVE

DISCUSSION

This chapter provides a discussion and evaluation regarding the results of the study. As this chapter shows, the results must be connected to the research questions. The aim of the discussion is to discuss the findings, determine the reliability of the results, and justify the reliability considerations. The research questions were:

RQ1: What are the applications of APS systems related to production scheduling?

RQ2: What are the limitations of APS systems related to production scheduling?

RQ3: How does the complexity in manufacturing and optimization strategy inform about the fit of APS use?

The primary purpose of the discussion is to establish a clear connection between the research questions and the findings that have emerged from the study. By critically evaluating the data and interpreting its implications, the aim is to shed light on the extent to which the research objectives have been achieved and contribute to the existing body of knowledge in the field. Furthermore, this chapter serves as an opportunity to assess the reliability of the results. It is essential to examine the validity and credibility of the findings, considering factors such as the research design and data collection methods. By evaluating the robustness of the study, the degree to which the conclusions drawn from the data are trustworthy and representative of the population under investigation can be ascertained.

In addition to evaluating reliability, a response to the limitations and potential sources of bias that may have influenced the results. Acknowledging these limitations is crucial for maintaining transparency and ensuring the integrity of the study. By openly discussing the constraints and constraints encountered during the research process, the study provides a more accurate understanding of the study's scope and applicability. Ultimately, this discussion chapter aims to not only present the findings but also to provide a comprehensive evaluation and interpretation of the results. By exploring the significance of the outcomes within the context of the research questions, addressing the reliability of the findings, and acknowledging potential limitations, enabling the study to contribute to the advancement of knowledge in the field and lay the foundation for future research endeavors.

5.1 Practical use of APS systems

The advantages and methods for achieving them are the main topics in this section. Concerns are also brought up because they play a crucial role in establishing suitability. *RQ1* is the motivation for discussing the practical use of APS systems, and through this section, the end result should be a discussion covering all the aspects of the information revolving around the use of APS gained through the case study and the literature review.

The case companies that were investigated for this master's thesis shared an interest in or utilization of an APS system. CCB already uses an APS system, and CCA is contemplating implementing one as well. What makes both companies interested in the same system is linked to the use of an ERP system. The same ERP system is utilized by both CCA and CCB, so it stands to reason that when looking for an APS system, the same APS system would be pertinent. It is more relevant to explain the actual use of the APS system using the case of CCB, as they have already implemented an APS system and used it for a while. It is important to express that different APS systems could use different optimization methods in form of different mathematical algorithms, as mentioned in section 3.3 when listing normal solutions to the JSSP, proposed by researchers.

CCB, as mentioned, has been using the APS system for some time and characterized its use of the system as fairly seamless. CCB uses the APS system on a very basic level, with zero optimization. Based on the SMM this usually would imply that APS has a low net utility value in this TO-BE environment. However, the benefits that APS provides in terms of seamless long-term planning were worth the cost of this system for CCB. Meaning the SMM views the link between optimization need and actual net utility value too black and white. CCB values the ability to perform the planning in a dynamic way, where they easily can simulate and therefore predict how the manufacturing will look like. This is an example of a situation where an APS system can be beneficial, even without being fully explored.

5.2 Benefits

This section aims to formulate an answer to *RQ1*, the applications of APS systems related to production scheduling. To address the possible benefits of APS systems in that context, the APS functionalities listed in Table 4.1 in section 4.2 are important. A discussion and review of the benefits is presented in this section, to further understand and tie them up against the case studies.

The capacity to simulate the production plan and test various variants and scenarios is the first capability that is obviously beneficial, according to

[Hvolby and Steger-Jensen, 2010]. A common term for this benefit can be formulated as the ability to perform dynamic planning. The planner is given the chance to foresee how production will proceed without needing to test it out in real life first. One of the traits from the literature that was most frequently cited and had a large number of reliable sources was the simulation aspect. The number of citations for simulation can be viewed in the Table 3.1. The notion aligns nicely with the CCB experiences that were reported. They often use the simulation tool and cited it as one of the system's key advantages. Along with the other functionalities of the APS system, the benefits of these functions are empirically justified to be more beneficial depending on the complexity of the production. The more complex the production is, the more benefits will an APS system subsidize. In Table 3.1, the functionalities subsequently to simulations are functions that are taken into account in the simulations. However, the amount of optimization present in the prospective APS system will determine how well the generated plans consider each topic accurately or with any consideration to e.g. what the prospective projects derive financially.

Dynamic planning and an APS system's capacity to detect unanticipated occurrences are strongly related. Before the plan is implemented, simulations can be run to help the planner foresee potential undesirable outcomes without having to actually experience them. This can help the business, especially when it comes to time usage, which can negatively affect delivery as a whole. The financial component can be improved by reducing material waste and using dynamic planning. The aspect of dynamic planning is clearly exposed when looking at the two case companies. CCA expressed that their current system is inconvenient when it comes to flexibility in changing the production plan, while CCB says that the APS system streamlines updates to the plans, because of its simulation and automatic suggestions when revisions are made.

By using visual aids such as graphs, charts, or diagrams, information can be conveyed in a clear and concise manner that reduces the potential for confusion or ambiguity as well as increasing the decision support for the planners. This is particularly important when it comes to production schedules, which can be subject to constant changes and adjustments. When shop floor workers and planning department personnel have a shared understanding of the production schedule, unnecessary time consumption due to ambiguities can be avoided. By minimizing the potential for miscommunication and misunderstandings, the business can operate more efficiently, dramatically leading to increased productivity and profitability. In addition, visually simplified plans can be speculated to improve overall workplace morale and reduce stress levels, as employees could feel more confident and informed about their roles and responsibilities. Overall, investing in visual simplification of plans could be a way to improve communication and coordination between different departments in the business, resulting in a more streamlined and productive operation.

One of the key decision-support benefits of an APS system is the ability to create optimized plans based on chosen constraints and priorities. This can be particularly valuable in complex production environments where numerous variables must be considered, including machine capacity, personnel availability, and material availability. Without an optimization tool, it can be difficult to identify the most efficient and effective solutions for production scheduling. An APS system can automatically generate multiple scenarios and provide variations to the plan that may not have been discovered through traditional planning methods. By identifying optimal solutions, businesses can reduce production time and costs, increase throughput, and improve customer satisfaction. However, despite these potential benefits, none of the case companies currently utilize optimization tools in their production scheduling processes. As such, highlighting the potential benefits of optimization through an APS system can help these businesses understand the potential for improved production efficiency and profitability. The adoption of an optimization-based APS system can provide businesses with a distinct competitive advantage in the market and enhance their financial performance.

The advantage of automatic plan generation relates to time consumption. This is a common factor throughout many of the benefits that have been mentioned. Simply put, less time needs to be spent developing plans by the planning department. A project's overall duration may be shortened if less time is devoted to plan generation and more time is devoted to manufacturing and implementation. APS' ability to handle order prioritization and sequencing are also benefits that are linked to time consumption. Simplification of the planning activities is somewhat the summary of the planning efficiency benefits, and simplification should lead to shorter time consumption.

The subsequent bullet points delineate the primary advantages of APS systems concerning production scheduling, as extracted from this section:

1. **Increased Testing Freedom:** The capacity to simulate the production plan and test various variants and scenarios. The planner is given the chance to foresee how production will proceed without needing to test it out in real life first.

2. **Increased Adaptability:** Dynamic scheduling facilitates enhanced flexibility in modifying the production plan. APS systems offer flexibility in responding to unforeseen events or changes in production requirements.

3. **Enhanced Visibility:** Information can be conveyed in a clear and concise manner that reduces the potential for confusion or ambiguity through visual aids. APS systems provide real-time visibility into the production schedule, enabling managers to monitor and track the progress of each task and order.

4. **Optimized Production:** The ability to create optimized plans based on chosen constraints and priorities. By identifying optimal solutions, businesses can reduce production time and costs, increase throughput, and improve customer satisfaction.

5. **Increased Efficiency:** The ability to significantly reduce the potential time consumption associated with manual plan generation by automating the process, thereby streamlining and expediting the creation of production schedules.

5.2.1 Prerequisites to achieve benefits

Another important question that arrived when studying the possible benefits of APS systems towards production scheduling is the prerequisites to achieve the desired benefits. As mentioned, APS is an add-on to an ERP system and this means that the quality of the APS system is directly affected by the data quality and up-to-dateness of the ERP system. The APS system retrieves data from the ERP system, and if this data is incomplete or insufficient, the APS system does not reach its potential as described in subsection 3.2.2, among other limitations and concerns revolving around the usage of APS systems. The basic data contains a lot of parameters which are all important for the APS system to schedule the best net utility valued schedule based on the capacity and resources.

The implementation phase is highly important for the further use of APS systems. The implementation of APS is in many ways linked to the same problems as with the implementation of ERP. ERP systems are a major change in any enterprise that starts implementing them, and there are several challenges identified through empiricism. However, implementing APS and ERP systems is widely acknowledged as one of the most critical challenges. When implementing APS, it is crucial to address similar challenges faced during ERP implementation, including management support in the form of a cohesive strategy, comprehensive data collection, extensive project management, DIY projects, substantial time and manpower requirements, lower priority compared to ongoing projects, cross-functional involvement of all departments, and a transformation in work processes. In order to achieve successful ERP implementation, several key factors are considered essential. These factors include having a project champion who can drive the implementation forward, developing a well-defined business plan and vision, securing top management support, establishing effective communication channels, undertaking business project re-engineering (BPR), conducting software development, testing, and troubleshooting, and finally, implementing a monitoring and evaluation framework to assess performance. Data collection and management support are some of the implementation challenges considered most prominent in APS implementation, but the success factors can arguably be the solution to the same challenges in APS implementation and therefore be a prerequisite to achieving the benefits of APS.

The simple answer to achieving the benefits of using APS systems is to avoid the limitations and concerns revolving around APS systems. However, the continuous work regarding keeping basic data on the production processes accurate and up to date is vital for the accuracy of the simulations. Adding automatic data-gathering could be a highly relevant measure to ensure that data is up to date at all times, without manual inaccuracies that could occur when if put in manually. The most common solution from the literature that has good results to cope with the quality of the data is to implement sensors or other measures to get real-time data on the processes.

5.3 Concerns and limitations

The main concerns and limitations regarding APS systems towards production scheduling are questioned in *RQ2*. The main limitations and concerns are listed in subsection 3.2.2. This section focuses on the specific concerns pertaining to the case companies. By understanding the specific challenges faced by the case companies, organizations can gain valuable knowledge to inform their own decision-making processes and enhance the likelihood of successful APS system implementation.

The fact that an APS system obtains data directly from the ERP system creates demands that the data in the ERP system is correct and up-to-date, and this is as mentioned earlier described in [Oluyisola et al., 2020]. This concern can be simplified by emphasizing that an APS system is dependent on correct data to function in the desired way. This can be seen as a limitation, due to the importance of correct human work with the ERP system is vital for the APS system to function in the desired way. It requires human accuracy and good routines in the work with the input data. The quality of input data could be dependent on what kind of manufacturer that using the APS system. Manufacturers are usually classified as MTS, MTO, ATO, or ETO, the main differences being the location of the COP. The difference and stability in the data quality between the four different manufacturer classifications could be other factors concerning the implementation and use of an APS system. MTS companies usually have large data samples of their usual PPC, meaning there are few unexpected events that could make the APS-generated schedule inaccurate. For ETO companies, the variation in projects is usually very large which usually means there are no previous data, depending on how one-of-a-kind the project is, and therefore harder to simulate accurately. Because of the natural differences between the case companies and their degree of product customization, this concern will apply differently to them. To link this to the case companies, CCA is probably more exposed to this concern, due to their slightly higher complexity score from the questionnaire as seen in Table 4.7. This could mean that it could be more difficult for them to constantly obtain accurate product data.

As mentioned about CCB, they do not fully explore the potential of their APS system. One of the causes of this can be the complexity of APS, which necessitates careful study in order to properly comprehend it and reap its benefits. The time consumption that is needed in the start-up phase with such a system can be addressed as a limitation. An APS system cannot be immediately implemented into a firm and used; the start-up period might be difficult and trying. The majority of the start-up phase entails system integration with all other systems and system training. This could be one of the reasons why CCB yet not have explored their system to the fullest.

The decision to invest in an APS system is not without its financial and temporal implications, as highlighted in subsection 3.2.2. The implementation of such a system requires a substantial financial commitment, and the process itself can be time-consuming. Given these considerations, it becomes imperative for the organization to ensure that the investment yields tangible benefits in the form of enhanced schedule efficiency. Therefore, a thorough evaluation of the potential benefits and cost-effectiveness is essential to justify the investment and maximize the value derived from the APS system. This is the ongoing assessment in CCA.

The following bullet points succinctly outline the key concerns and limitations of APS systems in the context of production scheduling, derived directly from the content within this section. These facets constitute the principal elements to be gleaned from this section:

1. **Data Vulnerability:** The requirement for accurate and up-to-date data within the ERP system is amplified by the integration of an APS system, which directly retrieves information from the ERP system. This concern will vary across companies, owing to inherent disparities in manufacturing strategies and the degree of product customization, thereby impacting the ease of attaining precise data.

2. **Expensiveness:** The introduction of such a system necessitates a significant financial investment, accompanied by a potentially protracted implementation process.

3. **Requires Training:** During the start-up phase, significant efforts should be dedicated to the integration of the APS system with existing systems and the necessary training of personnel.

5.4 Justification of statements

The statements for the questionnaire need to be justified and discussed in order to provide reliability to the SMM. The SMM is based on both the interviews and literature, whereas the interviews were helpful to understand the problems and challenges the real world offers, and the literature helped to create the questionnaire based on previous experiences. The justification and discussion of each statement included in the questionnaire is essential to ensure the validity and reliability of the SMM. By doing so, the resulting data can be trusted and used as a valuable source of information for researchers and practitioners in the field.

5.4.1 Optimization strategy statements justification

The common denominator for the optimization strategy statements is that they are subjective and responder-dependent. This is due to the nature of the optimization strategy dimension. Some of the statements are taking the future into account, not focusing on the business and how operations are performed today. The statements also need to deal with characteristics in manufacturing that are linked to the suitability of an APS system that generates optimized plans.

The terminology *optimization strategy* may be deemed somewhat imprecise when considering this particular dimension. Some of the statements do not directly correlate with the definition. The precise delineation of optimization and optimization strategy is established in section 1.5, and by looking at these statements in relation to the definitions, a discrepancy between the statements and the definition becomes apparent. Nonetheless, a discernible association exists between the assertions pertaining to optimization, compelling to employ this comprehensive term as the overarching descriptor for this dimension of the questionnaire. While the term may not precisely encapsulate all of the statements, it serves as a unifying descriptor that acknowledges the intertwined nature of optimization within the context of the questionnaire.

	Statement	**Justification**
1.	You see the potential benefits of the ability to simulate the production plan before release	The statement is referring to the simulation ability in APS systems [APICS, 2007]. It is relevant to investigate if the business sees the potential of simulation in its production planning, as readiness for change can be identified with the business seeing the real-life potential of a feature that could aid implementation [Kwahk and Lee, 2008].
2.	You think you have unrealized potential regarding the quality of your production schedule	Time-consuming activities related to frequent changes to the schedule, and experiences concerning inaccuracies in the plan are aspects the responder should take into account. Furthermore, lack of recognition of its own challenges and problems are shown in several studies to be a setup to failed implementation [Kwahk and Lee, 2008, Boyer and Sovilla, 2003].
3.	You often experience inaccuracies in the production plan that leads to unwanted free time in the machines	The statement is targeted towards inaccuracies in the production plan, with the hypothesis that a higher degree of optimization can solve this issue. Previous literature state that optimization is a good response to inaccuracies in schedules [Rinciog et al., 2020, Chen et al., 2020]. The responder should ponder if the business often experiences unwanted free time in the machines.

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Table 5.1 – continued from previous page

	Statement	Justification
4.	You often experience inaccuracies in the production plan that leads to overloaded tasks on the machines	The responder should ponder if the machines on the shop floor often are overloaded. The issue of overloaded machines may occur from unsatisfactory production planning, but not necessarily. However, the statement is included, as capacity planning and finite capacity scheduling are capabilities of APS systems [Ivert, 2012, Rinciog et al., 2020, Chen et al., 2020].
5.	You have a clear understanding of what constraints and penalty factors you would want to utilize in the possible simulations	An understanding of which constraints and penalty factors to consider in a manufacturing environment is vital for the optimization of the plan [Mettler et al., 2016, Eid et al., 2021, Sedlaczek and Eberhard, 2006], hence the responder needs to decide on the statement.
6.	Basic data for the production processes in the production exist	An APS system is dependent on data from the production processes. [Oluyisola et al., 2020, Wang et al., 2021c] states that data availability can be assessed as a concern to APS systems, hence this statement is important, to map out if basic data exists in the case of the respondent.
7.	The basic data of your production processes are stable and rarely change	Unstable data for the production processes are not suited for the use of optimization in an APS system [Alfnes and Hvolby, 2019, Ivert and Jonsson, 2014]. The system uses the data to generate optimized plans, and if the data often changes, it needs to be adjusted in the system to function in the desired way.

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Table 5.1 – continued from previous page

	Statement	Justification
8.	Service of machines and errors in machinery are fairly predictable	The statement concerns the reliability of the machines and aims to map if the business is experiencing frequent contingency problems with the manufacturing units. [La Fata and Passannanti, 2017, Bohlin and Wa¨ rja, 2010] are sources mentioning the importance of reliability in manufacturing for APS use.
9.	Guidelines/constraints of how the production planning is done are set at a holistic level among planners	The statement is strategy-oriented, and it is included due to the importance of a common direction and understanding of which constraints to emphasize. However, holistic strategies in optimization literature are a common occurrence [Zhai et al., 2019].
10.	Guidelines of priorities in the scheduling are set at a holistic level among the planners	Similar to the previous statement, however, this one focuses more on a common understanding related to the prioritization of different orders and specifically important parts, which are seen as important to achieving goals [Stanitsas et al., 2021, Yang et al., 2020].

Table 5.1: Optimization strategy statements justification

The ten statements chosen for the suitability measurement model are intended to form the basis of the optimization aspect of the model. Through the responses obtained from the questionnaire, it is anticipated that insights into the suitability of APS with respect to optimization strategy can be gained. It was challenging to develop more precise statements for the model due to the complex nature and definition of optimization. The optimization process involves multiple variables, constraints, and objectives, which makes it difficult to capture in simple statements. That is also why some of the statements are not directly correlating with the term optimization. Nevertheless, the statements included in the model are designed to capture the essential aspects of optimization that are relevant to the specific context of the study. By obtaining data on each of these statements, it is expected that a more nuanced understanding of the suitability with respect to optimization strategy can be gained. While the nature of optimization made it challenging to formulate precise statements, the ten statements chosen for the SMM provide a robust foundation for investigating the suitability of APS systems in relation to optimization strategy.

5.4.2 Complexity statements justification

Similar to the optimization strategy statements, the statements concerning complexity are subjective and responder dependent. However, the complexity statements were easier to formulate, due to the objective to map the current degree of complexity as it is today. The statements should be pretty straightforward for the responder to decide on, prejudiced that the responder has the necessary knowledge regarding the current situation in manufacturing.

	Statement	Justification
1.	Your current product structure is complex, meaning the finished product consists of several parts	A complex product structure is the basic element of the scheduling problem in the job shop, and establishing this is important for the assessment [Destouet et al., 2023]. The product structure is highly relevant in the context of JSSP [Xiong et al., 2022b].
2.	Many of your products are made one-of-a-kind (tailored especially for the customer/project)	APS is dependent on fairly consistent data for the manufacturing processes to generate a precise and accurate schedule [Li et al., 2022, Chansombat et al., 2019]. Hence, one-of-a-kind production and APS are not the most obvious combination. However, the complexity customized products introduce is an element that could utilize APS to the fullest, prejudiced that the basic data is maintained.
3.	A small error/inaccuracy in one of the production steps causes delays or other significant unwanted consequences	Delays in a complex production environment usually have a greater consequence [Wang et al., 2022a, Barni et al., 2020] for other parts and products down the line, and by asking this question the level of complexity in manufacturing is further mapped.

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Table 5.2 – continued from previous page

	Statement	Justification
4.	You spend many human working hours to generate the production schedule due to the need of calculating many variables and important interactions	This question is to further determine the complexity and if the end user will have a satisfying net utility value, and fueled by literature that mentions the value of freeing humans from this time-costing labor [Zhang et al., 2020, Mohan et al., 2019b].
5.	The products you produce have a high variance in processing-time	High variance in processing time for each product indicates a complicated scheduling environment, elevating the make-span time of the product [Caldeira and Gnanavelbabu, 2021, Amaro et al., 2022, Alkhateeb et al., 2022]
6.	Every part needs to pass through several machines in the manufacturing process	In Figure 3.2 the JSSP involves jobs with different processes in different machines [Destouet et al., 2023, Xiong et al., 2022b]. By asking this question, there is an opportunity to form an opinion on whether manufacturing is complex.
7.	You have several activities processing simultaneously at your job shop	More processes ongoing simultaneously insinuates a more complicated scheduling environment, elevating the make-span time [Zhang et al., 2022]. Furthermore, higher requirements are made considering the dynamics at the shop floor [Zhang et al., 2021].
8.	There is a choice in material selection for each part	Products with several material variants could mean a different process, either in time consumption or in e.g. machining, meaning it could complicate the work of scheduling [Min et al., 2019, Cheng et al., 2020].

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Table 5.2 – continued from previous page

	Statement	Justification
9.	Machines used in the shop floor activities need to be manually operated or need programming before each use	Manual setup for machines or manual labor could mean there are some differences in the overall processing times, and manual setup usually takes more time than the latter [Rauch et al., 2020].
10.	Shop floor workers follow schedules slavishly	[Wiers, 2009] states that following the APS-generated schedule slavishly, is vital for a desired outcome. Hence it is important to determine if this is the case in the potential job shop.

Table 5.2: Complexity statements justification

As a summary of the justification in this subsection, the aim of the statements regarding complexity in the responders' job shop is to cover as many aspects of complexity in the job shop as possible. Alike the optimization statements, it is hard to map the whole complexity of a manufacturing process within ten statements, but the statements are intended to provide a picture of the factors that contribute to the challenges faced by the planning department and the shop floor workers.

5.5 SMM

The development of the suitability measurement model was motivated by *RQ3*, the second overall aim, and is discussed in this section. To answer the question, APS suitability increases correlative with complexity and optimization strategy (Figure 3.3). If these two parameters are the ones decisive for the choice of a decision support tool targeted at scheduling, the model should give a good recommendation based on the questionnaire. The formulation of the statements draws upon existing literature as a foundation, ensuring its alignment with established research and knowledge in the field. The inclusion of ten statements for each parameter aims to yield a representative average value that encompasses both the complexity in manufacturing and the optimization strategy objectives under consideration. The reliability of the model depends on the quality of the statements in the questionnaire, and the number of them. The modest quantity of ten statements per dimension should be emphasized when evaluating the adequacy level. However, the number of ten statements per dimension should be sufficient to gain a presentable mean value for the two dimensions.

The talks with CCB indicated that there are more aspects to determine when assessing APS suitability, more than just the complexity and the optimization strategy. CCB's response to the questionnaire further amplifies the foundation of this notion. The SMM and the value guide only take the complexity in manufacturing and the optimization strategy into account, and CCB is a perfect example of where these two parameters are not entirely sufficient for a conclusive recommendation. There are several other aspects that presumably need to be investigated.

CCA's situation on the shop floor is something that highly influenced the decision to include the complexity and optimization strategy in the SMM. CCA's main trouble area regarding their production scheduling was the leveling of the production. The cause of this challenge was the correlation between the product structures and the different machining processes, supported by [Danilovic and Browning, 2007], making the sequencing of the different machining processes vulnerable to changes. Sequencing being one of the main challenges with complex manufacturing environments [Pongcharoen et al., 2004a] further motivated the decision to focus on complexity and optimization strategy.

5.5.1 Validation

The SMM is tested towards the case companies, and this section presents the results of the test, hence a validation of the model. As seen in Table 4.6 and Table 4.7, the mean value for CCA was set to 3 for the optimization strategy, and 5 for the complexity in manufacturing. The answers from CCA produced the following graphic:

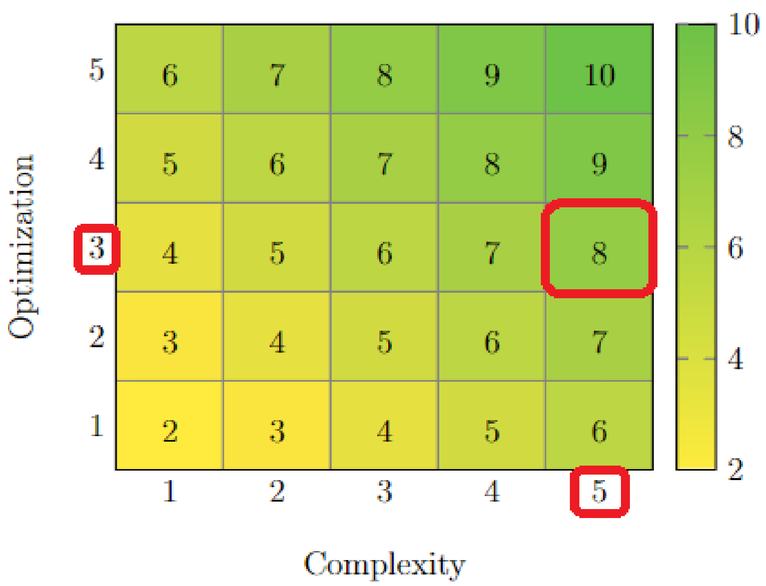

Figure 5.1: CCA's response illustrated in the SMM

CCA, therefore, ends up barely within the third and highest category concerning APS suitability. The third category (with SMM value from 8-10) states: *If other consideration parameters do not contradict with APS use, the implementation should be highly considered.* Solely based on optimization strategy and complexity, the recommendation for CCA is to consider APS implementation highly. The value of 3 for optimization strategy, possibly indicates that an APS system with a lower/medium degree of data depth (section 4.1) could suit their production planning. Whether CCA should invest time, money, and energy into the future use of an APS system, should be an overall assessment including more parameters, but if the two chosen dimensions are vital for the choice, the SMM provides a recommendation.

For CCB, the mean value for the optimization strategy was set to 3, the same as for CCA. The mean value for complexity was set to 4. This is slightly lower than CCA. The answers from CCB produced the following graphic:

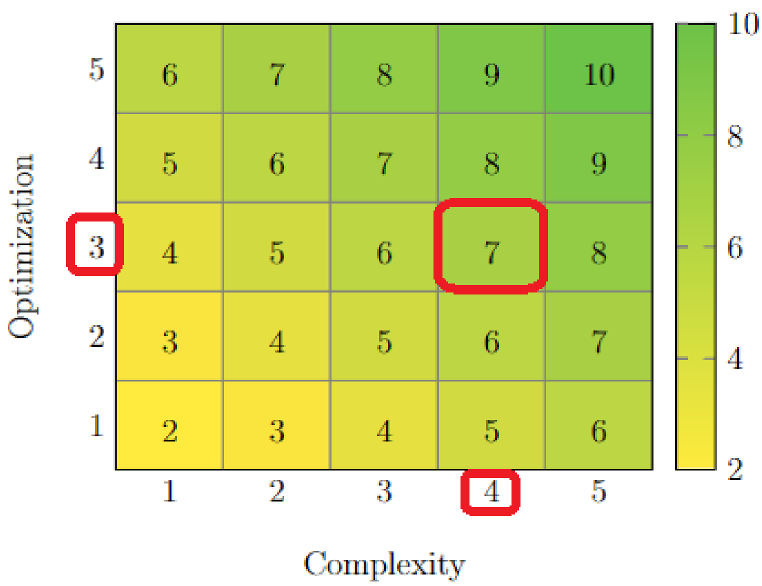

Figure 5.2: CCB's response illustrated in the SMM

In terms of APS suitability, CCB places itself in the middle of the spectrum, stating that APS can be advantageous but that the choice should not be based solely on complexity or desired optimization level. There should be more research done on other factors, like overall strategy. The conversation with CCB, however, made it very evident that they derive significant advantages from their APS system. The SMM's findings are therefore probably of little help to them, but it does demonstrate that businesses can benefit from utilizing an APS system without moving up to the top tier of this model.

In the case of the comparison between CCA and CCB, the responses from the CCA survey indicate that CCA is closer to an ETO manufacturing strategy than CCB. This is most apparent through the complexity statements, where

CCA scores higher than CCB. This suggests that the manufacturing process at CCA exhibits greater complexity and a heightened level of customization in comparison to that of CCB. However, the difference in mean value between the two responses to the complexity statements is not what was expected beforehand. This highlights a weakness in the questionnaire which is unavoidable, subjectivity. On the other hand, it describes how the complexity is perceived by the respondent. As complexity in, for example, the food business could be viewed equally complex if the respondent is not provided a viewpoint of what complexity is, the respondent's perception of complexity may mean that this approach can only be used in industries similar to the two case companies in this thesis.

5.5.2 Discretion

As emphasized, it is important to keep in mind that the SMM considers only two factors, optimization strategy and complexity, when evaluating the suitability of APS. While these factors are undoubtedly important, it is essential to recognize that there are many other considerations that should be taken into account when making decisions about whether or not to implement APS. These considerations may include factors such as the organization's broader strategy, its leadership, budgetary constraints, and so on. Thus, the SMM should not be used in isolation when making decisions about APS implementation, but rather as one of several tools to be used in the decision-making process. That being said, the SMM is still a valuable tool for evaluating the suitability of APS in terms of the present complexity in manufacturing and the optimization strategy. The SMM indicator provides a specific test for determining whether APS is appropriate in these regards, which can be useful in guiding decision-making. By taking a structured approach to evaluating complexity and optimization, the SMM can help organizations to gain a better understanding of the challenges they face and to identify potential solutions to these challenges. Moreover, the SMM can be used to generate data that can inform discussions around APS implementation and provide a basis for making informed decisions. By combining the insights gained from the SMM with other considerations, organizations can develop a more comprehensive understanding of the pros and cons of APS implementation and make decisions that are well-informed and aligned with their strategic objectives.

The validation of the SMM, incorporating the questionnaire responses from the case companies, indicates a relatively comparable outcome achieved among them. It is important to acknowledge that the model employs rounding of decimal numbers, which may introduce a certain degree of imprecision. However, given the limited decision parameters that exert influence on the SMM results, attaining precision at a decimal level is not deemed critical for the model's accuracy. While the rounding of decimal numbers may introduce minor discrepancies, the overall accuracy and reliability of the model are upheld due to the specific nature and narrow scope of the decision parameters that shape its outcomes. It is worth noting that the SMM's primary focus lies in evaluating the companies in general, rather than attaining absolute precision at the decimal level.

In the context of CCB, it is noteworthy that APS has demonstrated its advantageous impact on various aspects of production scheduling, extending beyond the specific parameters considered within the SMM. This serves to underscore the significance of dimensions that are not explicitly mapped in the SMM but could hold critical relevance for potential utility. By acknowledging the broader positive effects of APS for production scheduling within CCB, it becomes evident that the SMM, while effective in capturing certain dimensions, may not fully encompass all the multifaceted aspects and intricacies of suitability.

The SMM is highly influenced by Figure 3.3 extracted from [Ivert, 2009] shown in section 3.4. The importance of basic data is mentioned earlier as vital for an APS system to provide desirable outputs. In subsection 3.2.2 it is stated that data availability and quality is vital for the successful use of an APS system. The assertion that APS is better suited for more complex manufacturing environments may conflict with the importance of basic data. While it is true that basic data is easier to monitor and control in straightforward physical production environments with basic parts and known data, it is important to note that Figure 3.3 is based on APS needs rather than considering solely when APS is suitable for production planning. When both complexity and optimization goals are low, it is also easier to create accurate production plans without investing in an APS system. Hence, APS is considered more beneficial when manufacturing is complex due to the challenges posed by developing accurate schedules manually as the manufacturing process becomes more complex. A key assumption made in the SMM is that basic data for the parts and components are accurate and available.

5.6 Review of methods and bias

This section provides a review of whether the methods were utilized correctly and/or whether the research design was the optimal way of conducting the study. The conducted case studies are mainly executed through interviews, but later on, the questionnaire became a part of the case studies. The interviews were conducted by using an interview guide which was made beforehand by utilizing literature as a basis for the questions. However, not all of the questions were relevant for both case companies since only one of the companies actually had implemented the APS system. Furthermore, the interviews of the case companies were done at the duration of approximately one hour each. The reasoning for a relatively short interview was to make it painless for the interview object to accept. Obtaining participation from pertinent companies posed a notable challenge due to their demanding schedules and limited availability of spare time, necessitating an interview outline that accommodated the constraints of the interview subjects. The restricted time frame imposed constraints on conducting more extensive case studies. It should be acknowledged that the questionnaire, by its nature, incorporates inherent bias, as several statements within it were derived from information gleaned during the interview process. Even though the bias may have an effect on the questionnaire, every statement was backed up by literature, giving it higher reliability. For the SMM, a maturity model was first considered, but because of the definitions of maturity models, only some parts of the execution are similar to the SMM. The figure used to visualize the results of the questionnaire was based on a risk-model-assessment, as it represents the data in a visually simple way. The SMM could be visualized in different ways, and if several dimensions were to be added, it would not be suitable in its current form. Lastly, the literature review was done in a fairly systematic way without resorting to a systematic literature review. The search was done using keyword searches and snowballing of studies read. There were no limitations to what search engine to be used, as it was justified through literature to do so.

The reader may encounter potential confusion due to the usage of specific terminologies, namely PPC, production scheduling, and job shop scheduling, as these terms share inherent similarities and encompass overlapping concepts within the domain of operational scheduling. It is important to justify the somewhat confusing use of these terms based on their common objective, which involves organizing and coordinating activities associated with the production of goods. Despite their distinct labels, these terms are fundamentally rooted in similar principles and encounter comparable challenges in the context of scheduling and planning. Thus, the usage is warranted, acknowledging the underlying similarities and the shared goal of effectively scheduling and planning manufacturing operations.

5.7 Contribution to the field of research

The study serves as a valuable resource for decision-makers, researchers, and practitioners alike, shedding light on the potential of APS systems and guiding their successful implementation in the realm of production scheduling. The contribution to the field of research is divided into contribution to practice and contribution to theory. Contribution to practice refers to the impact and relevance of research findings on real-world applications and practical implications. When a paper contributes to practice, it means that it provides insights, recommendations, or solutions that can be directly applied or implemented in a particular domain or industry. Contribution to theory refers to the advancement of theoretical knowledge and understanding within a particular academic discipline. When a paper contributes to theory, it means that it generates new insights, concepts, models, frameworks, or theories that deepen the understanding of a subject or explain phenomena in a more comprehensive or accurate manner.

5.7.1 Contribution to practice

The study's findings hold significant implications for decision-makers who are considering investing in APS systems for production scheduling purposes. Through the use of case studies, the study provides valuable insights into how businesses within the sector carry out operations related to manufacturing scheduling. As the trajectory towards Industry 4.0 and the widespread adoption of automation intensifies, this thesis holds particular relevance for businesses aiming to explore the vast potential afforded by APS systems. The study's contributions shed light on the practical applications, benefits, and considerations associated with implementing APS in the context of production scheduling.

It can be contended that the SMM offers practical value by offering decision-makers real-world recommendations. However, its primary significance lies in its contribution to theory as a conceptual framework that addresses a gap in the existing literature regarding specific measurement parameters for APS suitability.

5.7.2 Contribution to theory

One of the principal contributions of this study lies in the formulation of a suitability measurement model that addresses a notable gap in the existing literature pertaining to the evaluation of metrics for assessing the suitability of APS systems. By developing a quantitative model, the study fills a void in the current body of knowledge, providing decision-makers with a valuable tool to systematically evaluate the suitability of APS systems in relation to two chosen dimensions. By using the SMM as a decision support instrument, decision-makers can make informed decisions about the deployment of APS in conjunction with optimization strategy and complexity in manufacturing. While there has been some research conducted on the individual dimensions of optimization strategy and complexity in manufacturing in relation to APS implementation, the combination of the two is not well-explored in the literature. Therefore, the development of the SMM could serve as a catalyst for future investigation into other assessment parameters that are relevant to APS implementation. This could lead to a deeper understanding of the factors that impact the success of APS implementation, which could ultimately result in more effective deployment of APS in manufacturing environments.

Furthermore, the study's findings not only enhance the understanding of APS systems' impact on production scheduling but also contribute to the broader discourse on I4.0. The research outcomes provide a new framework for future investigations and advancements in the field, fostering ongoing exploration and refinement of APS systems to meet the evolving needs and challenges faced by businesses in the dynamic manufacturing landscape.

CHAPTER

SIX

CONCLUSIONS

The chapter provides a summary of the research findings, draws conclusions from the results, and offers recommendations for future research and practice. The purpose of this chapter is to revisit the research questions, review the research objectives, and evaluate the extent to which the research has achieved its goals. Lastly, the chapter concludes with recommendations for future research and practice, based on the insights gained from the study. Overall, this chapter offers a comprehensive overview of the research, synthesizes the main findings, and provides a roadmap for further research and practical applications.

The research questions introduced in this thesis were aimed at what applications and limitations APS systems have related to production scheduling, and how the complexity in manufacturing and optimization strategy inform about the fit of APS use. Related to *RQ1*, the study examined the functionalities of APS systems, which were described in detail in the theory chapter. This endeavor was deemed significant in order to address the first overall aim of the study. The beneficial applications were categorized as decision support and planning efficiency benefits. The findings indicated that APS can provide decision support to planners by utilizing simulations to generate plans that are based on constraints that the planner can manipulate. The system can also simulate "what-if" scenarios to help identify unexpected events. The generated plans are usually presented visually, which can aid in the decision-making process. APS can also contain the possibility to create optimized plans given chosen constraints and priorities. In terms of planning efficiency, APS can automate the generation of plans, with or without optimization, depending on the type of optimization offered by the system and the optimization strategy of the business. The system can prioritize and sequence orders based on constraints, priorities, and capacity, leading to simplified and time-efficient planning activities. The last planning efficiency benefit addressed the ability to estimate the workload. Extracted from these benefits and the performed case studies, the main benefits encompassed increased testing freedom, increased adaptability, enhanced visibility, the possibility for optimized production, and increased efficiency. To achieve these benefits, data quality, and up-to-date information are critical factors, as the accuracy of the data used by the system directly affects the accuracy of the generated plan. The study also identified the implementation phase of APS as a significant prerequisite for success. Overall, the findings suggest that APS has the potential to offer significant benefits to production scheduling environments, particularly in terms of decision support and planning efficiency, provided that data quality and system implementation are appropriately addressed.

Related to *RQ2*, the literature review and the case studies were combined to determine the limitations of APS systems. This also held substantial significance in addressing the first overall aim of the study. The concerns and limitations were addressed by ascertaining the presence of shared concerns among peer-reviewed studies and the case companies. Decision complicatedness, data accuracy and availability, level of aggregation, uncertainty and variations, expensiveness, and the fact that it is time-consuming, were considered the biggest limitations obtained from the literature. Utilizing the knowledge gained from the case studies the main concerns and limitations were synthesized to data vulnerability, expensiveness, and the requirement for training.

RQ3 and the second overall aim add up to the development of the suitability measurement model that was created in the thesis. Through the investigation, it was determined that manufacturing environments with high levels of complexity and optimization strategy would be more appropriate for APS systems. The suitability measurement model was created to offer a quantitative result to a subject that is challenging to generalize and define with precision. The model shouldn't be relied upon exclusively when drawing conclusions; rather, it should provide a decision-maker with some guidelines with regard to some specific assessment parameters. It is not attempting to imply that the complexity in manufacturing and optimization strategy are the only or most crucial factors to consider when determining whether APS is appropriate; rather, it is attempting to provide a conceptual framework around two understudied aspects related to APS adoption.

Previous work related to production scheduling and APS systems shows that the overall strategy of a manufacturing company should lay the foundation of the decisions made. This was not a new discovery in terms of previous literature, but it can not be emphasized enough. The cost needs to be linked up to the potential benefits for each company, and each scenario. The size and ambition of the company will have a big impact on the ideal approach, as well as the type of products. The industry is, however, moving toward smarter solutions, which fits nicely with the investigation of APS systems.

CCA is recommended to invest in an APS system as an add-on to their ERP system. This recommendation is based on several factors, including their current challenges, the functionalities offered by APS, and most importantly, the experiences of CCB in utilizing APS for dynamic scheduling. APS could possibly solve their issue of low flexibility in the production plan and simulation could help them with the issue concerning leveling. Given the higher complexity score in the SMM for CCA, it is important to consider an APS system that is specifically designed to handle complex manufacturing. The system must be flexible enough to accommodate the customization and variability of the manufacturing process, and real-time data would be vital. As for CCB, they should further explore the APS system. Although further exploration of the APS system may entail time and training investment, it holds the potential for uncovering valuable applications that can enhance scheduling practices. CCB stands to benefit from identifying their constraints and priorities, enabling the possibility for optimized production. The utilization of optimized production could contribute to improved scheduling and increased efficiency in CCB's manufacturing processes.

In conclusion, the adoption of APS systems, in lieu of conventional planning procedures, holds the potential to yield substantial advantages in terms of streamlining operations and fostering knowledge acquisition within the industry. While the initial stages of APS implementation may pose challenges, diligent and proficient utilization can lead to long-term benefits. Notably, the prospect of dynamic scheduling stands out as a particularly favorable aspect of APS systems, offering the opportunity for real-time adjustments. It is worth highlighting that APS can offer advantages even when not fully leveraging its entire range of capabilities, as exemplified by CCB. Through their experience, it was observed that successful utilization of an APS system can be achieved without exhaustively employing all its features. Moreover, the adaptability and customization potential of APS should be underscored, as it enables users to employ the system to the desired extent, catering to their specific needs and preferences.

6.1 Further work

Due to the huge importance of overall strategy, a study concerning different strategies can be carried out to generalize which exact strategies could fit the different levels of decision support systems. For instance, different strategies can be divided into different groups to further make it possible to study each group and come to appropriate solutions regarding the importance of decision support systems related to production scheduling for each group. This would require a comprehensive case study of companies with different strategies and approaches to the area of research.

Further development of a more complex suitability measurement model can contribute to a more embracing foundation of suitability. Developing a model that takes more parameters into account will give a broader and more precise result for general suitability. The questionnaire would hence be longer and more comprehensive and could be divided into more categories that are more specific towards the respective dimensions. By pursuing something like that, parameters like overall strategy, economic aims, resources, and type of business are some of the most nearby ideas to take into account. Putting emphasis on which parameters are considered most important would be important in a model like that, so each parameter would need a value of importance for the result. Aspects of APS that could be relevant are the overall strategy between MTS, MTO, ATO, and ETO, the financial aspect, and a more thorough assessment of what is considered a good net utility value.

REFERENCES

[Albukhitan, 2020] Albukhitan, S. (2020). Developing digital transformation strategy for manufacturing. *Procedia computer science*, 170:664–671.

[Alfnes and Hvolby, 2019] Alfnes, E. and Hvolby, H.-H. (2019). Aps feasibility in an engineer to order environment. In *Advances in Production Management Systems. Production Management for the Factory of the Future: IFIP WG 5.7 International Conference, APMS 2019, Austin, TX, USA, September 1–5, 2019, Proceedings, Part I*, pages 604–611. Springer.

[Alkhateeb et al., 2022] Alkhateeb, F., Abed-alguni, B. H., and Al-rousan, M. H. (2022). Discrete hybrid cuckoo search and simulated annealing algorithm for solving the job shop scheduling problem. *The Journal of Supercomputing*, pages 1–28.

[Allaoui et al., 2019] Allaoui, H., Guo, Y., and Sarkis, J. (2019). Decision support for collaboration planning in sustainable supply chains. *Journal of Cleaner Production*, 229:761–774.

[Almeder et al., 2009] Almeder, C., Preusser, M., and Hartl, R. F. (2009). Simulation and optimization of supply chains: alternative or complementary approaches? *OR spectrum*, 31:95–119.

[Altendorfer and Minner, 2011] Altendorfer, K. and Minner, S. (2011). Simultaneous optimization of capacity and planned lead time in a two-stage production system with different customer due dates. *European Journal of Operational Research*, 213(1):134–146.

[Amaro et al., 2022] Amaro, D., Rosenkranz, M., Fitzpatrick, N., Hirano, K., and Fiorentini, M. (2022). A case study of variational quantum algorithms for a job shop scheduling problem. *EPJ Quantum Technology*, 9(1):5.

[APICS, 2007] APICS (2007). Using information technology to enable supply chain management. *APICS Certified Supply Chain Professional Learning System.*

[Bai et al., 2020] Bai, C., Dallasega, P., Orzes, G., and Sarkis, J. (2020). Industry 4.0 technologies assessment: A sustainability perspective. *International journal of production economics*, 229:107776.

[Barni et al., 2020] Barni, A., Pietraroia, D., Züst, S., West, S., and Stoll, O. (2020). Digital twin based optimization of a manufacturing execution system to handle high degrees of customer specifications. *Journal of Manufacturing and Materials Processing*, 4(4):109.

[Berchet and Habchi, 2005] Berchet, C. and Habchi, G. (2005). The implementation and deployment of an erp system: An industrial case study. *Computers in industry*, 56(6):588–605.

[Bhalla et al., 2022] Bhalla, S., Alfnes, E., Hvolby, H.-H., and Oluyisola, O. (2022). Sales and operations planning for delivery date setting in engineer-to-order manufacturing: a research synthesis and framework. *International Journal of Production Research*, pages 1–31.

[Bititci et al., 2015] Bititci, U. S., Garengo, P., Ates, A., and Nudurupati, S. S. (2015). Value of maturity models in performance measurement. *International journal of production research*, 53(10):3062–3085.

[Björkdahl, 2020] Björkdahl, J. (2020). Strategies for digitalization in manufacturing firms. *California Management Review*, 62(4):17–36.

[Bohlin and Wa¨ rja, 2010] Bohlin, M. and Wa¨ rja, M. (2010). Optimizing maintenance for multi-unit industrial gas turbine installations. In *Turbo Expo: Power for Land, Sea, and Air*, volume 44007, pages 755–764.

[Boyer and Sovilla, 2003] Boyer, M. and Sovilla, L. (2003). How to identify and remove the barriers for a successful lean implementation. *Journal of ship production*, 19(02):116–120.

[Bueno et al., 2020] Bueno, A., Godinho Filho, M., and Frank, A. G. (2020). Smart production planning and control in the industry 4.0 context: A systematic literature review. *Computers & Industrial Engineering*, 149:106774.

[Caldeira and Gnanavelbabu, 2021] Caldeira, R. H. and Gnanavelbabu, A. (2021). A simheuristic approach for the flexible job shop scheduling problem with stochastic processing times. *Simulation*, 97(3):215–236.

[Caraffa et al., 2001] Caraffa, V., Ianes, S., Bagchi, T. P., and Sriskandarajah, C. (2001). Minimizing makespan in a blocking flowshop using genetic algorithms. *International Journal of Production Economics*, 70(2):101–115.

[Castelo-Branco et al., 2019] Castelo-Branco, I., Cruz-Jesus, F., and Oliveira, T. (2019). Assessing industry 4.0 readiness in manufacturing: Evidence for the european union. *Computers in Industry*, 107:22–32.

[Chansombat et al., 2019] Chansombat, S., Musikapun, P., Pongcharoen, P., and Hicks, C. (2019). A hybrid discrete bat algorithm with krill herd-based advanced planning and scheduling tool for the capital goods industry. *International Journal of Production Research*, 57(21):6705–6726.

[Chaudhry and Khan, 2016] Chaudhry, I. A. and Khan, A. A. (2016). A research survey: review of flexible job shop scheduling techniques. *International Transactions in Operational Research*, 23(3):551–591.

[Chen et al., 2013] Chen, J. C., Huang, P. B., Wu, J.-G., Lai, K. Y., Chen, C.-C., and Peng, T.-W. (2013). Advanced planning and scheduling for tft-lcd color filter fab with multiple lines. *The International Journal of Advanced Manufacturing Technology*, 67:101–110.

[Chen et al., 2011] Chen, K., Ji, P., and Wang, Q. (2011). A case study for advanced planning and scheduling(aps). *Journal of Systems Science and Systems Engineering*, 20(4):460–474.

[Chen et al., 2020] Chen, X., An, Y., Zhang, Z., and Li, Y. (2020). An approximate nondominated sorting genetic algorithm to integrate optimization of production scheduling and accurate maintenance based on reliability intervals. *Journal of Manufacturing Systems*, 54:227–241.

[Cheng et al., 2020] Cheng, J., Zhang, H., Tao, F., and Juang, C.-F. (2020). Dt-ii: Digital twin enhanced industrial internet reference framework towards smart manufacturing. *Robotics and Computer-Integrated Manufacturing*, 62:101881.

[Dang and Barnes, 2012] Dang, Q. and Barnes, M. (2012). Metrics for evaluating planning efficiency in make-to-order manufacturing. *International Journal of Production Research*, 50(15):4229–4246.

[Danilovic and Browning, 2007] Danilovic, M. and Browning, T. R. (2007). Managing complex product development projects with design structure matrices and domain mapping matrices. *International Journal of Project Management*, 25(3):300–314.

[David et al., 2006] David, F., Pierreval, H., and Caux, C. (2006). Advanced planning and scheduling systems in aluminium conversion industry. *International Journal of Computer Integrated Manufacturing*, 19(7):705–715.

[de Paula Ferreira et al., 2020] de Paula Ferreira, W., Armellini, F., and De Santa-Eulalia, L. A. (2020). Simulation in industry 4.0: A state-of-the-art review. *Computers & Industrial Engineering*, 149:106868.

[Dellaert et al., 2000] Dellaert, N., Jeunet, J., and Jonard, N. (2000). A genetic algorithm to solve the general multi-level lot-sizing problem with time-varying costs. *International Journal of Production Economics*, 68(3):241–257.

[Destouet et al., 2023] Destouet, C., Tlahig, H., Bettayeb, B., and Mazari, B. (2023). Flexible job shop scheduling problem under industry 5.0: A survey on human reintegration, environmental consideration and resilience improvement. *Journal of Manufacturing Systems*, 67:155–173.

[Dolgui et al., 2019] Dolgui, A., Ivanov, D., Sethi, S. P., and Sokolov, B. (2019). Scheduling in production, supply chain and industry 4.0 systems by optimal control: fundamentals, state-of-the-art and applications. *International Journal of Production Research*, 57(2):411–432.

[Eid et al., 2021] Eid, M. S., Elbeltagi, E. E., and El-Adaway, I. H. (2021). Simultaneous multi-criteria optimization for scheduling linear infrastructure projects. *International Journal of Construction Management*, 21(1):41–55.

[Estlin and Mooney, 1997] Estlin, T. A. and Mooney, R. J. (1997). Learning to improve both efficiency and quality of planning. In *IJCAI*, pages 1227–1233.

[Farizal et al., 2021] Farizal, F., Gabriel, D., Rachman, A., and Rinaldi, I. (2021). Production scheduling optimization to minimize makespan and the number of machines with mixed integer linear programming. In *IOP Conference Series: Materials Science and Engineering*, page 012046. IOP Publishing.

[Fink, 2019] Fink, A. (2019). *Conducting research literature reviews: From the internet to paper*. Sage publications.

[Gao et al., 2020] Gao, D., Wang, G.-G., and Pedrycz, W. (2020). Solving fuzzy job-shop scheduling problem using de algorithm improved by a selection mechanism. *IEEE Transactions on Fuzzy Systems*, 28(12):3265–3275.

[Ghaleb et al., 2020] Ghaleb, M., Zolfagharinia, H., and Taghipour, S. (2020). Real-time production scheduling in the industry-4.0 context: Addressing uncertainties in job arrivals and machine breakdowns. *Computers & Operations Research*, 123:105031.

[Ghiyasinasab et al., 2021] Ghiyasinasab, M., Lehoux, N., Ménard, S., and Cloutier, C. (2021). Production planning and project scheduling for engineer-to-order systems-case study for engineered wood production. *International Journal of Production Research*, 59(4):1068–1087.

[Ghobakhloo, 2020] Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of cleaner production*, 252:119869.

[Gyenge et al., 2021] Gyenge, B., Kasza, L., and Vasa, L. (2021). Introducing the epp house (topological space) method to solve mrp problems. *Plos one*, 16(6):e0253330.

[Haddaway et al., 2020] Haddaway, N. R., Bethel, A., Dicks, L. V., Koricheva, J., Macura, B., Petrokofsky, G., Pullin, A. S., Savilaakso, S., and Stewart, G. B. (2020). Eight problems with literature reviews and how to fix them. *Nature Ecology & Evolution*, 4(12):1582–1589.

[Harjunkoski et al., 2014] Harjunkoski, I., Maravelias, C. T., Bongers, P., Castro, P. M., Engell, S., Grossmann, I. E., Hooker, J., Méndez, C., Sand, G., and Wassick, J. (2014). Scope for industrial applications of production scheduling models and solution methods. *Computers & Chemical Engineering*, 62:161–193.

[Hvolby and Steger-Jensen, 2010] Hvolby, H.-H. and Steger-Jensen, K. (2010). Technical and industrial issues of advanced planning and scheduling (aps) systems. *Computers in Industry*, 61(9):845–851.

[Ivanov et al., 2016] Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., and Ivanova, M. (2016). A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0. *International Journal of Production Research*, 54(2):386–402.

[Ivert, 2009] Ivert, L. K. (2009). *Advanced planning and scheduling systems in manufacturing planning processes*. Chalmers University of Technology.

[Ivert, 2012] Ivert, L. K. (2012). *Use of Advanced Planning and Scheduling (APS) systems to support manufacturing planning and control processes*. Chalmers Tekniska Hogskola (Sweden).

[Ivert and Jonsson, 2014] Ivert, L. K. and Jonsson, P. (2014). When should advanced planning and scheduling systems be used in sales and operations planning? *International Journal of Operations & Production Management*.

[Jacobs et al., 2014] Jacobs, F. R., Chase, R. B., and Lummus, R. R. (2014). *Operations and supply chain management*. McGraw-Hill/Irwin New York, NY.

[Jeon and Kim, 2016] Jeon, S. M. and Kim, G. (2016). A survey of simulation modeling techniques in production planning and control (ppc). *Production Planning & Control*, 27(5):360–377.

[Jiang et al., 2019] Jiang, C., Hu, X., and Xi, J. (2019). Integrated multi-project scheduling and hierarchical workforce allocation in the eto assembly process. *Applied Sciences*, 9(5):885.

[Jodlbauer and Strasser, 2019] Jodlbauer, H. and Strasser, S. (2019). Capacity-driven production planning. *Computers in Industry*, 113:103126.

[Jonsson et al., 2007] Jonsson, P., Kjellsdotter, L., and Rudberg, M. (2007). Applying advanced planning systems for supply chain planning: three case studies. *International Journal of Physical Distribution & Logistics Management*, 37(10):816–834.

[Jünge et al., 2019] Jünge, G. H., Alfnes, E., Kjersem, K., and Andersen, B. (2019). Lean project planning and control: empirical investigation of eto projects. *International Journal of Managing Projects in Business*.

[Kallio et al., 2016] Kallio, H., Pietilä, A.-M., Johnson, M., and Kangasniemi, M. (2016). Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of advanced nursing*, 72(12):2954–2965.

[Kapulin and Russkikh, 2020] Kapulin, D. V. and Russkikh, P. A. (2020). Analysis and improvement of production planning within small-batch make-to-order production. *Journal of Physics: Conference Series*, 1515(2):022072.

[Kemen and Musa, 2020] Kemen, B. and Musa, S. M. (2020). Planning and scheduling of a corrugated cardboard manufacturing process in iot. *Planning*, 5(1).

[Kjellsdotter Ivert and Jonsson, 2010] Kjellsdotter Ivert, L. and Jonsson, P. (2010). The potential benefits of advanced planning and scheduling systems in sales and operations planning. *Industrial Management Data Systems*, 110(5):659–681.

[Köchel and Nieländer, 2005] Köchel, P. and Nieländer, U. (2005). Simulation-based optimisation of multi-echelon inventory systems. *International journal of production economics*, 93:505–513.

[Kraus et al., 2021] Kraus, S., Jones, P., Kailer, N., Weinmann, A., Chaparro-Banegas, N., and Roig-Tierno, N. (2021). Digital transformation: An overview of the current state of the art of research. *Sage Open*, 11(3):21582440211047576.

[Kunath and Winkler, 2019] Kunath, M. and Winkler, H. (2019). Usability of information systems to support decision making in the order management process. *Procedia Cirp*, 81:322–327.

[Kwahk and Lee, 2008] Kwahk, K.-Y. and Lee, J.-N. (2008). The role of readiness for change in erp implementation: Theoretical bases and empirical validation. *Information & management*, 45(7):474–481.

[La Fata and Passannanti, 2017] La Fata, C. M. and Passannanti, G. (2017). A simulated annealing-based approach for the joint optimization of production/inventory and preventive maintenance policies. *The International Journal of Advanced Manufacturing Technology*, 91:3899–3909.

[Lee and Shin, 2015] Lee, J.-y. and Shin, M. (2015). A case study on application of dispatching rule-based advanced planning and scheduling (aps) system. *Journal of the Society of Korea Industrial and Systems Engineering*, 38(3):78–86.

[Lee et al., 2022] Lee, W., Chua, T., Katru, R., and Cai, T. (2022). Implementing distribution requirement planning and scheduling system for lens manufacturing company. In *2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pages 0701–0705. IEEE.

[Lee et al., 2002] Lee, Y. H., Jeong, C. S., and Moon, C. (2002). Advanced planning and scheduling with outsourcing in manufacturing supply chain. *Computers & Industrial Engineering*, 43(1-2):351–374.

[Leu and Liu, 2022] Leu, J.-D. and Liu, F.-P. (2022). Capacity planning of the semiconductors manufacturing supply chain: A decision method and application. In *2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pages 832–836.

[Li et al., 2009] Li, J., Gonzalez, M., and Zhu, Y. (2009). A hybrid simulation optimization method for production planning of dedicated remanufacturing. *International Journal of Production Economics*, 117(2):286–301.

[Li et al., 2022] Li, M., Zhong, R. Y., Qu, T., and Huang, G. Q. (2022). Spatial–temporal out-of-order execution for advanced planning and scheduling in cyber-physical factories. *Journal of Intelligent Manufacturing*, pages 1–18.

[Liu et al., 2020] Liu, C.-L., Chang, C.-C., and Tseng, C.-J. (2020). Actor-critic deep reinforcement learning for solving job shop scheduling problems. *Ieee Access*, 8:71752–71762.

[Liu et al., 2022a] Liu, J., Liang, R., and Xian, J. (2022a). An ai planning approach to factory production planning and scheduling. In *2022 International Conference on Machine Learning and Knowledge Engineering (MLKE)*, pages 110–114. IEEE.

[Liu et al., 2022b] Liu, J., Wen, X., Zhou, H., Sheng, S., Zhao, P., Liu, X., Kang, C., and Chen, Y. (2022b). Digital twin-enabled machining process modeling. *Advanced Engineering Informatics*, 54:101737.

[Liu et al., 2019] Liu, J.-L., Wang, L.-C., and Chu, P.-C. (2019). Development of a cloud-based advanced planning and scheduling system for automotive parts manufacturing industry. *Procedia Manufacturing*, 38:1532–1539.

[Lü et al., 2021] Lü, Z.-m., Jiang, T.-r., and Li, Z.-w. (2021). Multiproduct and multistage integrated production planning model and algorithm based on an available production capacity network. *International Journal of Minerals, Metallurgy and Materials*, 28:1343–1352.

[Lupeikiene et al., 2014] Lupeikiene, A., Dzemyda, G., Kiss, F., and Caplinskas, A. (2014). Advanced planning and scheduling systems: Modeling and implementation challenges. *Informatica*, 25(4):581–616.

[Man et al., 2020] Man, J. C. D., Strandhagen, J. W., Buer, S.-V., and Strandhagen, J. O. (2020). Planning and control frameworks of the future. *International Journal of Mechatronics and Manufacturing Systems*, 13(3):199–209.

[Masood and Sonntag, 2020] Masood, T. and Sonntag, P. (2020). Industry 4.0: Adoption challenges and benefits for smes. *Computers in Industry*, 121:103261.

[Mattfeld, 2013] Mattfeld, D. C. (2013). *Evolutionary search and the job shop: investigations on genetic algorithms for production scheduling*. Springer Science & Business Media.

[Mattsson, 2004] Mattsson, S.-A. (2004). *Logistikens termer och begrepp*. PLAN-Föreningen för produktionslogistik.

[Mettler et al., 2016] Mettler, E., Massey, C. M., and Kellman, P. J. (2016). A comparison of adaptive and fixed schedules of practice. *Journal of Experimental Psychology: General*, 145(7):897.

[Micale et al., 2021] Micale, R., La Fata, C. M., Enea, M., and La Scalia, G. (2021). Regenerative scheduling problem in engineer to order manufacturing: an economic assessment. *Journal of Intelligent Manufacturing*, 32:1913–1925.

[Min et al., 2019] Min, Q., Lu, Y., Liu, Z., Su, C., and Wang, B. (2019). Machine learning based digital twin framework for production optimization in petrochemical industry. *International Journal of Information Management*, 49:502–519.

[Missbauer and Uzsoy, 2022] Missbauer, H. and Uzsoy, R. (2022). Order release in production planning and control systems: challenges and opportunities. *International Journal of Production Research*, 60(1):256–276.

[Moghaddam and Saitou, 2019] Moghaddam, S. K. and Saitou, K. (2019). On optimal dynamic pegging in rescheduling for new order arrival. *Computers & Industrial Engineering*, 136:46–56.

[Mohan et al., 2019a] Mohan, J., Lanka, K., and Rao, A. N. (2019a). A review of dynamic job shop scheduling techniques. *Procedia Manufacturing*, 30:34–39. Digital Manufacturing Transforming Industry Towards Sustainable Growth.

[Mohan et al., 2019b] Mohan, J., Lanka, K., and Rao, A. N. (2019b). A review of dynamic job shop scheduling techniques. *Procedia Manufacturing*, 30:34–39.

[Moon et al., 2004] Moon, C., Kim, J. S., and Gen, M. (2004). Advanced planning and scheduling based on precedence and resource constraints for e-plant chains. *International journal of production research*, 42(15):2941–2955.

[Moon and Phatak, 2005] Moon, Y. B. and Phatak, D. (2005). Enhancing erp system's functionality with discrete event simulation. *Industrial management & data systems*.

[Mourão et al., 2020] Mourão, E., Pimentel, J. F., Murta, L., Kalinowski, M., Mendes, E., and Wohlin, C. (2020). On the performance of hybrid search strategies for systematic literature reviews in software engineering. *Information and software technology*, 123:106294.

[Mousavi et al., 2022] Mousavi, B., Heavey, C., Millauer, C., Azzouz, R., and Ehm, H. (2022). Data-driven simulation analysis of nervousness in advanced planning systems: A semiconductor supply chain case study. *Available at SSRN 4182406*, page 30.

[Mousavi et al., 2019] Mousavi, B. A., Azzouz, R., Heavey, C., and Ehm, H. (2019). Simulation-based analysis of the nervousness within semiconductors supply chain planning: insight from a case study. In *2019 Winter Simulation Conference (WSC)*, pages 2396–2407. IEEE.

[Musselman et al., 2002] Musselman, K., O'Reilly, J., and Duket, S. (2002). The role of simulation in advanced planning and scheduling. In *Proceedings of the Winter Simulation Conference*, volume 2, pages 1825–1830 vol.2.

[Nadj et al., 2020] Nadj, M., Maedche, A., and Schieder, C. (2020). The effect of interactive analytical dashboard features on situation awareness and task performance. *Decision support systems*, 135:113322.

[Nam et al., 2018] Nam, S., Shen, H., Ryu, C., and Shin, J. G. (2018). Scp-matrix based shipyard aps design: Application to long-term production plan. *International Journal of Naval Architecture and Ocean Engineering*, 10(6):741–761.

[Neumann et al., 2022] Neumann, A., Hajji, A., Rekik, M., and Pellerin, R. (2022). A two-level optimization approach for engineer-to-order project scheduling. *IFAC-PapersOnLine*, 55(10):2587–2592.

[Nouinou et al., 2023] Nouinou, H., Asadollahi-Yazdi, E., Baret, I., Nguyen, N. Q., Terzi, M., Ouazene, Y., Yalaoui, F., and Kelly, R. (2023). Decision-making in the context of industry 4.0: Evidence from the textile and clothing industry. *Journal of Cleaner Production*, page 136184.

[Oluyisola et al., 2022] Oluyisola, O. E., Bhalla, S., Sgarbossa, F., and Strandhagen, J. O. (2022). Designing and developing smart production planning and control systems in the industry 4.0 era: a methodology and case study. *Journal of Intelligent Manufacturing*, 33(1):311–332.

[Oluyisola et al., 2020] Oluyisola, O. E., Sgarbossa, F., and Strandhagen, J. O. (2020). Smart production planning and control: Concept, use-cases and sustainability implications. *Sustainability*, 12(9):3791.

[Ouelhadj and Petrovic, 2009] Ouelhadj, D. and Petrovic, S. (2009). A survey of dynamic scheduling in manufacturing systems. *Journal of scheduling*, 12:417–431.

[Parente et al., 2020] Parente, M., Figueira, G., Amorim, P., and Marques, A. (2020). Production scheduling in the context of industry 4.0: review and trends. *International Journal of Production Research*, 58(17):5401–5431.

[Park et al., 2021] Park, K. T., Son, Y. H., Ko, S. W., and Noh, S. D. (2021). Digital twin and reinforcement learning-based resilient production control for micro smart factory. *Applied Sciences*, 11(7):2977.

[Piengang et al., 2019] Piengang, F. C. N., Beauregard, Y., and Kenné, J.-P. (2019). An aps software selection methodology integrating experts and decisions-maker's opinions on selection criteria: A case study. *Cogent Engineering*, 6(1):1594509.

[Pongcharoen et al., 2004a] Pongcharoen, P., Hicks, C., and Braiden, P. (2004a). The development of genetic algorithms for the finite capacity scheduling of complex products, with multiple levels of product structure. *European Journal of Operational Research*, 152(1):215–225.

[Pongcharoen et al., 2004b] Pongcharoen, P., Hicks, C., and Braiden, P. (2004b). The development of genetic algorithms for the finite capacity scheduling of complex products, with multiple levels of product structure. *European Journal of Operational Research*, 152(1):215–225.

[Rashid et al., 2019] Rashid, Y., Rashid, A., Warraich, M. A., Sabir, S. S., and Waseem, A. (2019). Case study method: A step-by-step guide for business researchers. *International journal of qualitative methods*, 18:1609406919862424.

[Rauch et al., 2020] Rauch, E., Linder, C., and Dallasega, P. (2020). Anthropocentric perspective of production before and within industry 4.0. *Computers & Industrial Engineering*, 139:105644.

[Rinciog et al., 2020] Rinciog, A., Mieth, C., Scheikl, P. M., and Meyer, A. (2020). Sheet-metal production scheduling using alphago zero. In *Proceedings of the Conference on Production Systems and Logistics: CPSL 2020*. Hannover: publish-Ing.

[Romero-Silva et al., 2015] Romero-Silva, R., Santos, J., and Hurtado, M. (2015). A framework for studying practical production scheduling. *Production Planning & Control*, 26(6):438–450.

[Ruivo et al., 2020] Ruivo, P., Johansson, B., Sarker, S., and Oliveira, T. (2020). The relationship between erp capabilities, use, and value. *Computers in Industry*, 117:103209.

[Sagegg and Alfnes, 2020] Sagegg, O. J. and Alfnes, E. (2020). Erp systems for manufacturing supply chains : applications, configuration, and performance.

[Salur and Kattar, 2021] Salur, M. N. and Kattar, W. K. (2021). The impact of enterprise resource planning (erp) on the audit in the context of emerging technologies. *Ekonomi Maliye İşletme Dergisi*, 4(2):115–123.

[Sanders and Premus, 2005] Sanders, N. R. and Premus, R. (2005). Decision support in advanced planning and scheduling systems. *European Journal of Operational Research*, 164(2):311–321.

[Schumacher et al., 2016] Schumacher, A., Erol, S., and Sihn, W. (2016). A maturity model for assessing industry 4.0 readiness and maturity of manufacturing enterprises. *Procedia CIRP*, 52:161–166. The Sixth International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV2016).

[Sedlaczek and Eberhard, 2006] Sedlaczek, K. and Eberhard, P. (2006). Using augmented lagrangian particle swarm optimization for constrained problems in engineering"> using augmented lagrangian particle swarm optimization for constrained problems in engineering. *Structural and Multidisciplinary Optimization*, 32:277–286.

[Shen et al., 2006] Shen, W., Wang, L., and Hao, Q. (2006). Agent-based distributed manufacturing process planning and scheduling: a state-of-the-art survey. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 36(4):563–577.

[Silva et al., 2023] Silva, B., Marques, R., Faustino, D., Ilheu, P., Santos, T., Sousa, J., and Rocha, A. D. (2023). Enhance the injection molding quality prediction with artificial intelligence to reach zero-defect manufacturing. *Processes*, 11(1):62.

[Sobottka et al., 2020] Sobottka, T., Kamhuber, F., and Heinzl, B. (2020). Simulation-based multi-criteria optimization of parallel heat treatment furnaces at a casting manufacturer. *Journal of Manufacturing and Materials Processing*, 4(3):94.

[Stanitsas et al., 2021] Stanitsas, M., Kirytopoulos, K., and Leopoulos, V. (2021). Integrating sustainability indicators into project management: The case of construction industry. *Journal of Cleaner Production*, 279:123774.

[Steger-Jensen et al., 2019] Steger-Jensen, K., Hvolby, H.-H., Dukovska-Popovska, I., Vestergaard, S., and Svensson, C. (2019). Enabling green manufacturing using advanced planning and scheduling (aps) technology. In *2019 10th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*, pages 181–186.

[Strandhagen et al., 2019] Strandhagen, J. W., Buer, S.-V., Semini, M., and Alfnes, E. (2019). Digitalized manufacturing logistics in engineer-to-order operations. In *Advances in Production Management Systems. Production Management for the Factory of the Future: IFIP WG 5.7 International Conference, APMS 2019, Austin, TX, USA, September 1–5, 2019, Proceedings, Part I*, pages 579–587. Springer.

[Stüve et al., 2020] Stüve, D., Meer, R. v. d., Lütke Entrup, M., and Ali Agha, M. S. (2020). Supply chain planning in the food industry. In *Hamburg International Conference of Logistics (HICL) 2020*, pages 317–353. epubli.

[Tan et al., 2019] Tan, Q., Tong, Y., Wu, S., and Li, D. (2019). Modeling, planning, and scheduling of shop-floor assembly process with dynamic cyber-physical interactions: a case study for cps-based smart industrial robot production. *The International Journal of Advanced Manufacturing Technology*, 105:3979–3989.

[Tang et al., 2007] Tang, O., Grubbström, R. W., and Zanoni, S. (2007). Planned lead time determination in a make-to-order remanufacturing system. *International Journal of Production Economics*, 108(1-2):426–435.

[Thürer et al., 2022] Thürer, M., Fernandes, N. O., and Stevenson, M. (2022). Production planning and control in multi-stage assembly systems: an assessment of kanban, mrp, opt (dbr) and ddmrp by simulation. *International Journal of Production Research*, 60(3):1036–1050.

[Vinci Carlavan and Rossit, 2021] Vinci Carlavan, G. and Rossit, D. A. (2021). One-of-a-kind production in cyber-physical production systems considering machine failures. *Journal of Integrated Design and Process Science*, 25(2):100–119.

[Wang et al., 2021a] Wang, B., Tao, F., Fang, X., Liu, C., Liu, Y., and Freiheit, T. (2021a). Smart manufacturing and intelligent manufacturing: A comparative review. *Engineering*, 7(6):738–757.

[Wang et al., 2022a] Wang, G.-G., Gao, D., and Pedrycz, W. (2022a). Solving multiobjective fuzzy job-shop scheduling problem by a hybrid adaptive differential evolution algorithm. *IEEE Transactions on Industrial Informatics*, 18(12):8519–8528.

[Wang et al., 2021b] Wang, L.-C., Chen, C.-C., Liu, J.-L., and Chu, P.-C. (2021b). Framework and deployment of a cloud-based advanced planning and scheduling system. *Robotics and Computer-Integrated Manufacturing*, 70:102088.

[Wang et al., 2021c] Wang, L.-C., Chen, C.-C., Liu, J.-L., and Chu, P.-C. (2021c). Framework and deployment of a cloud-based advanced planning and scheduling system. *Robotics and Computer-Integrated Manufacturing*, 70:102088.

[Wang et al., 2022b] Wang, M., Huang, Y., and Zhang, J. (2022b). Current situation and development of advanced planning and scheduling system based on group optimization algorithm in discrete industry. *Highlights in Science, Engineering and Technology*, 23:215–220.

[Waschneck et al., 2018] Waschneck, B., Reichstaller, A., Belzner, L., Altenmüller, T., Bauernhansl, T., Knapp, A., and Kyek, A. (2018). Optimization of global production scheduling with deep reinforcement learning. *Procedia Cirp*, 72:1264–1269.

[Wiers, 2009] Wiers, V. C. (2009). The relationship between shop floor autonomy and aps implementation success: evidence from two cases. *Production Planning and Control*, 20(7):576–585.

[Wohlin, 2014] Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. In *Proceedings of the 18th international conference on evaluation and assessment in software engineering*, pages 1–10.

[Wolfshorndl et al., 2020] Wolfshorndl, D. A., Vivaldini, M., and De Camargo Junior, J. B. (2020). Advanced planning system as support for sales and operation planning: study in a brazilian automaker. *Global Journal of Flexible Systems Management*, 21(Suppl 1):1–13.

[Xiong et al., 2022a] Xiong, H., Shi, S., Ren, D., and Hu, J. (2022a). A survey of job shop scheduling problem: The types and models. *Computers Operations Research*, 142:105731.

[Xiong et al., 2022b] Xiong, H., Shi, S., Ren, D., and Hu, J. (2022b). A survey of job shop scheduling problem: The types and models. *Computers & Operations Research*, page 105731.

[Yang et al., 2020] Yang, S., Zhao, W., Liu, Y., Cherubini, F., Fu, B., and Pereira, P. (2020). Prioritizing sustainable development goals and linking them to ecosystem services: A global expert's knowledge evaluation. *Geography and Sustainability*, 1(4):321–330.

[Yazdani and Daim, 2022] Yazdani, A. and Daim, T. (2022). *Software Assessment for Capacity Planning and Feasibility Check of the Master Production Schedule*. Routledge.

[Yin et al., 2018] Yin, Y., Stecke, K. E., and Li, D. (2018). The evolution of production systems from industry 2.0 through industry 4.0. *International Journal of Production Research*, 56(1-2):848–861.

[Zennaro et al., 2019] Zennaro, I., Finco, S., Battini, D., and Persona, A. (2019). Big size highly customised product manufacturing systems: a literature review and future research agenda. *International Journal of Production Research*, 57(15-16):5362–5385.

[Zhai et al., 2019] Zhai, S., Riess, A., and Reinhart, G. (2019). Formulation and solution for the predictive maintenance integrated job shop scheduling problem. In *2019 IEEE International Conference on Prognostics and Health Management (ICPHM)*, pages 1–8. IEEE.

[Zhang et al., 2020] Zhang, C., Song, W., Cao, Z., Zhang, J., Tan, P. S., and Chi, X. (2020). Learning to dispatch for job shop scheduling via deep reinforcement learning. *Advances in Neural Information Processing Systems*, 33:1621–1632.

[Zhang et al., 2021] Zhang, F., Mei, Y., Nguyen, S., Zhang, M., and Tan, K. C. (2021). Surrogate-assisted evolutionary multitask genetic programming for dynamic flexible job shop scheduling. *IEEE Transactions on Evolutionary Computation*, 25(4):651–665.

[Zhang et al., 2022] Zhang, Z., Guan, Z., Gong, Y., Luo, D., and Yue, L. (2022). Improved multi-fidelity simulation-based optimisation: application in a digital twin shop floor. *International Journal of Production Research*, 60(3):1016–1035.

[Zheng et al., 2020] Zheng, J., Mi, X., and Liao, H. (2020). Advanced planning and scheduling based on the constraint theory and improved tabu search algorithm. *Recent Patents on Engineering*, 14(2):221–228.

[Zheng et al., 2021] Zheng, T., Ardolino, M., Bacchetti, A., and Perona, M. (2021). The applications of industry 4.0 technologies in manufacturing context: a systematic literature review. *International Journal of Production Research*, 59(6):1922–1954.

[Zheng et al., 2022] Zheng, Z., Zhang, K., and Gao, X. (2022). Human-cyber-physical system for production and operation decision optimization in smart steel plants. *Science China Technological Sciences*, 65(2):247–260.

[Zhong et al., 2013] Zhong, R. Y., Li, Z., Pang, L., Pan, Y., Qu, T., and Huang, G. Q. (2013). Rfid-enabled real-time advanced planning and scheduling shell for production decision making. *International Journal of Computer Integrated Manufacturing*, 26(7):649–662.

[Zoryk-Schalla et al., 2004] Zoryk-Schalla, A. J., Fransoo, J. C., and de Kok, T. G. (2004). Modeling the planning process in advanced planning systems. *Information Management*, 42(1):75–87.

APPENDICES

Conceptual block
"advanced planning and scheduling" OR "advanced planning & scheduling" OR "aps" OR "collaborative planning" OR "decision support systems"
Contextual block
"job shop scheduling" OR "production planning and control" OR "manufacturing planning and control" OR "production scheduling" OR "job shop scheduling problem" OR "JSSP"
Contextual block II
"optimization" OR "complexity"

Figure 8.1: Keyword search

Optimization strategy

Statement					
1. You see the potential benefits of the ability to simulate the production plan before the release	1	2	3	4	5
2. You think you have unrealized potential regarding the quality of your production schedule	1	2	3	4	5
3. You often experience inaccuracies in the production plan that leads to unwanted free time in the machines	1	2	3	4	5
4. You often experience inaccuracies in the production plan that leads to overloaded tasks on the machines	1	2	3	4	5
5. You have a clear understanding of what constraints and penalty factors you would want to utilize in the possible simulations	1	2	3	4	5
6. Basic data for the production processes in the production exist	1	2	3	4	5
7. The basic data of your production processes are stable and rarely change	1	2	3	4	5
8. Service of machines and errors in machinery are fairly predictable (Some statistics of the probability exist)	1	2	3	4	5
9. Guidelines/Constraints of how the production planning is done is set at a holistic level among planners	1	2	3	4	5
10. Guidelines of priorities in the scheduling are set at a holistic level among the planners	1	2	3	4	5

Figure 8.2: Optimization strategy questionnaire for SMM

Complexity

Statement					
1. Your current product structure is complex, meaning the finished product consists of several parts	1	2	3	4	5
2. Many of your products are made one-of-a-kind (tailored especially for the customer/project)	1	2	3	4	5
3. A small error/inaccuracy in one of the production steps causes delays or other significant unwanted consequences	1	2	3	4	5
4. You spend many human working hours to generate the production schedule due to the need of calculating many variables and important interactions	1	2	3	4	5
5. The products you produce have a high variance in processing time	1	2	3	4	5
6. Every part needs to pass through several machines in the manufacturing process	1	2	3	4	5
7. You have several activities processing simultaneously at your job shop	1	2	3	4	5
8. There is a choice in material selection for each part	1	2	3	4	5
9. Machines used in the shop floor activities need to be manually operated or need programming before each use	1	2	3	4	5
10. Shop floor workers follow schedules slavishly	1	2	3	4	5

Figure 8.3: Complexity questionnaire for SMM

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