Improving sawmill scheduling through Industry 4.0

– A CASE study at VIDA AB

Förbättring av sågverksplanering genom Industry 4.0 –

En fallstudie på VIDA AB

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Summary

Today, we are standing on the brink of the fourth industrial revolution, called Industry 4.0. This new era has developed from combining new technologies into the manufacturing system, such as artificial intelligence, additive printing, and cyber-physical systems. As one of the largest industries in Sweden, and the fifth largest producer of wooden products globally, operating in one of the most eminent technological countries, one might assume that the Swedish forest industry would be at the forefront of this evolution in the industry. However, due to segregated digital supply chains and a lack of knowledge about the concept, manufacturers struggle to implement a strategy towards the concept. Nevertheless, it does exist an interest in adapting the concept of Industry 4.0 into the industry.

One of the key impacts that Industry 4.0 will have on manufacturing systems is the availability of real-time information through the entire value network, allowing decision-making on reality rather than assumptions. It is therefore evident that Industry 4.0 will have a significant impact on operational decision-making, including scheduling. Scheduling manufacturing systems concerns the operational decision-making deciding on “when” to produce the product. Further, scheduling in sawmilling is complex, building on experience and information from several different processes.

With this background, it became evident that further research regarding processes' ability to support operational decision-making in Industry 4.0 was needed. Therefore, the purpose of this study was to outline the potential of Industry 4.0 for operational scheduling in the sawmill industry. The intent is to explore improvements in the processes' ability to support operational decision-making in Industry 4.0.

Information gaps between the scheduler and the processes were mapped using a single-case study, collecting data through participant observations and interviews. Processes in direct contact were evaluated based on their ability to support operational decision-making in Industry 4.0 by using the “Acatech Industrie 4.0 maturity Index”.

The results showed that the processes possessed varying abilities to support operational decision-making. Therefore, a four-step roadmap was constructed to improve its processes' ability to support operational decision-making. In the initial stage were improvements of digital capability and integration between the processes and the scheduler recommended. The lacking information about the logs constitution disrupted the scheduler's ability to forecast product output, which resulted in re-scheduling in the following processes. Additionally, improving the processes’ ability to visualize relevant data to the scheduler could improve the trustworthiness of the manufacturing system.

Keywords: digitalization, forest industry, maturity analysis, process improvement, scheduling, wood processing

Sammanfattning

Vi står idag på randen till den fjärde industriella revolutionen, Industri 4.0. Denna nya era har utvecklats tack vare en kombination av nya tekniker i tillverkningssystemet, såsom artificiell intelligens, additiv utskrift och cyber-fysiska system. Som en av Sveriges största industrier, och den femte största tillverkaren av träprodukter globalt, med verksamhet i ett av de mest framstående tekniska länderna, kan man anta att den svenska skogsindustrin skulle ligga i framkant för denna utveckling i branschen. Idag finns det ett stort intresse av att tillämpa konceptet i branschen, men på grund av bristande kunskap och segregerade digitala försörjningskedjor kämpar tillverkarna med att implementera strategier mot Industry 4.0.

En av de största effekterna som Industry 4.0 kommer att ha på tillverkningssystem är tillgången på realtidsinformation genom hela värdekedjan, vilket möjliggör beslutsfattande baserat på verkligheten snarare än antaganden. Det är därför uppenbart att Industry 4.0 kommer att ha en betydande inverkan på det operativa beslutsfattandet, inklusive produktionsplanering. Vidare är produktionsplaneringen i sågverket komplexoch bygger på erfarenhet och information från flera olika processer.

Med denna bakgrund är det uppenbart att det behövs ytterligare forskning om processers förmåga att stödja operativt beslutsfattande inom Industry 4.0. Därför är syftet med denna studie att beskriva potentialen i Industry 4.0 för operativ produktionsplanering inom sågverksindustrin. Avsikten är att utforska möjligheter för förbättringar av processernas förmåga att stödja operativt beslutsfattande i och med Industry 4.0.

Genom användandet av fallstudie, deltagarobservationer och intervjuer med en produktinosplanerare vid sågverket, har informationen som använts från olika processer kartlagts och potentiella informationsbrister har identifierats. Processerna med direktkontakt med produktionsplaneraren har utvärderades utifrån deras förmåga att stödja operativt beslutsfattande i Industry 4.0 med hjälp av ”acatech Industrie 4.0 mognadsindex”.

Resultaten visade att processerna hade olika förmågor för att stödja operativt beslutsfattande. Därför konstruerades en färdplan för företaget för att förbättra processernas förmåga att stödja operativt beslutsfattande. I det inledande skedet var förbättringar av digital kapacitet och integration mellan processerna och schemaläggaren rekommenderad. Den bristande informationen om stockdimensioner störde schemaläggarens förmåga att prognostisera produktutfall, vilket resulterade i omplanering i följande processer. Dessutom kan förbättrad förmåga att visualisera relevanta data till produktionsplaneraren förbättra tillverkningssystemets pålitlighet.

Nyckelord: digitalisering, skogsindustri, mognadhetsanalys, processförbättring, planering, träbearbetning

Acknowledgement

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On a last note, I would like to thank my classmates during these five years of studying, especially my course-mates during this thesis work Mikael Olsson and Gustaf Sparrevik, who have lit up even the darkest of existence and shared both success and fallbacks.

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1 Introduction

This section is the background of the study presented and the problem area surrounding the choice of the study. Followed by a description of the purpose, delimitations, and an outline of the study.

1.1 Problem background

Going from the third industrial revolution where computers took over the manufacturing systems, are we today standing on the brink of the fourth revolution, called Industry 4.0. New technologies like artificial intelligence, additive printing, and cyber-physical systems are today seeing the first light. Concepts like “smart factories” have begun to pop up, characterized by increased flexibility, productivity, efficiency, and sustainability, ensuring competitiveness in the global market (Kagermann, Wahlster, & Helbig 2013). Following the need for manufactures to be ever so more flexible and adaptable towards their customers.

Several countries have already adapted the approach to outline their way forward towards the fourth revolution. In Germany, where it first was announced, is the forecast that it will deliver 425 billion euros of added value in Germany until 2025 (GTAI n.d). Following Germany, has several countries followed, including France, China, and Japan (BMWI n.d). Besides benefits such as increased efficiency, productivity, and flexibility (Kagermann et al. 2013), it could act as a tool to re-possess industrial Europe through smart machines and knowledgeable workers (Alpman 2014). In Sweden, several big companies already implemented strategies towards Industry 4.0, including big manufacturers such as Volvo (VerkstadsForum 2019) and Scania (Elmgren 2020). However, as one of the largest industries in Sweden and the fifth-largest producer of wooden products globally (Skogsindustrierna 2019), is the digital transformation in the forest sector lacking (Holmström 2020).

With the advantage of operating in one of the most digitally advanced countries globally, the industry can lead the global forest sector into this new era (Getzoff 2020). However, is this not the case where it is evident that the forest industry struggles with digital transformation and adopting this new concept (Holmström 2020). Variations in the raw material and complex production flow with joint production (Grönlund & Borg 1992), long lead times, and operations in remote places complicate the matter (Holmström 2020). Increased sustainability awareness has developed new markets with different needs regarding on-time delivery and product cost, *e.g.,* wood in multi-story houses, allowing for additional value creation in the supply chain. However, to reach these new markets, the industry must create improved frameworks to help the sawmill follow up on production, production planning, and product profitability analysis (Stendahl & Eliasson 2014) to understand the complex production system (Hietala et al. 2019). However, Industry 4.0 components have the potential to improve the industry’s value creation, and these new technologies are gradually being tried. For instance, computer tomography which enables optimal disjointing of logs based on precise measures of the log’s constitution. Another novel method consists of using smart sensoring technologies that create individual fingerprints of logs, enabling tracking of the product through the entire supply chain (Pahlberg 2017). These technologies are on their way, but the question is if the forest industry is ready for it?

1.2 Problem description

Organizations need to be at the forefront of development by continuously innovating the products and modernizing the production processes (Oztemel & Gursev 2020). However, manufacturers have difficulties grasping the concept of Industry 4.0 since it is rather a goal than a strategy. Since technologies introduced in Industry 4.0 need to fit the manufacturing context they should be operated. Therefore, research about this new concept should focus on developing technologies and help manufacturers implement strategies towards Industry 4.0 to fit it into their working environment (Oztemel & Gursev 2020).

Modern sawmills characterize as production units with large values flowing through the facility at an impressive rate. The raw material cost is the largest budgeted cost in operation, followed by capital, labor, and operations costs (Lundahl 2009). Because of this, the sawmill needs to utilize its equipment and raw material as effectively as possible. Thanks to increased knowledge and skills about optimization technologies, advanced scheduling models have been constructed to cope with the complex production seen in the forest industry. However, knowledge gaps still exist about the production system and how it behaves in the wood industry (Shahi & Pulkki 2013; Larsson et al. 2016). Further are the uncertainties in raw material quality complicating the forecast of product yield (Karltun & Berglund 2010a).

To help manufacturers adapt to the Industry 4.0 concept, Oztemel and Gursev (2020) call for an increased understanding of the production systems to develop strategies to help them fit the concept into their working environment. The timber value chain is complex, consisting of long lead times and diverging multiple product flow not seen in many other industries. To help manufacturers in the forest industry implement Industry 4.0 strategies, Holmström (2020) argues that digital maturity models could help manufacturers grasp the concept and fit it into their reality.

Scheduling is essential in this complex production system to fulfill customer demand and reduce lead times, inventory, and material buffers (Vollmann, Jacobs, Berry, & Whyback 2011). Scheduling manufacturing systems concerns the operational decision-making deciding on “when” to produce the product and is used to reach high on-time delivery, low manufacturing costs through high utilization of resources, and low inventory costs through short turnaround time (Olhager 2013). The introduction of Industry 4.0 will increase access to real-time data, radically changing how scheduling will be performed (Parente et al. 2020).

Research regarding the scheduling of sawmills has mainly focused on improving the value-optimization from the log (Berglund & Karltun 2007). However, is the contextual conditions influencing the scheduling process scarcely researched. Hence, this creates an interest in further research on the matter since it is evident that, *e.g.*, IT developers face challenges when constructing supporting tools to the schedulers because of the dissimilarities to other industries (Karltun & Berglund 2010a). It is also evident that research regarding understanding the complex production system is lacking (Hietala et al. 2019), creating challenges implementing technologies introduced in Industry 4.0 (Oztemel & Gursev 2020) to the context of sawmilling. Further, by evaluating the organization's current state in the context of Industry 4.0, roadmaps could be created to reap the benefits introduced with Industry 4.0 (Holmström 2020). Therefore, will this study will focus on the contextual condition influencing the schedulers' work by evaluating how processes in the value chain fulfill scheduling in the new industrial era using an Industry 4.0 maturity model.

1.3 Aim

The purpose of this study is to outline the potential of Industry 4.0 for operational scheduling in the sawmill industry. The intent is to explore opportunities for improvements in the processes supporting operational scheduling. To assist in fulfilling the purpose of the study has the following research questions been formulated:

- What information is used in the operational decision-making to schedule production?
- To what degree do the processes in the facility assist in fulfilling the operational decision-making, according to Industry 4.0?
- How could the operational decision-making be improved by implementing an Industry 4.0 strategy, and how could such a strategy be constructed?

1.4 Delimitations

This study intends to investigate the processes' ability to support operational decision-making through scheduling and their readiness for Industry 4.0 scheduling. However, due to the complex information flow, is some delimitations needed. As described in Figure 1, this study focuses on the direct communication between the scheduler and the source of information. No investigation of secondary information flow obtained by the sources is under investigation.

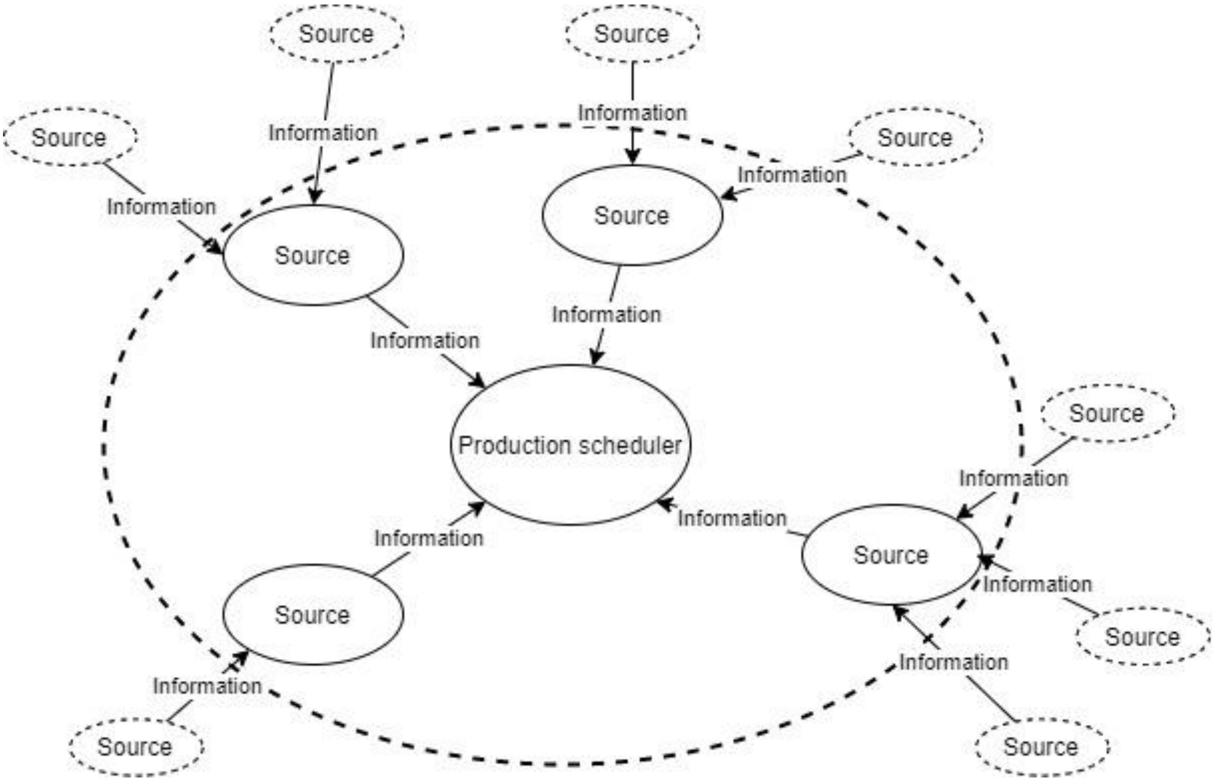

Figure 1. Systematical boundaries of processes under investigation in terms of information used by the scheduler.

Further is the study not focusing scheduling process *per se*. Instead, it focuses on the processes' ability to support decision-making in the operational scheduling. Hence, does it not provide any new improvements in the scheduling procedure. Alternatively, does it provide a framework for the CASE company to improve its processes to support operational decision-making in Industry 4.0.

1.5 Outline

The study consists of seven sections (**Fel! Hittar inte referenskälla.**), beginning with an introduction to the background and purpose of the study.

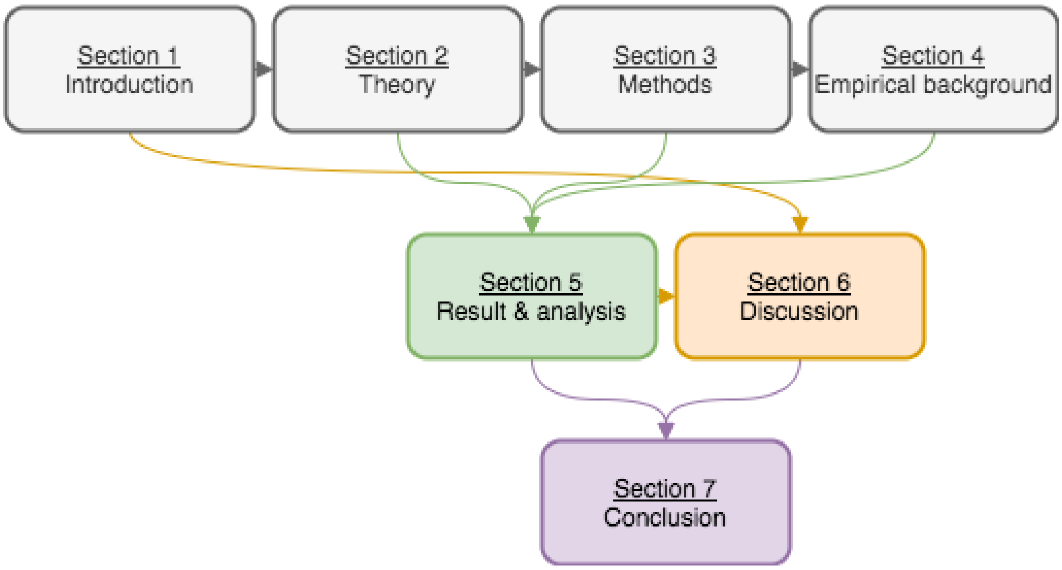

Figure 2. Illustration of the outline of the study.

Further, are theories presented in the theories section relevant to answering the study's purpose. In the following section are chosen methods declared. In the empirical background is standard processes in the sawmill operation presented, followed by a presentation of the CASE company. After that, are results and analysis presented based on the premises presented in the methods section with parallels to the theories and empirical background. In the discussion section is the results compared to previous studies and the problem background. In the final chapter is a conclusion of the results presented together with suggestions for future studies.

2 Theory

This section presents the chosen theories and models for analysis to fulfill the purpose of the study. It starts with a description of planning and scheduling with the corresponding objective. Following an introduction of the Industry 4.0 concept and technologies surrounding it. Finally, is models presented to evaluate the current state of Industry 4.0 maturity. The section concludes with a chapter of the conceptual framework for this study

2.1 Planning and scheduling

Human work subdivides into different perspectives in the context of the workplace. It could be from a technical perspective, which relates to the technical system in the organization. This perspective further divides into two parts. The first part is the primary technical system which includes the premises and equipment devoted to maintaining production capability. It is described in different ways concerning technical limitations, availability, problems, and reliability. The second part is the secondary system that assists the company's administration and procedures but is not directly associated with value-adding activities (Gasser, Fischer, & Wäfler 2011). The secondary system consists of information systems used as decision tools for a scheduler, whereas the primary system decides what premisses the scheduler is operating.

2.1.1 Decision-making in planning and scheduling

The overarching objective of planning and scheduling could divide into three parts, high on-time delivery, low manufacturing costs through high utilization of resources, and low inventory costs through short turnaround time (Olhager 2013). However, do these objectives not always align, and management needs to prioritize some aspects depending on the context. Different prioritizations could also occur at different times depending on the point of time, *e.g.*, could an organization prioritize resource utilization in an economic boom and prioritize low turnaround time during a recession (Olhager 2013).

Planning and scheduling in manufacturing try to answer the questions of “what”, “how”, and “when” to produce an item. It divides into different hierarchical levels; strategic, tactical, and operational, depending on how detailed the plan is and its timeline (Figure 3) (Olhager 2013). Decisions on the higher levels create input data for the lower ones (Olhager 2013).

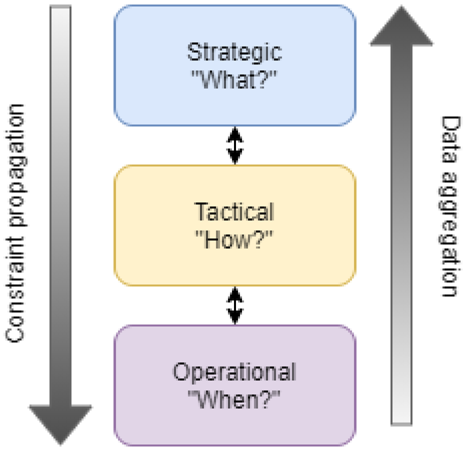

Figure 3. Hierarchical levels of production planning and scheduling. Own illustration based on Kreipl & Pinedo 2004, p. 82 with minor modifications.

In the highest tier, the strategic tier is questions regarding “what” to produce answered. It has the most extended planning horizon and aggregation of data. The strategic level has the most extended planning horizon and the most aggregated data. It often concerns several production facilities in the organization, and data is based on prognosis of production capacity and demand. The long planning horizon allows the organizations to identify needs for investment to reach the demand (Olhager 2013).

In the following tier, the tactical, consists of decisions regarding “how” to produce. The tactical level consists of both prognosis and customer orders, narrowing the time horizon. *Available to promise* is a key aspect at this stage to give delivery promises to the customer (Olhager 2013), therefore are estimations about production data of importance (Kreipl & Pinedo 2004).

In the lowest tier, operational tier, is questions regarding “when” to produce answered. It is in the lowest tier scheduling is performed. In the operational planning, or scheduling, is the time horizon further narrowed, often concerning days. Specific products are given a specific time of production and, detailed work orders are produced. The detailed scheduling considers several constraints such as inventory costs, tardiness costs, setup costs, and exact production data, *e.g.,* processing time and due dates (Kreipl & Pinedo 2004). One distinct difference between scheduling and the previous planning tiers is that optimization of the objective is measured in time units (*e.g.,* minimization of setup costs). In contrast, is it measured in monetary terms (*e.g.,* minimization of total cost) in the higher tiers (*ibid.*).

Depending on the characteristics of the industry, scheduling faces different issues (Kreipl & Pinedo 2004). Manufacturing systems divide into two main types continuous and discrete manufacturing (Olhager 2013). The borderline between these two types is somewhat blurry and may overlap. Because of the intermittent production of products in discrete manufacturing, will every work order be needed to be scheduled by itself, simultaneously, the scheduler must consider production capacity to all other products that compete with the same resources (Olhager 2013). Mainly could these differences be categorized in three types:

- Firstly, the planning horizon, where continuous manufacturing often tends to have a longer planning horizon.
- Secondly, the so-called “clock-speed” tends to be higher in discrete manufacturing, where schedules need to be changed or adjusted to a greater extent.
- Lastly, customization degree tends to be higher in discrete manufacturing.

2.1.2 Information system in planning and scheduling

Manufacturing organizations use information systems (IT systems) to collect, store, and process data into information and distribute it to the right user. The information shared could then be used as a basis for decisions in the organization. The use of IT systems varies between organizations, however, is the traditional set of IT systems easiest visualized in an ISA framework (Åkerman 2018) (Figure 4). The ISA 95 is a widely known standard of how to manage a production environment. “Purdue Enterprise Reference Architecture” (PERA) is used as a basis of the ISA 95 framework. It consists of levels from 0 to 4, ranging from devices used to measure and manipulate the physical process to business planning and logistics in the entire organization. Each of the levels is associated with a set of IT systems traditionally used.

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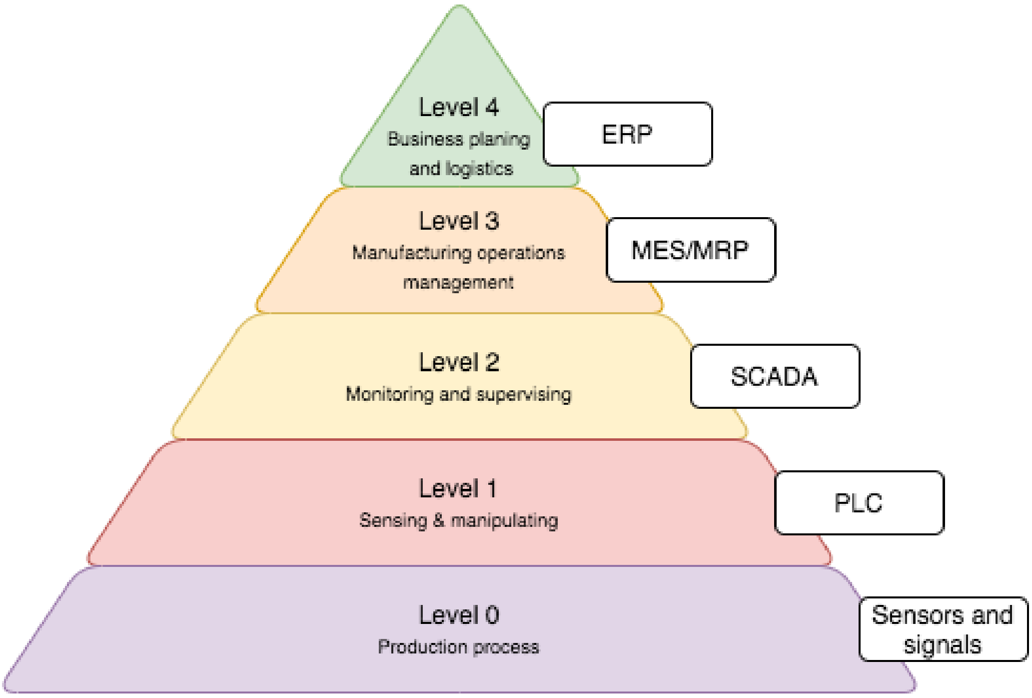

Figure 4. Information systems divided into the hierarchical levels presented by the ISA framework. The ISA framework consists of four layers and describes different systems to control each layer (Åkerman 2018, p. 2).

The lowest level, the production process, consists of measuring devices measuring the actual production. Level 1 consists of systems used to sense and manipulate processes, *e.g.*, programmable logic controllers (PLCs). In level 2 are the systems used to monitor and supervise the equipment through SCADA (supervisory control and data acquisition). At this level, data about product placement in the production chain is monitored and creates follow-up data on production) (Kreipl & Pinedo 2004; Olhager 2013). In level 3 is MES (manufacturing execution systems) used to execute the plan, developed in the ERP (enterprise resource planning) system at the highest level (Åkerman 2018).

Information delay

The occurrence of unexpected events is one of the leading causes of disturbance in the schedules, calling for counter-measures, such as rescheduling or modifying the allocated resources. Additionally, Muehlen & Shapiro (2010) mention that it is often a time-lag between disturbance occurs and appropriate counter-measures are in place. This delay creates in-optimal solutions based on feasibility rather than on the optimal solution (Kallrath 2002). Further, could this delay mean a potential loss of business value (Muehlen & Shapiro 2010).

The delay between events occurs, and proper countermeasures are in place emerges from the organization's ability to capture and process data into information and to react to this information. Muehlen & Shapiro (2010) describes four factors that influence this delay:

- **Data latency** is the time between an event occurred until an information system has captured it.
- **Analysis latency** is the time it takes for IT systems to process data into relevant information in the form of, *e.g.*, a notification, a report, or an indicator value.

- **Decision latency** is the time between a decision-maker has gotten relevant information about the event until the initiation of appropriate counter-measures. This latency includes the actual processing of information to relevant decision alternatives and assessing consequences for each of them.
- **Implementation latency** concerns the delay between when a countermeasure has been set in until it has given desired effect.

2.2 Industry 4.0

Industry 4.0 was first used in Germany in 2011 (Kagermann et al. 2013) and describes the change from machine dominant manufacturing to digital manufacturing (Oztemel & Gursev 2020). The sequence of industrial revolutions is illustrated in Figure 5.

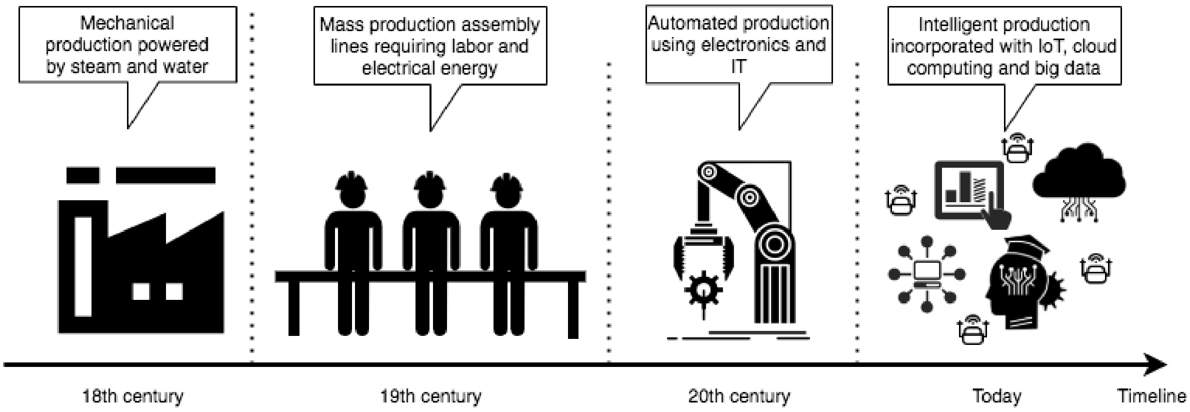

Figure 5. Historical overview of industrial revolutions, consisting of four distinct eras starting in the 18th century with mechanical production until today with intelligent production with IoT, CPS, and big data (Oztemel & Gursev 2020, p. 133).

The industrial era is divided into four industrial revolutions (Figure 5). Ranging from the 18th century with the introduction of mechanical production, mass production in 19th century, and automated production in the middle of the 20th century (Oztemel & Gursev 2020). Industry 4.0 evolved from the collaboration and integration of several different technologies, and the technologies themselves already exist in several industries (Parente et al. 2020). These technologies are not clearly defined, and the boundaries between them vary. However, are they all envisioned to leverage towards smart production (Parente et al. 2020). Fundamental to Industry 4.0 is the usage of *cyber-physical systems* (CPS) in manufacturing, which uses *Internet of Things* (IoT), where every entity in the organization is connected to the internet and information is distributed horizontally and vertically in the supply chain with the help of *cloud computing* (Kagermann et al. 2013). Stemming from these three majors have additional technology evolved and integrated into the concept of Industry 4.0 *e.g.,* autonomous decision-making, big data analysis, simulation, cybersecurity, additive printing, and augmented reality (Parente et al. 2020).

Since Industry 4.0 is an ongoing transformation, could the final result of full implementation not be quantified (*e.g.,* Parente et al. 2020; Schuh et al. 2020a). However, has several benefits been observed in organizations that adapted an Industry 4.0 approach (Oztemel & Gursev 2020; Schuh et al. 2020a), such as decrease downtime, lower costs, distinguish themselves in the market, and improve delivery, service, and quality (Liao et al. 2017). Kagermann et al. (2013)

have listed several potential benefits that could come with an implementation of Industry 4.0 into the organization:

- **Meeting individual customer demand**, Industry 4.0 will allow for individual customer-specific criteria to be fulfilled in all production phases and enable last-minute changes. Due to the flexibility in the production facility, will Industry 4.0 allow for profit realization even in low production volumes.
- **Achieve flexibility**, CPS technology and integrated supply chains will allow for configuration of different business processes, allowing the organization to adapt to disturbances or changes in demand quickly.
- **Optimizing decision-making** with end-to-end transparency through the entire supply chain will allow organizations to optimize their decisions based on real-time data due to early verification of disturbances and response, decreasing the information delay (Schuh et al. 2020b).
- **Resource productivity and efficiency**, CPS allows manufacturing processes to optimize on a case-by-case basis through the entire supply chain. Instead of stopping production due to unexpected events, *e.g.*, lack of resources, could the processes be optimized and quickly adapted to the present circumstances across the supply chain.
- **Creating value opportunities through new services**, thanks to increased transparency and extensive collection of big data analyzed with smart algorithms, could new innovative services develop.
- **Responding to demographic change in the workplace**, interacting the workforce with the technological systems could decrease physical and physiological workload. Allowing for flexible and diverse career paths that allow people to keep working and remain productive longer.
- **Improved work-life balance**, through the overall flexibility and the use of CPS and smart assistance systems, allowing the workforce to be more flexible in their work-life, *e.g.*, by allowing decision-making from a distance with real-time data.

The foundation in Industry 4.0 is to use information and communication technologies to realize real-time decision-making in the production system (Liao et al. 2017). According to Parente et al. (2020), technologies like CPS, IoT, and horizontal and vertical integration arguably affect the traditional scheduling paradigm. Therefore, are these technologies further explained in the following chapters, together with potential benefits and challenges.

2.2.1 Cyber-physical system (CPS)

In its pure form, CPS is a virtual copy of the physical production allowing for processing and analyzing the physical world without interfering with it (Oztemel & Gursev 2020) and is believed to be one of the most impactful technologies in Industry 4.0 (Parente et al. 2020). According to Thiede et al. (2016), CPS consists of four components; the physical world, data acquisition, a virtual world, and feedback/control. Figure 6 shows a schematic illustration of the interactions of the components in CPS.

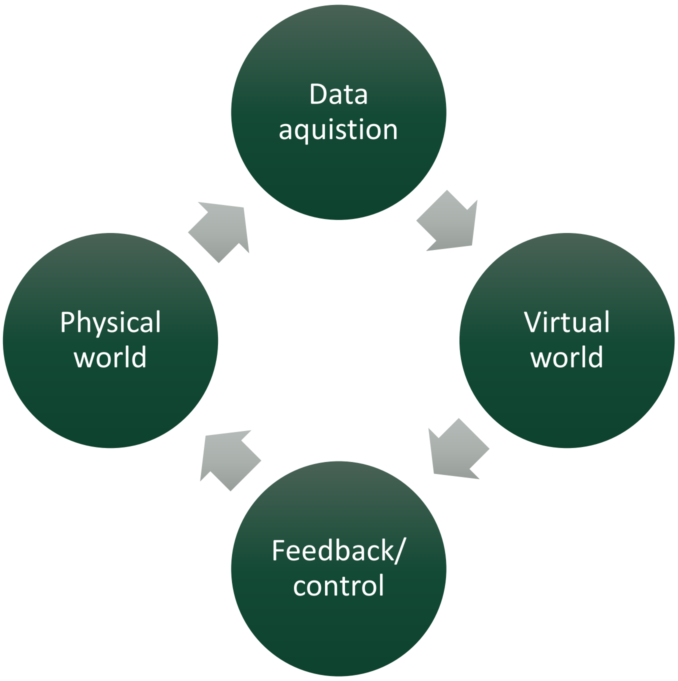

Figure 6. Schematic overview of the main components in CPS, where information is viewed as arrows showing the information flow between components (Thiede et al. 2016, p. 9).

The CPS monitors the physical world through sensors collecting data about the physical production through state and disturbance variables. Through a virtual copy created by computer simulation, data is processed to information and different scenarios tested on their effect on a set of predefined key performance indicators (KPIs). Changes tested in the virtual world are then implemented by a set of actuators in the physical world (Thiede et al. 2016).

According to Oztemel & Gursev (2020) CPS consists of two essential elements:

- An integrated network of sensors and systems communicating with one another over the IoT
- And, a virtual copy created through computer simulation of the information gathered in the physical world.

These elements will allow CPS to deliver opportunities such as more accessible information, optimized decision-making, and improvements in production and resource utilization (Oztemel & Gursev 2020). Further, Parente et al. (2020) argue that CPS will allow for decentralized decision-making, where shop-floor agents (e.g., machines in the factory) will decide autonomously instead of going through a central control unit beforehand. According to Thiede et al. (2016), should the degree of decentralized decision-making depend on the application and be transparent on the decision-premises. If not, prejudice about the system could hinder development and adoption (Muccini et al. 2016).

2.2.2 Internet of Things

An essential component in CPS is the Internet of Things (IoT) which will allow for fast communication within and between CPS systems. This fast communication will optimize decision-making through the supply chain (Thiede et al. 2016). In IoT, every machine is connected to the internet, sharing information to humans and other machines. Oztemel & Gursev (2020) defines IoT as:

“The inter-networking of physical devices, vehicles, buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect and exchange data.”

The IoT will allow operators to control the production from a distance allowing for closer integration with the production system and decentralized decision making (Oztemel & Gursev 2020; Parente et al. 2020). The IoT builds on four different levels: the perception layer, network layer, support layer, and application layer (Leloglu 2017) (Figure 7)

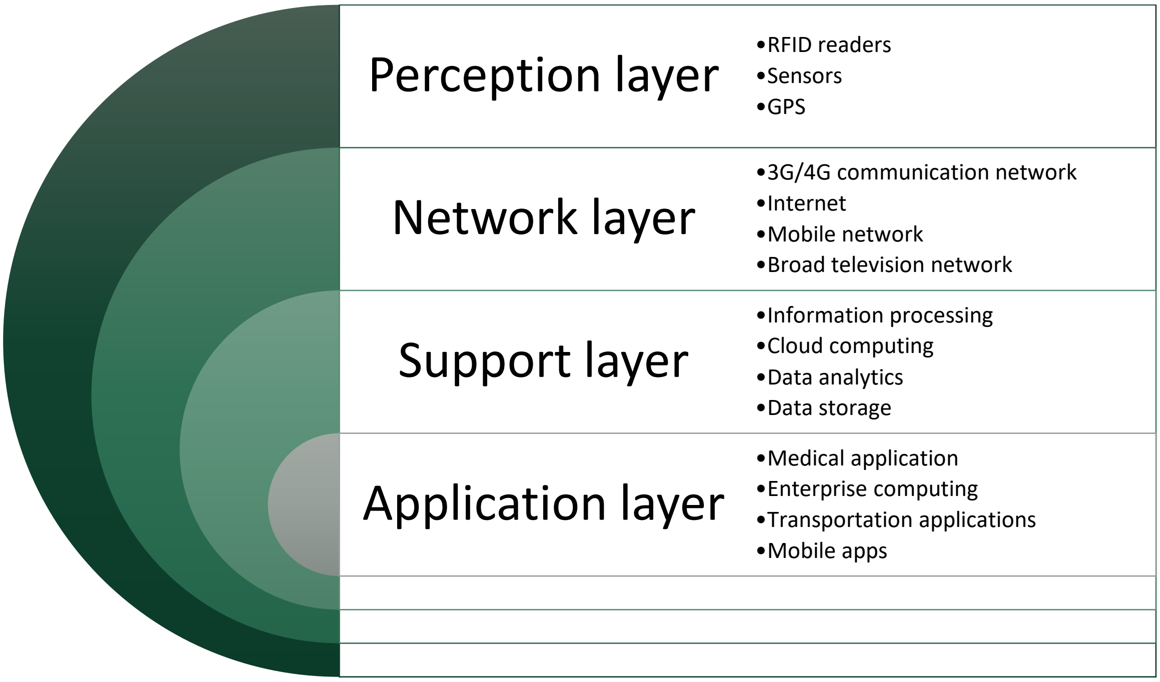

Figure 7. The four layers of internet of things, IoT, described by Leloglu (2017, p. 126).

Each of the layers supports the usage of IoT in different stages of information treatment. The perception layer collects data from the physical world through smart sensoring technologies and identifying unique objects using tagging technologies like RFID (Radio Frequency Identification Device) tags (Farooq et al. 2015; Leloglu 2017). The network layer then transfers the data to relevant supporting layers through, *e.g.,* 3G/4G networks. The data is then processed into information, stored in the supporting layer. In the application layer, closely operating with the supporting layer, information is visualized and applied to decision-makers, either human or machine (Leloglu 2017).

Integrating the IoT with the customers, formerly called the Internet of Services and Thing (IoT&S), will allow for easier sharing of information and increased transparency, adding up to improve and further customize products and services. Through the use of “smart products,” the customers will be able to customize their products by constant feedback regarding satisfaction (Jian-Yu et al. 2017). However, to allow for this high degree of customization, production systems must be built to be flexible, and the scheduling must be easily adjustable and reactive to changes in demand (Parente et al. 2020).

2.2.3 Horizontal and vertical integration

The concept of Industry 4.0 beds on the easy access of information through the entire value network. According to Parente et al. (2020), horizontal and vertical integration will be among the majors affecting scheduling in this new concept.

Vertical integration integrates various IT systems used in various stages of manufacturing and planning processes both within and between several different organizations and customers (Kagermann et al., 2013). Information is instantly available regarding products, demand, due dates, resource availability/delays through the supply chain network, and constantly updated through IoT,

Horizontal integration refers to up- and downstream integration of IT systems within the organization's value network at all hierarchical levels (Kagermann et al., 2013). By closely incorporating marketing, engineering, production, and sales resources within an organization could be used in a horizontal value network. Horizontal integration allows for dynamic scheduling across the organization, where resources are pooled and allocated between facilities to reduce stalls in operation (Parente et al. 2020).

The increased integration of the value network will improve the accuracy and reliability of the schedules. The scheduler will always have access to real-time information in the entire supply chain *e.g.,* delays in resource delivery or variation in offer and demand, allowing schedules always to be up-to-date (Parente et al. 2020).). Typical scheduling problems could decrease, like building up inventory or carrying out non-value-adding activities by taking on- and off-site deviations into account (Dallasega et al., 2017). However, with information sharing both within and between organizations, trust is needed to enable open sharing between peers. Chen (2017) recommends that standards and practical protocols be created to allow organizations to trust one another and the workers within them.

2.2.4 Scheduling 4.0

As mentioned previously, Industry 4.0 allows for a higher degree of customization and improved information sharing, among others. However, flexibility in the scheduling paradigm must be improved (Parente et al. 2020). Traditionally decision-making involves a delay between when an event is captured until appropriate counter-measures has been implemented and have the appropriate effect (Kallrath 2002; Muehlen & Shapiro 2010). However, due to the increased integration between production systems IT systems due to Industry 4.0, information will be shared in real-time, minimizing the gap between events and sufficient counter-measures (Schuh et al. 2020b). The use of technologies in Industry 4.0, especially CPS, will significantly impact scheduling in operations (Rossit & Tohmé 2018; Parente et al. 2020). According to Rossit & Tohmé (2018) will the scheduling of the production system be performed autonomously by the CPS systems. In Figure 8 is a schematic overview of the CPS integration within the ISA 95 standard presented, suggested by Rossit & Tohmé (2018)

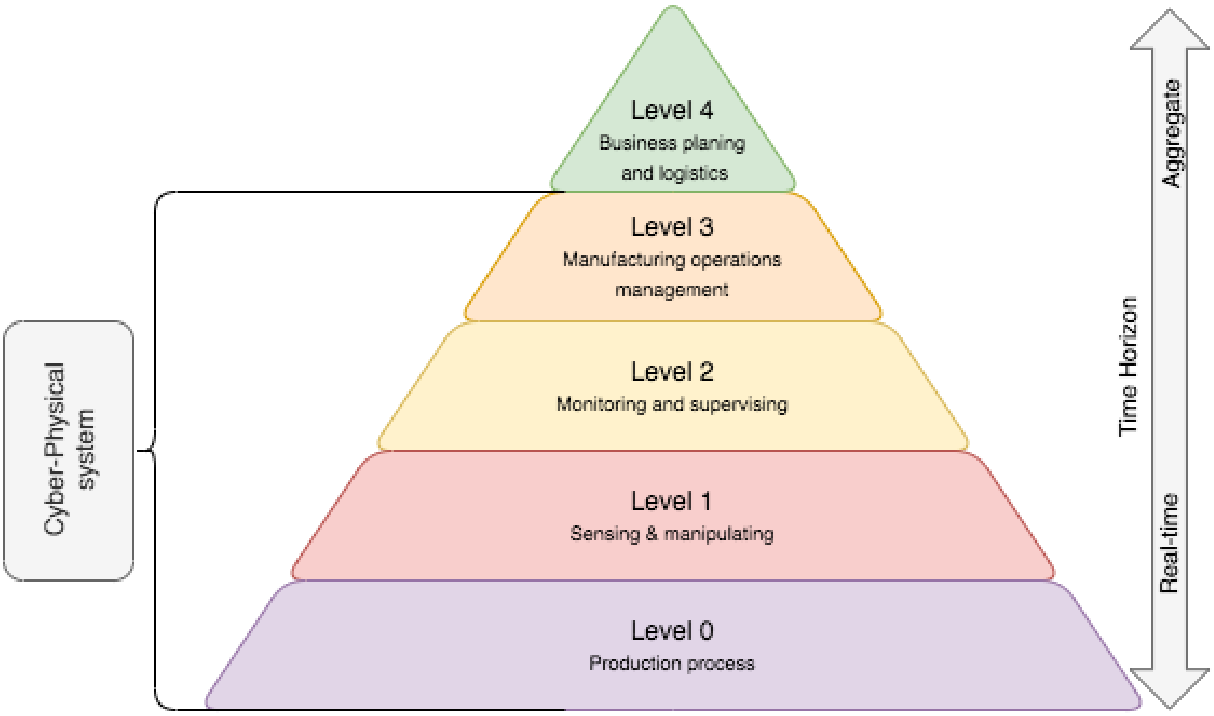

Figure 8. Levels of ISA 95 integrated with cyber physical system. The ISA framework consists of four layers from the existing production process to overarching planning at business and logistics level. In Industry 4.0 will the three lower layers be integrated within the CPS (Rossit & Tohmé 2018, p. 112).

Given the implementation of Industry 4.0, the production planning will consist of two main systems: Enterprise resource planning (ERP) and CPS (Rossit & Tohmé 2018). On the aggregate level, the decisions about goals to be pursued will be handled by the ERP systems in level 4. The CPS will automatically and systematically handle other decisions in the lower levels.

As mentioned previously, Industry 4.0 allows for a higher degree of customization and improved information sharing, among others. However, to cope with this, flexibility in the scheduling paradigm must be improved (Parente et al. 2020). Schedules should be able to modify and experiment with the schedule continuously as production takes place, testing the schedules in the virtual world presented in CPS (Parente et al., 2020). Rossit & Tohmé (2018) believe that dynamical scheduling where hardware can rearrange order execution to reduce stalls based on predefined tolerances set using inverse optimization could fill the need for flexibility in the schedules. In Figure 9 is an example presented on how such a scheduling process could look like in Industry 4.0.

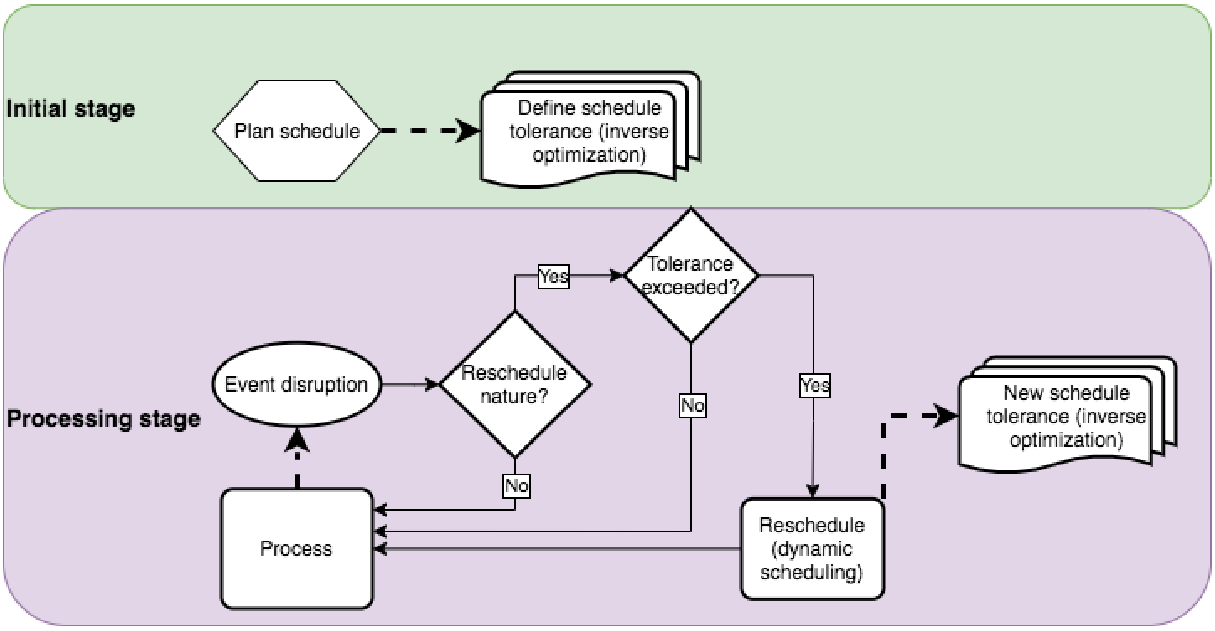

Figure 9. Smart scheduling scheme described by Rossit & Tohmé (2018, p. 113).

In the initial stage, the schedule is optimized with the current optimization model used, and tolerances that the production should not exceed are defined, *e.g.*, with inverse optimization. In the processing stage, when an event has disrupted the systems, it first decides if the nature of the disruption is an event that may need rescheduling. If yes, the system calculates if the tolerance is exceeded based on the tolerance levels calculated in the initial stage. If the tolerance is exceeded, the production system needs to be rescheduled with dynamic scheduling, and if not, the processing could continue (Rossit et al., 2019).

2.3 Industry 4.0 maturity

To implement new organizational strategies, one must first understand the current state (Holmström 2020). A maturity model aims to describe the anticipated, desired, or typical evolution path from one stage to another, identifying the key characteristics of its progression to provide a tool for companies to plan their development (Colli et al. 2019). It describes the evolution path of different maturity stages structured based on cumulative capabilities and a defined number of measurement categories. Additionally are maturity models an excellent tool to understand the current state of Industry 4.0 maturity in an organization, and based on this, create strategies towards full implementation (Mittal et al. 2018).

Today, several different maturity models adapted to Industry 4.0 exists, where Mittal et al. (2018) have reviewed several of them. The authors reviewed 15 maturity models and presented nine maturity models that delivered a well-defined assessment approach or/and improvement recommendation. Only two models took the context into the matter, supporting data collection with interviews and observations with key personnel to give tailored recommendations for improvement. One of them is the "acatech Industrie 4.0 Maturity Index" (Schuh et al. 2020b). The model presented by Schuh et al. (2020b) has been adopted by both organizations (Schuh et al. 2020a) and researchers (*e.g.* Gürdür et al. 2018; Colli et al. 2019). The maturity model fulfills all the basic principles for a maturity model identified by Pöppelbuß & Röglinger (2011); clarifying the application domain, defining the central constructs to the maturation process, defining maturity levels and addressed dimensions, and clarifying how the model is related to these constructs (Colli et al. 2019).

The “acatech Industrie 4.0 Maturity Index” model was first described in 2017, with an updated version in 2020 (Schuh et al. 2020b), and is based on a succession of maturity stages, to describe the transformation towards Industry 4.0. Each maturity stage could be identified in four dimensions: resources, information systems, organizational structure, and culture. Each dimension is connected to two key principles connected to several capabilities that should be improved to reach a higher maturity stage. The maturity model could be used to assess either specific functional areas or the entire organization by combining the results of the functional areas divided into development, production, logistics, services, and marketing & sales.

Further, the maturity stages defined by Schuh et al. (2020b) are presented, followed by the four dimensions and the key principles to assess.

2.3.1 Maturity stages

Schuh et al. (2020b) define six stages of maturity in the development of industry 4.0 in an organization (Table 1).

Table 1. Maturity stages according to the Acatech Industrie 4.0 Maturity Index (Schuh et al. 2020b)

Maturity stages	Computerization	Connectivity	Visibility	Transparency	Predictive capability	Adaptability
Capabilities	Isolated information systems and traditional organizational structure	Part of the information system is interconnected	Real-time data to support decision-making	Data is analyzed and used to understand root-causes, supporting decision-making	Scenario simulation to support counteracting decision	Autonomous decision-making and continuous adaption

The first stage is the computerization stage, where IT systems are isolated from each other. Computerization delivers benefits such as enabling cheap manufacturing and with some precision to make modern products. However, it is possible to find machines with no digital interface that operates manually. Terminals are often used to provide the missing link between business applications and machines. Organizations at this stage typically have a traditional organizational structure aiming at individual department's efficiency and management control of the innovation processes (Schuh et al., 2020b).

In the second stage, the connectivity stage, IT systems are connected and mirror the organizations’ core business process. Operational technology is partly used to detect or cause changes in industrial processes, however, are these not fully integrated. There is a widespread willingness to embrace changes and innovation within the company. However, traditional project management rules making it hard to make rapid adjustments within the company (Schuh et al., 2020b).

In the visibility stage, sensors are used to follow production in real-time to obtain information at any given moment and make decisions on real-time information. CPS is introduced into the production system in this stage, and systems are integrated to provide a comprehensive picture of the status quo. In this stage, the scheduler could with certainty give exact delivery dates to the customer of particular products. However, data is restricted to certain system boundaries and cannot flow through the entire company. In this stage, the organizational structure transforms, up- and downstream communication is used to collect innovation ideas and implement changes. The discussion climate is open, and employees feel comfortable sharing their ideas and knowledge with management and colleagues. In summary, the visibility stage is about understanding when something occurs (Schuh et al., 2020b).

Following the visibility stage, understanding why something occurs, the following stage, the transparency stage, is about understanding why something occurs. Technology is used to analyze the data retrieved from the processes into information. Big data is a commonly used term in this stage and is used to combine and process extensive heterogeneous data retrieved from the production to analyze it. Employees are comfortable using data for their decision-making process across every level of the company. Changes appear quickly because of agile management techniques' (Schuh et al. 2020b).

In the fifth stage, the company uses the CPS to predict the future through scenario analyses and builds on the groundwork in stages three and four. Management can make decisions to heavily reduce the number of unexpected events through counteracting measures at the right time. Due to the ability to anticipate future events, the decision-making structure needs to be changed to enable rapid decision-making in the entire organization (Schuh et al., 2020b).

In the last stage, decisions are made autonomously to cope with changing the business environment quickly. The goal is to have decision processes that choose the best possible result in the shortest timeframe, and corresponding measures are implemented automatically without human assistance. The degree of autonomous decision-making depends on the complexity of the problem and the cost-benefit ratio. However, management is always able to retrieve information about the decision process. Change is regarded as the norm in this stage, and dynamic collaboration across the value network is common to continuously review both existing skills and the development of core competencies (Schuh et al. 2020b).

2.3.2 Maturity dimensions

The dimensions are divided into four different maturity dimensions and together build up the organizational structure and connect to the maturity stages earlier described (Table 2) (Schuh et al. 2020b). Two key principles are connected to each of the dimensions. Depending on the extent that these capabilities are implemented determines in which maturity stage each of the dimensions reaches in the organization.

Table 2. Maturity dimensions according to the Acatech Industrie 4.0 Maturity Index (Schuh et al. 2020b)

Maturity dimensions	Resources	Information system	Organizational structure	Culture
Key principles	Digital capability and structured communication	Information processing and integration	Organic organization and dynamic collaboration	Willingness to change and social collaboration

In the “acatech Industrie 4.0 Maturity Index” the resource dimensions refer to tangible, physical resources possessed by the company *e.g.*, workforce, machinery, equipment, materials, and the final product. These need to be configured to support efficient and structured communication through the organisation, e.g., by collecting data from the physical processes and analyzing it correctly. In this dimension development of CPS is essential to reach a higher maturity stage. Education is essential to improve the workforce's digital competence (Schuh et al. 2020b).

The information system prepares, store, and process data into information to aid decision-making in the organization. However, traditionally decision-makers fail to use the information to support the decision-making and are more based on forecasts and assumptions. According to Schuh et al. (2020b), there are two reasons for this; (I) data is not sufficiently processed into information, and (II) information systems are isolated from each other.

In the organizational structure, both internal structure and external position in the value network should be investigated. The organizational structure defines a set of "rules" on how collaboration should be structured internally and externally. Further, it set the basis for the decision-making hierarchy in the organization. To adapt to changing business environment, should the organizational structure be organic where employees have a high degree of autonomy and can quickly adapt (Schuh et al. 2020b).

No matter how many new systems are introduced into the company, if not the employees are on-board and are willing to change their behavior, will the organization not reap the benefits from these new systems. Therefore, should the organization focus on the cultural dimension in the workplace. The focus should be to build up an open communication platform where employees of any work title can express themselves freely and share their information and knowledge with colleagues to build up a willingness and acceptance to change (Schuh et al. 2020b).

2.4 Conceptual framework

Based on the literature review and the chosen theories, a conceptual framework was developed to outline the potential of Industry 4.0 in scheduling at the sawmill industry (Figure 10). Further, was it divided into three fundamental steps, each of them answering different parts of the thesis purpose in terms of research questions:

- Understand the current state of information usage in the scheduling process and a
- Understand the current processes ability to fulfill Industry 4.0 scheduling
- Create a road forward for the organization to improve processes, allowing for Industry 4.0 scheduling

Figure 10. Conceptual framework for the study.

To understand the current use of information in the scheduling process, were theories surrounding planning and scheduling used. These were used to understand the traditional scheduling paradigm and assess both benefits and disadvantages with such an approach. To further dig into the problem and understand the organization's ability to support Industry 4.0 scheduling, were theories about Industry 4.0 maturity, process communication, process adaptability, and horizontal and vertical integration used. In the final step, and to answer the last research question, were theories such as Industry 4.0 and Scheduling 4.0 used to create a road forward.

3 Method

In this section is the methods used to answer the study's purpose described. The choice of methods collecting and analyzing the data is presented, followed by a description of quality assurance in the study.

3.1 Approach

This study has taken an abductive approach with an iterative process, aiming at outlining the potential of Industry 4.0 in sawmill scheduling. The abductive approach is a combination of the two more common approaches; deductive and inductive. In the inductive approach, the theoretical framework is developed after the data collection and emerges from it, and a hypothesis is developed to explain the phenomena. Rather than in the deductive approach, a hypothesis is developed with theories and then tested with the collected data (Bryman 2005, p.42-47). In an abductive approach are data collection stained by theoretical concepts, in this case, Industry 4.0. The theoretical framework is then further developed and fitted to the empirical findings to understand the phenomena studied and answer the research question.

3.2 Data collection

Based on the background presented in this study, it is evident that the phenomena of information in the scheduling are not fully understood (Berglund & Karltun 2007), which supports the usage of qualitative methods for data collection (Corbin & Strauss 2008). The qualitative method is an excellent tool to elaborate further into the topic of scheduling in the sawmill. Further, qualitative research has the advantage of providing complex textual descriptions of people's experiences of a given issue (Mack et al. 2005).

In this study, two qualitative methods were used to collect data; observations and interviews. Several data collection methods allow the researcher to triangulate the phenomena and obtain various types of data on the same problem (Patton 2002; Corbin & Strauss 2008). The observation served the purpose of understanding what information the scheduler used to schedule production. The corresponding interviews were then used to understand why and if there existed any limitations in the information.

Because of variations in the scheduler's work at the sawmill (Karltun & Berglund 2010a), data collection occurred over five days, every day of the workweek, to grasp the variations in the work. The first day was used to confirm the methods and configure the observation protocol and the decision probe. It was also evident in the early stage of the data collection that the methods chosen did not grasp the entire span of activities performed by the scheduler. Therefore, open interviews were incorporated into the observations, allowing the observer to ask questions about a complex matter or a specific thought process.

A total of 275 notes were taken in the protocol, together with six decision probes, each approximately five minutes long. The notes consist of observations that the observer noticed together with explanations handed by the scheduler and the open-ended questions. When the data from the observations had been summarized, was it sent to the scheduler to give the ability for the scheduler to change specific notes or explain further if something was unclear.

3.2.1 Participant observations

Participant observation is an excellent method to study schedulers in their natural environment (Crawford et al. 1999). Further, observation has the advantage of being direct and a good method to complement other data such as interviews (Robson 2011, p.316). Data from interviews could be skewed, *e.g.,* could the respondent answer how it is supposed to happen rather than how it really happens, then could observations be used to confirm the data (Mack et al. 2005, p.13). Additionally, Mack et al. (2005) believe that participant observations are outstanding in understanding the breadth and complexity of human experience in development projects. Observations could also unveil factors necessary for a thorough understanding of the research problem that was unknown when the study was designed, following the abductive reasoning in this study (*ibid.*).

Recording all accounts and observations is of great importance, not only for the data collection, but it also creates a deeper understanding of the phenomena and makes it easy for the researcher to go back through the notes when something is unclear and find new explanations (Bryman 2005). According to (Mack et al. 2005), it is essential to distinguish between reporting and describing what the observer sees and how the observer interprets it, something that a protocol could help with, giving a clear description of what type of data should be collected (Bryman 2005). In this study, recordings were made using a modified observation protocol developed by Crawford et al. (1999), see Appendix 1. Data collected consisted of tasks, time of the task, information source, a description of the information type (*e.g.,* production results, market sales, etc.). A column was also used for additional notes that could be of importance. If the scheduler performed a decision in the task, this was noted with a number for further investigation. Every decision was followed up with a decision probe, asking nine follow-up questions about the decision. Further explained in the following chapter.

To minimize the change of behavior, something troublesome in participant observations (Mack et al. 2005) was the person observed informed of the procedure and type of data supposed to be collected.

3.2.2 Interviews

Interviews can provide rich and illuminating material to the study (Robson 2011, p.279). Therefore, a decision probe was used consisting of semi-structured questions, suggested by Crawford et al. (1999) (see Appendix 2). Decision-making in scheduling is complex and often uses several sources of information (Crawford et al. 1999). The decision probe then served the purpose of attaining more profound knowledge about this complex process. Further, did the decision probe allowed the scheduler to give key insights on improvements in the information gathering, *e.g.* if the scheduler believed the information was insufficient. All the semi-structured interviews were first audio-taped and later transcribed.

Early in the data collection, it was clear that the scheduler made many decisions and that it would not be possible to follow up on each of them. Therefore, was the data collection reconfigured to only use the decision probe on decisions with complex information usage. It was also clear that the decision probe and the observation protocol did not cover all the things the scheduler wanted to share with the observer. Therefore, open-ended questions were used when the observer felt the need for additional data.

3.3 Analyzing the data

Qualitative analysis converts data into findings, however, there is no obvious method and depends on the study (Patton 2002). A big challenge in qualitative research is making sense in the large amount of data gathered, which is often hard to replicate (Patton 2002). A thematical analysis is a commonly used tool to comprehend the massive data set common in qualitative research (Cassell et al. 2018). Qualitative research is a method to identify and analyze patterns or themes in the dataset and a flexible method (Braun & Clarke 2006).

Thematic analysis is often divided into an inductive or a theoretical approach depending on how the theoretical framework drives the coding (Braun & Clarke 2006). Due to the purpose of investigating Industry 4.0 in sawmill scheduling was the theoretical approach used in this study. The theoretical approach is driven by the theoretical interest in the researched area, where the theoretical framework will guide data coding, as opposed to the inductive approach, where the dataset drives the thematization. Braun & Clarke (2006) believes that the theoretical approach gives a more detailed analysis of some aspects of the data to answer the research question. The thematic analysis was divided into six phases, similar to the one presented in Braun & Clarke (2006) (Table 3).

Table 3. Steps in the thematic analyze used in this study (Braun & Clarke (2006)

Phase	Description of the process
Familiarizing with the data	Transcribing data, reading and re-reading the data, noting down initial codes
Generating initial codes	Coding interesting features of the data in a systematic fashion across the entire data set, sort data relevant to each code
Searching for themes	Sorting codes into potential themes, gathering all data relevant to each potential theme
Reviewing themes	Checking if the themes work concerning the coded extracts and the entire data set, generating a thematic “map” of the analysis
Defining and naming themes	Refine the specifics of each theme and the overall story the analysis tells, generating clear definitions and names for each theme
Producing the report	Selection of vivid, compelling extract examples, the final analysis of selected extracts, relating back of the analysis to the research question and theories.

The goal of the analysis was to match the data set into themes that could relate to the theoretical findings of industry 4.0. In the initial stage, were the author familiarized with the dataset. Since the same person conducted data collection and analysis, was this stage already started in the collection phase. Processing data in an early stage already at the data collection phase when it is “fresh” also minimizes the risk of losing important notes (Mack et al. 2005). Key ideas about initial codes were noted for further investigation in the latter phases. Since the interviews were collected through audio recording, there was also a need to transcribe these interviews. All the data collection was collected in the author's and respondent’s native languages. This language was held through the entire analysis and translated in the last phase to minimize inaccurate interpretation.

In the second phase, the actual coding of the data began. All the notes were grouped based on similarities. Interesting features were coded that could help to understand the phenomena and answer the research questions. Notes were taken about the codes' source to keep the context of the codes (Bryman 2005).

The third phase was each code grouped into four categories: processes, input, output, and disturbances. The "processes" were defined as the manufacturing processes and departments that the PP interacted with. The "input" was defined as the information that the scheduler attained by the processes, "output" was defined as the information sent out to the processes. Codes that could be correlated to some noticed disturbance by the observer were categorized into the "Disturbance" category.

In the fourth phase, a virtual information map from the scheduler's point of view was created based on the processes category. Input and output from the scheduler were linked to each of the processes, along with disturbances noticed. Codes within the category were further grouped to create larger themes. This phase is an essential step in the analysis since it allows the authors to go back and find new codes, themes, and connections. It also allows the author to look at the dataset with "new" eyes (Braun & Clarke 2006).

When no new themes in the dataset could be found, it was considered saturated, and the fifth phase of the analysis began to define the themes found in the dataset. The data within the themes were analyzed to refine the themes further to find the essence of each theme. When a clear definition of each of the themes had been established, producing the report began. As noted by several different researchers (e.g. Patton 2002; Bryman 2005; Braun & Clarke 2006), it is important to demonstrate how the analysis has been conducted to support the themes and the underlying dataset to give substance to the report, which was carried out in the last phase.

3.3.1 Maturity assessment

As mentioned earlier, were the dataset coded and thematized into four different categories. The processes were then assessed for their ability to support Industry 4.0 scheduling using the "Acatech Industrie 4.0 maturity index" (Schuh et al. 2020b). However, were the model slightly changed to fit the purpose of the study. Therefore was similar changes made as Colli et al. (2019) presented:

- An additional stage was implemented called "none" to evaluate processes that had no digital information sharing with the scheduler
- Further, where the "connectivity", "visibility", and "transparency" grouped to a "transparent" stage
- A final stage was implemented called "integrated"

Further where the matrix of the dimensions slightly changed to fit the context of production scheduling. Parente et al. (2020) noted that some of the technologies incorporated in Industry 4.0 to a higher degree affect production planning. Therefore, were only two dimensions chosen to investigate further. These were "resources" and "information systems" from now on, renamed to “Technology” and “Connectivity”. These dimensions were then connected to a set of attributes based on the theoretical framework:

- Technology: Digital capability and adaptability
- Connectivity: Horizontal and vertical integration

Through IoT are relevant data acquired from the activities and processed and analyzed using CPS systems to support decision making (Parente et al. 2020). Parente et al. (2020) note the importance of separating the ability to collect and process data and the ability to adapt to the processed and analyzed data. Therefore, were two attributes defined in the dimension of technology. The first one is the digital capability, which was defined as the activity’s ability to collect relevant data and process it into information satisfactorily communicated to the production planner. Further, were the second attribute concerning the activity’s adaptability to changes.

If the technology dimensions concern the internal use of information in the process to support decision-making, does the connectivity dimension measure how good the process is to allow for adaptability in other processes in the supply chain. According to (Parente et al. 2020), will Industry 4.0 allow for horizontal and vertical integrated production systems that communicate by IoT. Each activity can adapt in real-time as changes or disruption occurs in the supply chain. Therefore, two abilities were defined in the connectivity dimensions. The first one concerning the activity’s degree of integration with other activities in the supply chain. The second attribute concerns the horizontal integration with the scheduler.

Fel! Hittar inte referenskälla. was used to evaluate the process's ability to support scheduling in Industry 4.0.

Table 4. Industry 4.0 maturity stages (Colli et al. 2019; Schuh et al. 2020b)

Stage	Technology	Connectivity
Integrated	The process autonomously adapts to changes in the supply chain with no human intervention	The process IT system is integrated with the entire supply chain, allowing for fast communication and optimization of the entire supply chain
Autonomous	The process can autonomously adapt according to information received after an analytical process	The process IT system is fully integrated with the other processes in the internal supply chain, allowing for optimization of the internal supply chain
Aware	Some tools make it possible to process and analyze the data from the process and are sufficiently communicated to the user to support decision making	The process IT system is integrated with some of the processes on sight, allowing for decision-making in integrated processes
Transparent	There are interfaces at place, making data easily accessible and visualized	The process IT system is not integrated. However, is the process able to communicate information to other processes
Basic	Digital data are generated and collected	The process IT system is segregated, and information is shared manually with other processes.
None	Data is collected manually	There exists no IT system allowing for digital communication

Notice that each of the attributes earlier described is incorporated into each of the dimensions. To achieve a higher rank should all of the attributes be fulfilled in the corresponding dimension. A rank of the abilities is presented in Appendix 3 together with an example of the evaluation. The results were then grouped in Table 4 for the individual processes.

3.4 Methods delimitations

Due to the complexity of the sawmill scheduling, some delimitations are needed. Data collection has only focused on the sources directly linked to the scheduler and information obtained from these. How these sources by themselves are attaining this type of information has not been studied.

Further, choices have been made about the maturity dimensions examined during the study. The dimensions of organization and culture have been neglected in this study. According to Schuh et al. (2020b), the “acatech Industrie 4.0 Maturity Index” be adapted to the context. Different processes, *e.g.*, scheduling, could be more affected by specific dimensions. Choosing only to investigate the technology and connectivity dimensions was based on Parente et al. (2020), that scheduling in Industry 4.0 will be affected by increased information sharing and the ability to adapt to disturbances.

3.5 Quality assurance

Validity, reliability, and generalizability are central concepts when assuring the trustworthiness of a study (Robson 2011, p.77). However, the trustworthiness in CASE studies is often up to debate (Robson 2011, p. 154). One of the problems is the study's replicability, where other researchers cannot replicate the study because identical circumstances will probably not occur at the time of replication. Maxwell (1992) distinct between internal generalizability within the settings and external generalizability beyond the settings. External generalizability is not often considered in qualitative design because it is often used to explain and study the phenomena within the settings. However, internal generalizability must be considered when conducting a qualitative design. It is important not to exclude data and respondents that could threaten or disturb the results. Therefore, where the scheduler observed chosen together with the management.

Validity is a measurement of how accurate, correct, or true the study results are (Robson 2011, p. 156). Maxwell (1996) described that there are mainly three types that could threaten the validity of the study:

- The first one is the *description,* where it is crucial to describe in a proper way what the observer has seen or heard, *e.g.,* with audio-taping and qualitative notes.
- Secondly, is an *interpretation* where the author should check the appropriateness of the framework used.
- Lastly, Maxwell describes the threat of not *considering other explanations*. This could be countered by actively seeking data that are not consonant with the theory.

In this study, two different methods were used, interviews and observations. By using several different methods, *i.e.,* data triangulation, Robson (2011) believes that it could counter the threats to validity in the study.

3.6 Ethical considerations

Research ethics consider mainly the interaction between researchers and the people they study (Mack et al. 2005, p.8), and should be taken into account in every research activity (Robson 2011). Several different ethical issues must be considered when conducting a study. Mack *et al* (2005, p.9) conceptualize three core principles based on The Belmont Report, that is universally accepted:

- The first one is *respect for persons*, where the researcher should strive for the autonomy of research participants and protect people from exploitation when autonomy is diminished.
- Minimizing the risks associated with the research and maximizing the benefits for the research participants is essential, which is the second core principle, also called *beneficence*.
- The last core principle is *justice*, concerning the risks and benefits resulting from the research and that it should be fairly distributed to the participants in the research.

Informed consent is one of the main tools to achieve the principle of respect for persons. It should, in general, be used in every data collection activity that requires more than casual interaction (Mack et al. 2005, p.10). Both when conducting interviews and observations, the importance of informed consent is high. Therefore, before data collection, the scheduler signed a consent form, which covered the purpose of the research and what was expected by them. It also contained information about how confidentiality was protected and illustrated that participation is voluntary and that withdrawal is possible at any time with no repercussions.

To achieve the other two core principles, beneficence and justice, should the participant could be able to read through the transcript and give comments about the collected data after the interview and observations. Reading through and giving comments is a meaningful method since it decreases the risk of misunderstanding. Further, it allowed the participants to further reprocess the information and give meaningful benefits in terms of deeper knowledge about the subject.

4 Empirical background

In this section is a description of a typical sawmill industry processes presented followed by a presentation of the CASE-company

4.1 Sawmill

The primary method to disjoint logs into boards and planks is the so-called block-sawing technique, where the logs' sides are reduced into blocks. These blocks are then disjointed from each other by cutting blades. The format of the block and position of the sawing blades are decided by the cutting pattern (CP). There are nearly endless possibilities to configure the CP, but two main factors are the dimension of the log and how the demand for different assortments are. Further, the logs could be disjointed in two ways, either batch-wise, where the sawing machine uses a fixed tuning for each of the logs in the batch. Using the fixed tuning approach, sorting of logs is needed regarding dimensions, quality, and more. The other approach is to have a continuous flow of logs into the sawmill and using variable tuning, where the sawing machine is able to vary between several CPs. However, one should note that some degree of variable tuning is often used in fixed tuning, *e.g.*, could the centerpieces in the log be fixed and the sawing machine only varies the outer blades. **Fel! Hittar inte referenskälla.** describes a typical material flow from a log to a finished board or plank.

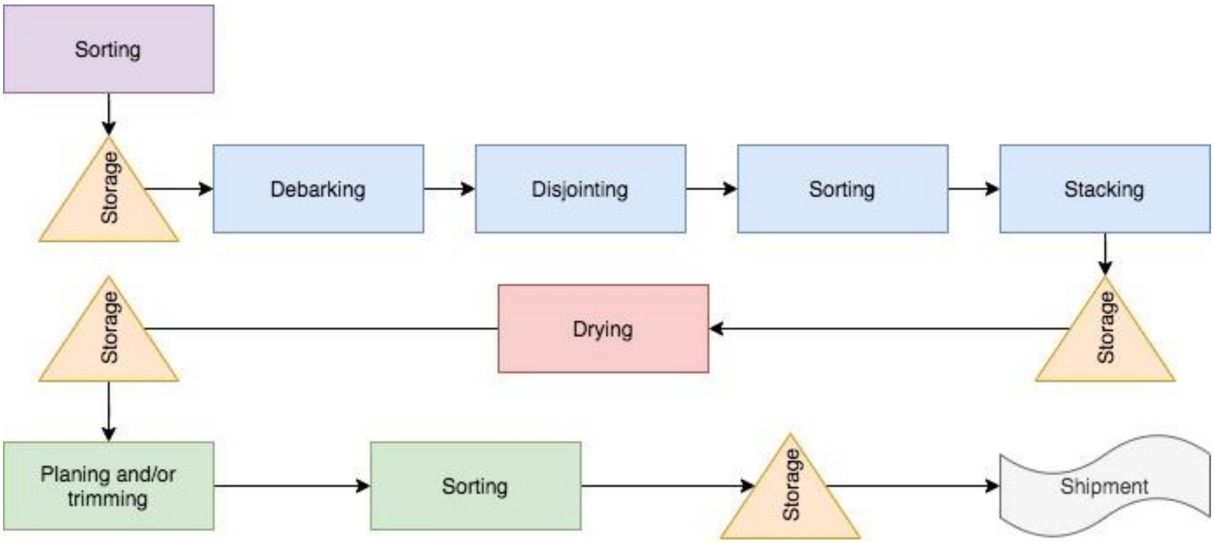

Figure 11. Common processes in a modern sawmill operation.

Prior to the sawmill, sorting the logs is often needed, either by characteristics. As earlier noticed, do sawmill with fixed tuning often sort logs to a higher degree than in the variable tuning. When the logs enter the actual sawmill, are they first debarked and after that disjointed into lumber. The unseasoned lumber is then sorted and stacked into raw material packages based on characteristics *e.g.* dimensions and quality. Using forklifts are the raw material packages transported to the storage or directly to the drying facilities. There are mainly two types of drying facilities used to dry the lumber, either chamber kilns or progressive kilns. In the chamber kilns are similar raw material packages dried batch-wise instead of the progressive kilns where the lumber is dried continuously.

The dried lumber is then transported to another storage facility or directly to a finalization facility, commonly a planning or final trimming facility. In these facilities, the lumber is cut to the right length, and additional value-adding activities may occur, *e.g.*, planning. The lumber is then stacked and transported to the final goods inventory.

4.2 VIDA

VIDA is today one of the largest producers of sawn timber in Sweden (Skogsindustrierna 2019) and recently became part of the Canfor group (Canfor 2019). They have approximately 1 250 employees spread out over 22 production facilities, where 12 of them are sawmills, located mainly in the county of Småland, Västra Götaland, and Skåne. They purchase around five million cubic meters of solid lumber under bark annually and produce approximately 2,385 million cubic meters of sawn wood products, primarily for wood construction. About 75 % of the sawn wood products are exported, mainly to Europe, USA, Australia, Africa, and Asia (VIDA n.d).

4.2.1 VIDA Alvesta AB

The sawmill in Alvesta produces around 186 000 cubic meters of sawn wood products, with a wood consumption of 410 000 cubic meters of solid wood under the bark (VIDA n.d). The sawmill is seated in the center of Småland, where the head office of VIDA AB also is located.

The sawmill saws small-dimension timber with standard lengths of 275 centimeters for pine and 305 centimeters for spruce. The logs are disjointed with block-sawing using variable tuning. After the sawing machines, are the unseasoned lumber measured and sorted into 50 different bins depending on dimensions and quality.

Both chamber and progressive kilns are used to dry the boards and planks at sight. All the lumber is finished in one of the two planing mills. The planing mill possess a great set of different tuning settings and vary between customers. A final sorting of the products is carried out in the facility, where planing mill number 1 could sort the lumber into three different bins. An option is also available to sort out lumber with poor quality prior to the planing instruments. In planing facility number 2 is the lumber sorted into bins, however, were there no possibility to sort out after the planing instruments. The planed boards and planks are then stored at the warehouse for shipment and transported out to customers by train or truck. At the site are two heating plants built which use the waste from the sawmill, such as bark and splints for heating. The municipality for district heating owns one plant, and VIDA Alvesta AB owns one to heat the drying kilns.

57 personnel are employed directly linked to the sawmill, drying, and planing facilities. However, as earlier mentioned, the main office for VIDA AB is seated on the same sight. Some of the employees at the sawmill sit together with the employees of the parent company VIDA AB. In addition to the operators, repairers, and truck drivers, the crew consisted of one CEO, one sawmill manager, a planing mill manager, one responsible for the drying facility, one main repairman, one responsible for the heating plant, two shipping logistics, and two production schedulers. The scheduler observed during the study, was responsible for scheduling the sawmill and the smaller planing mill (number 2). Additionally, did the two schedulers cooperate

when scheduling the drying facility. Further, will the scheduler observed be shortened PS (Production scheduler).

5 Result and analysis

In this section is the results from the thematic analysis presented. It starts with a description of the current use of information in the scheduling at the sawmill, continuing with assessing the current Industry 4.0 maturity level in each of the processes supporting the scheduling. Finally, is a roadmap towards Industry 4.0 operational decision making presented

5.1 Processes

The thematic analysis resulted in ten noted processes that the scheduler was in direct contact with and used to schedule the production at the site (Table 5). Important to note is distinguishing between processes and activities. A process is usually defined as a series of activities to achieve a certain result. However, depending on the scope of the study, processes could be defined in different ways. In this study, the author defined a process as a series of activities achieving a particular result. The purpose of the process is presented in Table 5 and additional examples of activities.

Table 5. Processes that the scheduler used to schedule production. With the corresponding purpose and activities

Process	**Purpose**	***e.g.*, activity**
Raw material supply	Deliver logs to the sawmill	Delivery of logs, transport the logs via truck
Log yard	Storing the logs before the sawmill	Measuring of truckloads, store the logs, transport the logs
Disjointing	Convert the logs into unseasoned boards and planks	Transportation of logs, debarking, profiling, disjointing, scheduling
Sorting	Sort unseasoned timber products into bins	The measure of unseasoned lumber, trimming unseasoned lumber
Stacking	Stack unseasoned timber products into raw material packages	Stack lumber, transportation of raw material packages
Before kilns inventory	Store unseasoned raw material packages	Transportation of raw material packages
Drying	Dry unseasoned raw material packages	Transportation of raw material packages, drying of raw material packages, scheduling
After kilns inventory	Store dried raw material packages	Transportation of raw material packages
Planing	Plane the dried timber products	Transportation of raw material packages, planing, stacking, scheduling
Finished goods inventory	Ship out the finished goods	Transportation of finished goods, shipment of finished goods
Sales & customer service	Sell finished goods	Receive customer requests,

As this study focuses on scheduling the sawmill operation, one could note that typical scheduling activities occur in three of the presented processes; disjointing, drying, and planing, explained further in the next chapter. However, each of the processes presented was used to schedule and meet customer demand.

5.2 Planning and scheduling in the operation

The use of information from the different processes is summarized in Figure 12, with the corresponding information presented in Table 6 to answer the first research question:

RQ1: What information is used in the operational decision-making to schedule production?

As earlier described was 11 different processes distinguished that the PS had direct contact with to schedule production. In Figure 12 is this connection to the scheduler illustrated, followed with a description of what type of information that was communicated in Table 6. Each information in Table 6 could be tracked back to a process and a communication line in Figure 2 by its numbers.

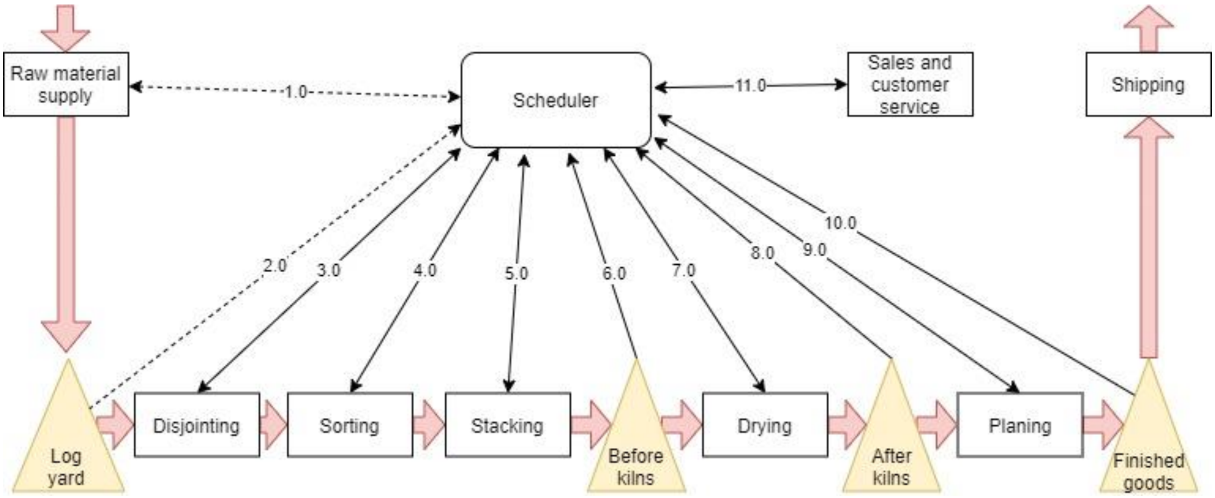

Figure 12. Information flow between the scheduler and the processes in the sawmill operation. The communication between the scheduler and the facility and staff is divided into 11 different processes. The flow of information is illustrated as solid or dashed lines, where the former illustrates if the information was integrated with the scheduling process. Additionally, does the arrows illustrate if information was obtained as input to the scheduler or as output from the scheduler to the process. Each information line is tagged with a number, connecting to table 6 presenting the type of information observed.

Table 6. The information obtained and sent by the scheduler is divided into input and output of information. Input represents the information used by the scheduler to schedule production, whereas, output is information sent out to the processes. Each type of information is separated with a number, were the first number tells from which processes it connects to. The input and output of information is and its connection to the scheduler is presented in Figure 12

	Process	**Input**	**Output**
1.0	Raw material logistics	Shipment deliveries (1.1) Quantity by train (1.2)	Quantity in store (1.3) Change of raw material (1.4)
2.0	Log yard	Quantity in store (2.1)	
3.0	Disjointing	Product dimension output (3.1) Product report (3.2)	Product-mix adjustment (3.3) Info adjustments (3.4)
4.0	Sorting	Product output (4.1) Quality (4.2) Product report (4.3)	Product-mix adjustments (4.4) Info adjustments (4.5)
5.0	Stacking	Bin information (5.1) Product report (5.2)	Bin adjustments (5.3) Info adjustments (5.4)
6.0	Before kilns inventory	Quantity of packages (6.1)	Reservation of packages (6.2)
7.0	Drying kilns	Processing time (7.1) Quantity in the process (7.3)	Sequencing of packages (7.2)
8.0	After kilns inventory	Quantity of packages (8.1) Package position (8.2)	Reservation of packages (8.3)
9.0	Planing	Production report (9.1) Work order schedule (9.2) End time (9.4) Processing time (9.7) Quality (9.8)	Adjustment of schedule (9.5) Work orders (9.6)
10.0	Finished goods inventory	Package position (10.1)	
11.0	Sales & customer service	Order request (11.1) Order priority (11.2) Shipment dates (11.3) Orders received (11.7) Order instructions (11.8) Delivery date (11.9)	Order acceptance (11.4) Order clarification (11.5) Production dates (11.6)

Communication in Figure 12 is visualized as integrated (solid line) or not integrated (dashed line). Further is the information flow illustrated as arrows, representing input of information to the PS or output of information out to the facilities. The type of information is visualized in Table 6, were information is divided into “input” and “output” to distinguish the difference between information used to schedule and information shared to the processes. In the following sub-chapters will the scheduling of the processes be presented. The chapters are divided into three main production areas at the site; the sawmill, the drying kilns, and the planing mill. The information used is tagged with a number connected to Figure 12 and Table 6, were the first number states the origin of the information.

5.2.1 Sawmill scheduling

Scheduling often faces different challenges depending on whether it is in continuous or discrete manufacturing (Olhager 2013). However, it is common with some overlapping (Kreipl & Pinedo 2004). Due to variable tuning in the sawmill with a continuous stream of mixed log dimensions processed continuously, the PS faces challenges typical to continuous manufacturing. Nonetheless, does the manufacturing have parts of the production that could be seen as discrete, concerning the event when raw material species changes.

Regarding the scheduling of the sawmill operation, this mainly concerned small product mix changes, to adapt the sawmill to the forecasted demand. The changes were based on a combination of orders received (11.7) and the PS's experience of products with high demand. When changing the products produced, was a percentual increase of the price often changed by the PS (3.3). The product mix in the sawmill could also be manipulated in other ways *e.g.* with fixed prices changes. However, did the PS believe that the percentual change was the easiest to use when only smaller changes were needed, it also gave the possibility to go back to the former state easier. The PS first changed the disjointing process (3.3), and additional changes were also performed in the sorting and stacking facility to let the processes sort out the new products added (4.4, 5.3). The sorting and stacking facility was integrated, meaning that the stacking facility recognized changes in the sorting facility. However, did the PS change the settings in the bins to make sure that the bins containing the removed products were emptied to make room for the new product (5.3).

Since the PS was unaware beforehand of the specific volumes produced in each of the assortments and how much that would be sorted out or downgraded due to inadequate quality, was the inventory before kilns controlled (6.1) before changes were realized. If not, was the restriction slightly changed in the disjointing process (3.3). To make sure that the bins containing the specific products would be full when the restriction was met, similar control was carried out in the stacking process (5.1). When the PS was satisfied with the number of products produced in the specific assortment, the product was removed or decreased from the product list (3.3). The changes were communicated to the operators (3.4, 4,5, 5.4).

Besides the minor changes in product mix, was it one occasion when more extensive changes in the sawmill occurred due to changeover between timber species in production. This was mainly based on the quantity of pine logs in the timber yard (2.1). The PS then created a new product list and implemented it to each of the processes in the sawmill (3.3, 4.4, 5.3). The PS wanted to process as much as possible of the pine logs to minimize setup time in the sawmill. Therefore, was the time of the date when changeover would occur communicated to the logistics department to focus on delivering pine logs to the timber yard (1.4). During the week when pine was sawn, constant communication with the logistics department was held about quantity in store of pine (1.3) and forecasted time of date for changeover back to spruce (1.4).

Additionally, was the PS able to gather information about historic production capacity (3.2, 4.3, 5.2) summarized in a production report and product dimension output (3.1) from the disjointing process visualized as a percentage of total production in each of the product dimensions. Additional information about output in each of the timber grades for each product dimension (4.1), *i.e.*, the assortments, could then be visualized in the sorting process. The unseasoned lumber was graded and sorted with the help of laser scanners. However, these were not fully trusted, and additional operational quality control was sometimes needed (4.2). The operational quality check of the unseasoned lumber was not the PS's primary area of responsibility. However, due to the knowledge about the effect of the defects further down in the supply chain, did the PS control this together with the operators and production manager to minimize disturbances in the following processes.

5.2.2 Drying scheduling

There were a mixture of chamber and progressive kilns at sight. The two schedulers together scheduled the sequencing of the kilns in a shared excel-document. The sequencing was based on two types of principles depending on the situation. The first principle, and the prioritized one, was to MAKE-TO-ORDER (9.2) based on the planing mill schedule. Due to the risk of damages occurring when unseasoned lumber is stored undried, was the second principle to MAKE-TO-STOCK to reduce the quantity in-store before kilns. Further, was the PS able to gather information on the current forecasted processing time in all of the drying kilns (7.1)

5.2.3 Planing mill scheduling

Manufacturing in the planing mill facility consisted of mainly MAKE-TO-ORDER and discrete manufacturing. The PS scheduled the planing mill operation in two phases, similar to the one presented by Olhager (2013) for discrete manufacturing. In the initial phase, were the accepted order booked to the raw material expected to be used, together with a suspected time of use (6.2, 8.3). This procedure gave insights if there was any lack of raw material packages. PS also noted down the order and specifications in a separate excel-document. In this excel-document were the orders roughly scheduled. The document was believed to give a more transparent overview of the accepted orders and allowed the scheduler to group orders with similarities. Additional information, such as the number of raw-material packages to be used, was added to the document.

In the second planning phase, approximately one or two weeks before the PS schedule to initiate the work order, was the customer order converted into a work order and scheduled for production. The customer order could be visualized in a customer order database (11.8) and was easily converted into a work order. The PS added information about the expected processing time (9.1) for the work order and raw material packages placement (8.2) to ease the workload for the truck driver. The PS had recently developed an excel-document telling the specific placement of different assortments in the warehouse.

The PS scheduled production for about one to two weeks and the sequencing of work orders could be visualized in a GANT-chart (9.2), telling the expected processing time for each of the work orders. The Gant-chart was autonomously updated when the work order was finished, setting the actual processing time for the work order. There were mainly two events that the PS looked out for; (I) longer processing time than forecasted, and (II) lack of resources. The PS, therefore, continuously controlled the actual processing time in the planing mill process (9.7) by comparing the current number of packages produced and the ordered amount. Additionally, the PS controlled resource availability in the inventory after kilns (8.1) and the drying kilns (7.3). If the work order was booked to assortments coming out to from the drying kilns, was expected processing time controlled to ensure that they would be available in time. The actual final decision of the work order initiation occurred when the work orders were delivered to the planing mill operators (9.6), which occurred so that they had work orders to fill two separate shifts (day and evening shift). Until then, was the PS able to adapt the sequencing of work orders if disturbances would occur.

Additional to the tactical scheduling of the operations was PS involved in the operational planning concerning the availability to promise, which is one of the key aspects in operational planning (Olhager 2013). It could both concern new customer orders or changes in current ones already accepted. It initiated with a contact from the sales personnel if the customer order could be fulfilled in the requested time (11.1). The PS could rather quickly say if they could accept the order or not. The PS controlled the rough schedule of the accepted order (9.2) in the excel-document, and could together with information of raw material packages in-store (6.1, 7.3, 8.1), tell if they could accept the order or not (11.4). If accepted, did the sales personnel confirm the order with the customer. After confirmation, the PS attained a notification from the system and sales personnel (11.7) of the new customer order added to the database.

5.2.4 Key gaps in the information

During the observation, key gaps in the information were noted to give specific improvements measures to improve the scheduling towards Industry 4.0 (Colli et al. 2019). These gaps could both be based on the PP insights or observed disturbances by the observer.

Lacking prognosis of short-term output

To give reasonable estimations of available to promise in the operational planning, does the PS need a good prognosis of future output (Kreipl & Pinedo 2004). PS mentions that in the longer time perspective are the product output from the sawmill outlet stable. However, it could vary in the shorter time period depending on raw material characteristics, *e.g.,* log dimensions and quality, information that the PS could not attain. This effect especially disturbed the scheduling of the larger dimensions in the planing mill since there are no possibilities to force out large dimensions from smaller logs. The variability in the greater dimensions in the shorter time horizon, approximately one month, could mean a need for rescheduling in the planing mill due to the lack of raw material packages in proper dimensions.

Feedback about quality

PS believes that it is hard to assess and feedback the quality to the sawmill, were defects often is noticed in the planing mill. Control measures are in place that measure the quality of each product before trimming. However, if something is missed by the control measures or defects occur after the trimming, could these defects cause disturbances in the following processes. To complicate the matter, could these defects occur in specific time periods or on specific assortments, making it hard to track back to the actual event due to long lead time between quality control in the sorting process and quality control in the planing mill. Defects in the raw material packages could mean lower output of desired product and extended processing time in following processes. For example, could wrongly stacked packages disturb the intake in the planing mill and extend the processing time.

Feedback about the processing time for individual work orders

Allowing processes to feedback production data is important in tactical and operational planning (Kreipl & Pinedo 2004). As mentioned earlier, the PS assessed the processing time for each work order based on earlier experience about similar work orders. However, the work orders often vary between customers due to the discrete manufacturing with a high degree of customization. The actual processing time could be hard to assess because of the varying effects of different factors. Further, was the processing time set by the PS used as a basis for the GANT-chart which visualized the initiation time for each of the work orders scheduled. The work order currently under work where not updated in real-time, though it was only updated when the work order had been finalized. Due to the lacking feedback of processing time, the PS was forced to manually control the work order's expected finalization and disturbed the PS ability to give exact delivery dates, often forcing the PS to prolong the delivery date considering sudden disturbances.

Customer order request in "limbo"

In the operational planning of the facility were the PS involved in the availability to promise to customer. The PS believed that there was a state of "limbo" between acceptance by PS and confirmation by the customer. The state of "limbo" hindered the PS ability to accept other incoming requests if the earlier order accepted had not been confirmed yet. The PS needed to have all the different orders not yet confirmed by the customer in mind when accepting new orders to make sure that resources were available. Additionally, the PS often needed to communicate back and forth between sales personnel to investigate the current state of confirmation of the order.

Follow-up on changes in the disjointing process

Today there exists no ability to follow up on the actual results from the disjointing process. The disjointing process only tracks the output in each product dimension, whereas the sorting facility tracks the output in each assortment considering; dimensions, length, and quality. Due to the lack of integration between the processes, the scheduler cannot easily follow up on changes carried out in the disjointing process and their effect on the output of different assortments

Lacking simulation of changes

One of the problems in controlling the disjointing process is the substitutional effect. Different product dimensions are not fully substitutional, *e.g.,* will an increase in the product demand, not interchangeably mean that the unwanted product will decrease. Therefore, is often several changes needed to attain the correct quantity in each of the product dimensions. The PS cannot simulate the changes made, however, due to experience, the PS often knows the direct substitution of different product dimensions. Additionally, is the output from the sawmill regularly controlled, and additional changes are made accordingly.

5.3 Maturity assessment of the processes

To understand the current state of Industry 4.0 and the processes' ability to support operational decision-making, have each of the processes been evaluated based on the framework earlier presented in chapter 3.3.1. The current level of maturity was assessed in two dimensions (Colli et al. 2019) with the corresponding ability to support operational decision making in Industry 4.0 (Parente et al. 2020):

- Technology: Digital capability and adaptability
- Connectivity: Horizontal and vertical integration

Therefore, will this chapter present the results collected to answer the second research question:

RQ2: To what degree do the processes in the facility assist in fulfilling the operational decision-making, according to Industry 4.0?

The current state of information usage earlier presented and key gaps in the information form the basis of this evaluation, the result could be viewed in Figure 13.

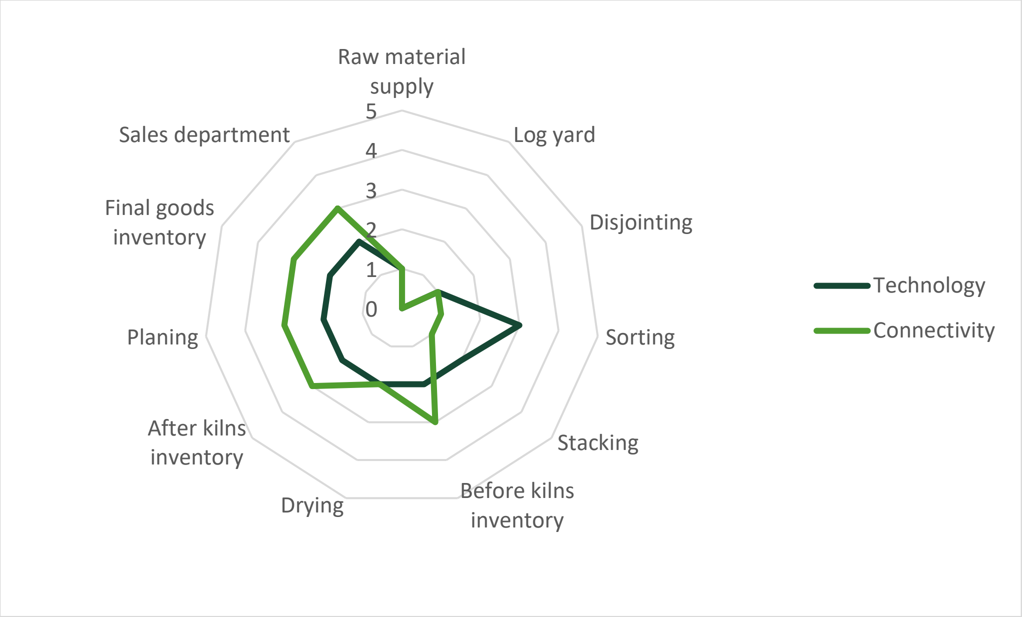

Figure 13. Maturity assessment of the processes used in operational scheduling at the sawmill. Divided into six stages: 0=None, 1=Basic, 2=Transparent, 3=Aware, 4=Autonomous, 5=Integrated.

At first glance on Figure 13, one could observe that processes closer to the final customer achieves a higher rank in the two dimensions. In contrast, processes surrounding the sawmill operation achieve a lower rank. Summing all the processes score was the entire sawmill operation concerned as transparent in the technology dimension and transparent in the connectivity dimension in fulfilling industry 4.0 scheduling. However, by looking at each process separately, one could distinguish where improvements are needed. Therefore, will each of the process's maturity rank be described and the premise behind the ranking.

1. *Raw material supply*

The raw material supply process ranked as “basic” in the technology dimension. The digital capability was lacking due to inadequate information about the characteristic of the logs, which hindered the scheduler's ability to forecast and simulate short-term output.

The transparent dimension is ranked as “basic”. Information was shared manually through e-mail conversations, allowing for only local communication between the scheduler and the logistics department.

2. *Log yard*

The log yard ranked as “none” in the technology dimension. No entities were collecting digital data at the log yard, and information was gathered visually. Similar to the raw material supply process, information about raw material characteristics were lacking, hindering the ability to forecast short-term output.

The log yard was not connected to any IT system, and digital communication between PS and other processes could not be observed. It was therefore ranked as “None” in the connectivity dimension

3. *Disjointing process*

The disjointing process ranked as “basic” in the technology dimension. The digital capability was lacking the ability to analyze and simulate changes. Additionally, did the process lack the ability to visualize the choice of cutting pattern for individual logs historically.

Further, was the process ranked as “basic” in the connectivity dimension. Horizontal integration between the PP and the disjointing process was in place. However, did the process lack vertical integration with other processes that implicated the follow-up on changes.

4. *Sorting process*

In the technology dimension, was the sorting process ranked as “aware”. Essential information about output in different assortments could be gathered, and the analytical process behind the decision on the grading and choice of trimming length was sufficiently visualized. However, was there no presence of autonomous adaptability to changes in the internal supply chain, and adjustments were carried out manually.

As earlier mentioned was the sorting process integrated vertically with the stacking process. However, it ranked as “basic” in the connectivity dimension due to the inability to communicate with the disjointing process.

5. *Stacking process*

The stacking process was evaluated as “transparent” in the technology dimension. The digital capability was in place, however, the process could not autonomously adapt to changes, and no presence of analytical capabilities was observed.

As earlier noticed, part of the sorting and stacking process was vertically integrated, and horizontal integration was in place with the PS. However, the process ranked as “basic” due to the inability to communicate with the disjointing process and processes further down in the production chain.

6. *Before kilns inventory*

The before kilns inventory was evaluated as “transparent” in the technology dimension, due to segregated systems and lacking knowledge of specific package placement. The PS could obtain placement of different assortments in an excel-document. However, were their no ability to track specific packages placement in the inventory. Further, was information about the quantity in different assortments retrieved in a separate program.

The before kilns inventory was evaluated as “aware” in the connectivity dimension since it supported decisions in other integrated processes. All the inventories after the sawmill were integrated, and an overlook over quantity in each assortment was easily visualized. The inventories were also integrated with the scheduling system, which enabled the PS to book raw-material from the inventory to customer orders supporting decisions about changes in the sawmill product mix.

7. *Drying process*

The drying process was evaluated as “transparent” in the technology dimension. The PS could obtain sufficient information of current processing time in different kilns and supported decision-making, *e.g.,* if there was a need to reschedule. Further, was the information keenly visualized in a virtual setting over the kilns. However, were there no possibility to analyze and forecast processing time for different assortments before the drying manager had created the drying recipe.

As for the connectivity dimension, was the drying process evaluated as “transparent”. The process was able to communicate with the inventory IT system vertically and horizontally with the PS. However, lacked the process the ability to sufficiently send out information about changes in processing time to other processes.

8. *After kilns inventory*

The after kilns inventory was similar to the before kilns inventory, ranked as “transparent” in the technology dimension. Information about assortment placement was visualized, however, not the placement for specific packages. Further, the used systems were segregated, and information about the quantity in specific assortments was obtained in a separate system.

As earlier mentioned, the inventory IT system integrated with all the inventories after the sawmill, obtaining an “aware” rank in the connectivity dimension. The process was integrated with the other inventories after the sawmill and the scheduling program.

9. Planing mill process

The planing process ranked as “transparent” in the technology dimension. The information gathered from the planing mill mainly concerned the processing time for current orders and sequencing of work orders. The processing time was insufficiently gathered by comparing the current number of packages produced and the ordered amount. The sequencing of work orders was keenly visualized in a GANT-chart. However, did the process lack the ability to update processing time continuously.

In the connectivity dimension, did the process rank as “aware”. The scheduling program was horizontally integrated with the planing process and vertically integrated with the inventories.

10. Final goods inventory

The final goods inventory was ranked as “transparent”, similar to the other inventories after the sawmill. The final goods inventory was mainly information about package position gathered using a similar excel-document as the earlier inventories to track assortment placement. One should note that the final goods inventory, were not part of the scheduler operating range. However, due to the knowledge about orders completion and product specifics of the customer order, was the PS often asked about these subjects.

Further, it was ranked as “aware” in the connectivity dimension due to the vertical integration with other processes, supporting decision-making.

11. Sales department

The sales department was ranked as “transparent” in the technology dimension. The PS could quickly obtain information from the sales department on the booked customer orders and was easily transferred into work orders. However, did the PS lack information about the current state of confirmation from the customer of already accepted orders.

As for the connectivity dimension, where the process ranked as “aware”. The database on customer orders where integrated with the scheduling program for the planing mill, which allowed for easy transformation from customer orders to work orders. Further, it was also connected with the inventory, which allowed for booking raw material to specific orders. The integration with the inventories enabled PS to assess future quantities needed for each of the assortment.

5.4 Roadmap towards Industry 4.0

This chapter will present a road map for the CASE company based on the theoretical findings of Industry 4.0 and the current state of maturity assessed in the earlier chapter. Current key gaps presented in chapter 5.2.4 will be used to understand the benefits of implementing an Industry 4.0 strategy. This chapter will cover the final research question:

RQ3: How could the operational decision-making be improved by implementing an Industry 4.0 strategy?

To reap the benefits of Industry 4.0 should all the dimensions develop at a similar rate. (Colli et al. 2019; Schuh et al. 2020a). It should, therefore, in the initial phase, be a focus on attaining consistency between processes. After reaching consistency between processes, the organization could start closing the gap between Industry 4.0 and the current state.

Based on the findings, it is evident that the organization is on a good path towards Industry 4.0. Several processes already attain the transparent stage in the "acatech Industrie 4.0 Maturity Index", which is the first stage in industry 4.0. However, some of the processes are lacking, and the initial focus should be to improve these. In Figure 14 is a roadmap presented based on the current stage of maturity of Industry 4.0. The roadmap is divided into four phases, based on Schuh et al. (2020b) work, with corresponding improvements in the processes connected to the organization.

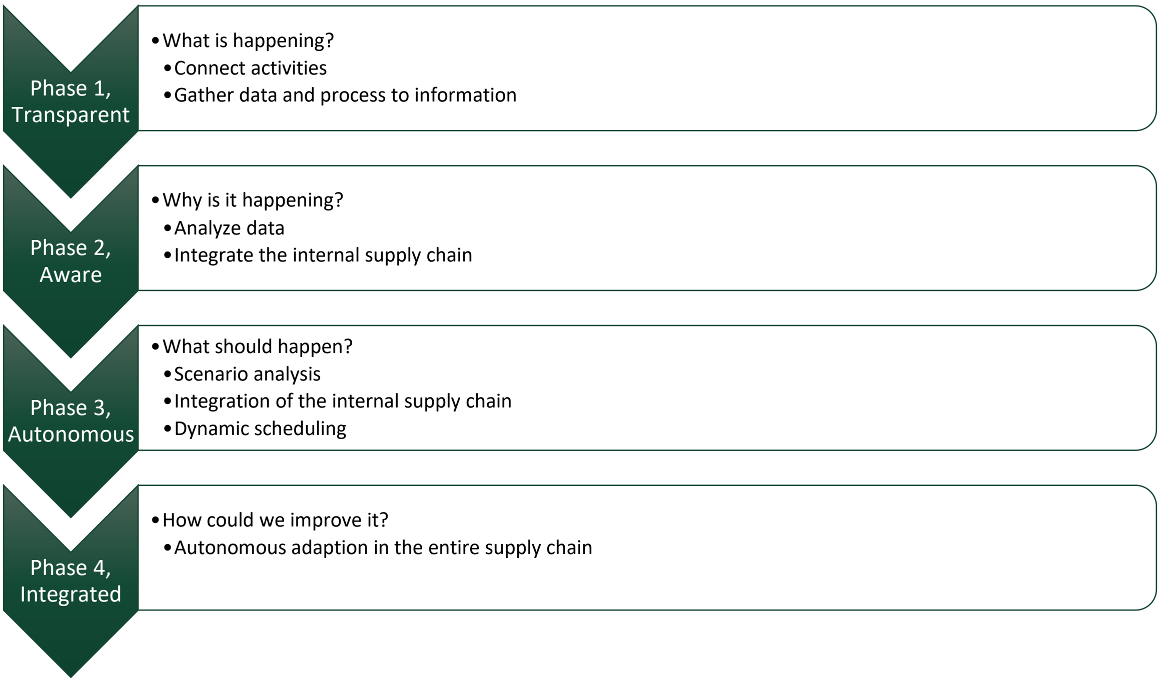

Figure 14. A roadmap towards Industry 4.0 for the CASE company.

Initially should focus be on improving the technology and connectivity in the processes; raw material supply, log yard, and the disjointing. By improving the digital capability in the log yard and raw material supply, the scheduler could improve the short-term forecasting output from the sawmill. Further, integrating the log yard with the raw material supply and the scheduling through a standardized IT system will allow for fast communication, and the risk of building up inventory could be minimized (Dallasega *et al.,* 2017). By improving the digital capability and connectivity in the disjointing process, the scheduler could analyze changes and weigh them against each other. The schedules in the planing mill process could then be more fitted to the output in the sawmill. Integrating the disjointing process with the sorting and stacking facility will allow for improved follow-up on the production (Kreipl & Pinedo 2004), and a virtual shadow of the facility could be created (Thiede et al. 2016). This step is one of the foundations to create aware processes that could adapt to changing environments (Schuh et al. 2020b).

When a transparent stage has been reached in each of the processes, where relevant data is collected and shared with those who need it (Colli et al. 2019), could the CASE company start to improve the processes and start to understand “why” things are happening. Good examples of this type of process already exist at the CASE company. In the sorting process, the scheduler and operators understood why specific products were graded into particular bins, and could make decisions based on it. However, by further integrating the processes based on recognized standards, the CASE company can further reap the benefits of these analyses and understand the root causes for disturbances (Schuh et al. 2020b).

In the third phase, the organization will predict “what will happen” by simulating future scenarios and identifying the most likely one. This stage depends heavily on the groundwork done in the earlier stage of maturity (Schuh et al. 2020b). Through dynamic scheduling, the process can autonomously adapt and reschedule and therefore decide on “what should be done”. By complete integration of the internal supply chain, the processes can reschedule themselves based on changes with the help of dynamic scheduling. Disruptions in the internal supply chain are measured and shared to other processes, where tolerances are defined for autonomous decisions if rescheduling is needed (Rossit & Tohmé 2018).

The entire organization's network integrated and autonomously is achieved in the fourth and final phase. Assets in the supply chain can interact with each other and reconfigure themselves to optimize performance not only for the internal supply chain but for the entire supply chain (Colli et al. 2019). Every entity in the supply chain is connected through the IoT, and data are processed and analyzed using CPS, which is fully integrated with other CPS systems in the supply chain. Furthermore, the scheduler’s work will drastically change, from scheduling individual processes to scheduling and optimizing entire supply chains through ERP systems (Rossit & Tohmé 2018). The individual decision will instead be carried out autonomously by the CPS system (Thiede et al. 2016).

6 Discussion

In this chapter are the results further discussed with parallels to the problem background. Continuing, are the suitability for the chosen methods discussed in the later parts of the chapter

6.1 Empirics and analysis

Through the observations, it was evident that the scheduler used several sources of information to schedule production. Similar observations as the once observed in Karltun & Berglund (2010b) in terms of information usage have been observed. It was evident that the scheduler used several types of information, including the availability of different product assortments and timeliness, similar to Karltun & Berglund (2010b) findings, this type of information was obtained both manually and digitally.

The change of product-mix in the sawmill needed much experience, following the results from Karltun & Berglund (2010b). The program used by the sawing machines based the decision on a price list, where each of the products in the product mix had a specific value to be able to steer production towards certain products. The PS needed to possess great knowledge about substitute effects of different product dimensions to be able to steer production, and several changes were often needed.

By simulating changes in production with the use of CPS, the company will be able to easily see the result of changes in the virtual world, as the one presented in Thiede et al. (2016). This will minimize unwanted goods and allow for fast and correct decision-making in the real world. In the current state of the sawmill, are the scheduler not able to simulate the changes of the product mix in the sawmill, and is manually controlled after implementation. Additionally, it is merely impossible to control the actual sawing of specific logs. Currently, the program used to chose cutting patterns for individual logs not storing the decision process, creating unreliability. Improving the disjointing process ability to analyze and visualize decisions could, therefore, improve the system's trustworthiness (Parente et al. 2020).

To achieve full integration of Industry 4.0 in the sawmill scheduling, further technologic advancement is needed. Tracking the wood products through the sawmill and continuing processes is of key importance to be able to fully utilize the CPS system (Thiede et al. 2016). However, is tracking individual products complicated because of the physical environment, limiting the use of individually marked bar codes. However, by implementing smart sensoring, for example, the one tested by Pahlberg (2017), using the actual wood itself as a fingerprint and introduce smart cameras that could follow the specific product could improve the vertical integration between several different processes. For example, could the follow-up on the disjointing process be improved, where each of the timber products measured in the sorting facility is connected to a specific log in the disjointing process. Further, could these types of technologies be used to track defects in products and packages easily. During the observations, a disturbance in the trimming facility occurred, and defects were created on the packages, not visible to the naked eye. Due to the complexity of finding and retrieve these packages was it prioritized down. However, by increasing the visibility and implementing smart sensors into the facility could these types of defects easily be tracked, and root-cause for the disturbance could be distinguished and eliminated.

Autonomous decision-making comes with many benefits, *e.g.* reactive response, the release of time for the worker, and optimized decisions (Parente et al. 2020). However, when applying autonomous decision-making into systems, one must also decide on the degree these will be carried out and the need for transparency (Thiede et al. 2016). During the observations, it was evident that some activities in the process had been allowed for autonomous decision-making. Autonomous decision-making mainly occurred where it existed a need for fast decision-making, *e.g.*, in the disjointing of logs where the program could optimize the output from the log based on parameters set by the scheduler. However, it was evident that the program lacked transparency of the decision-making process by not storing and sufficiently visualizing the decision it was based on. This created doubt to the program from the scheduler point of view, and was therefore occasionally followed up manually. Nonetheless did some of the processes possess this transparency, *e.g.*, the sorting process, delivering data on the actual decision made, allowing the scheduler to control the actual decision.

Integrating and increasing the transparency between the scheduler and the sales management could also increase the organizations' flexibility to changing demand and unexpected events. Currently was the customer order in “limbo” between acceptance and confirmation of the order from the customer. The “limbo” state created a need to continuously control the order confirmation to schedule production and accept other customer orders. Integrating the scheduling with the sales personnel goes both ways. By allowing the sales department to get insights about the current schedule, they then get insights on upcoming production dates and speed up confirmation of similar customer orders, allowing for longer sequences of similar product groups in the planing mill facility.

By further integrating the logistics with the scheduling of the sawmill, could improve efficiency in the organization. Allowing the logistics to get further insights about production state and planned time for change of species will allow the logistics to distribute resources to different facilities easier if, e.g., there occurs a disruption in production. By integrating the scheduling with the logistics department, improved efficiency in the organization could be attained, together with minimizing the risk of building up inventories.

Further, should one note the ethical consideration of implementing Industry 4.0 scheduling and autonomous decision-making and its effect on the workforce. Some might argue that the implementation of Industry 4.0 will remove the personal contact between colleagues. During the observations, it was evident that personal contact with the scheduler was of importance. Something that also has been discussed in Berglund & Karltun (2007). The scheduler believed that it was important to meet the workers at the facilities to bond and create fellowship with the workers on the shop floor. As noted by Rossit & Tohmé (2018), will several work procedures performed by the scheduler be incorporated within the CPS. However, will this release time for the scheduler, letting the scheduler focus on improvements in the facility and contact with colleagues.

6.2 Method discussion

6.2.1 Data collection

Collecting data through observations could be complicated, where lots of data should be collected, meanwhile disturbing as little as possible (Bryman 2005). However, is it a key method to understand the scheduling complexity (Crawford et al. 1999). The use of already developed protocols ease the workload for the observer, and the time could instead be focused on collecting and understanding the data observed. However, one should note that these notes do not give the general picture of the things observed, and knowledge attained from the observations could sometimes be hard to put into words in the initial stage of noting.

As noted by Karltun & Berglund (2010b), are the schedulers work at the sawmill rather complex, and several different factors are taken into account simultaneously. To complicate the matter, does each decision have a hint of experience possessed by the scheduler, which makes it hard to grasp the general picture of scheduling and nearly impossible to attain all of the information used by the scheduler at once. Interviews connected to these decisions were therefore of advantages, where the scheduler was given the possibility to further explain the decision and information considered. However, because of the scheduler's rich amount of decisions, was this type of data collection reduced to not disturb the scheduler, and interviews were held about decisions of importance. The choice of what decision to follow up through interviews was based on both the schedulers' and the observers’ opinions. Due to this, could important information be missed by the scheduler because of the individuals’ opinion of what matters. However, could the risk of missing out be minimized due to the use of data fatigue and data triangulation (Robson 2011).

During the last session with the scheduler, was the data collection method used in this study discussed. The scheduler believed that the data collection had been of interest for the person, delivering meaningful insights into the person’s work process, by rethinking why things were performed in certain ways. Therefore could participant observations serve the purpose of delivering benefits to the study and the person observed and thereby following the ethical considerations presented by Mack et al. (2005) of beneficial.

6.2.2 Method for analysis

The framework used to assess the maturity in each of the processes' ability to support Industry 4.0 scheduling has been adapted from Colli et al. (2019) and Schuh et al. (2020b) to fit the purpose of this study. The framework used to evaluate the processes in this study is based on a framework developed to evaluate entire organization (Colli et al. 2019; Schuh et al. 2020b). Attaining the full picture of an organization may be of advantage in some cases. However, as Parente et al. (2020) mentioned, will certain technologies in Industry 4.0 affect scheduling to a higher degree. Further, narrowing the scope could be closer to reality (Bryman 2005), and improvement measures could be adapted to fit the context.

The evaluation of maturity could also be skewed based on the preference of the author. However, by presenting the prerequisite in the form of a predefined framework and the fundamental background of the ranking, could reliability in the study be achieved (Robson 2011).

6.2.3 Generalizability

As earlier discussed, could sawmill in Sweden be configured differently depending on the operation's goal. Additionally, could the schedulers have a different operation range from the one observed in this study. Therefore, could the result from this study not be generalized to other sawmills, and each has different limitations and needs to evolve in different ways. However, could the approach be used to distinguish improvement in processes ability to support operative and tactical decision making in other industries.

7 Conclusions

In this section will the conclusion of the study be presented following the aim of this study. A recommendation of future studies will follow this

7.1 Contributions

In this study has information used by the scheduler at a sawmill been mapped, to outline the potential of Industry 4.0 for operational scheduling. Processes' ability to sufficiently gather and visualize data has been assessed from the scheduler’s point of view to explore opportunities for improvements.

The scheduling at the sawmill is affected by several processes in operation, ranging from log supply to the sales department. Information regarding current and future resource availability is essential in the scheduler's work together with market demand. Further, the process's resource availability is affected by several factors in the processes prior, including processing time and raw-material quality.

On average, the processes rank as transparent in the “acatech Industrie 4.0 Maturity Index” in connectivity and technology, delivering relevant information to the scheduler. However, does the ability vary and focus should be on attaining consistency between the processes.

Concerning technology, raw material supply, log yard, and disjointing process attain ranks lower than “transparent”. In the raw material supply and log yard should digital capability be improved, collecting and processing data about the log characteristics and thereby improving forecast of product output from the sawmill. Further, by improving the disjointing process digital capability, storing and tracking CPs for individual logs processed could improve trustworthiness to the system. The improved digital capability in the processes will also allow for improved and more trusted schedules in the following processes, minimizing the need to reschedule.

In terms of connectivity, raw material supply, log yard, disjointing, sorting, and stacking process obtain ranks lower than “transparent”. The processes cannot communicate with each other, creating a need for manual interference. By improving the vertical integration, could the follow-up on production be improved and allow for backtracking of products through the facility and understanding root causes of disturbances in the facility, granting improved productivity.

This study does not give any distinct technologies that could improve the company’s processes, merely outlining the potential of Industry 4.0 by supplying a finger point of what processes should be focused on in an initial stage. As Industry 4.0 is an ongoing evolution, must the company find its own path in terms of technologies and should be comprehensively investigated, especially since the term is rather new to the industry. However, by being at the forefront of this evolution, could the company collect valuable competitive advantage in the global market.

7.2 Further studies

This study's intent was not to investigate and evaluate the scheduling procedure at the sawmill, merely on improving the processes' ability to support operational decision-making. However, would it be of interest to further investigate into possible advantages of adopting dynamic scheduling into the sawmill. Dynamic scheduling has some advantages, such as allowing for rescheduling on pre-defined requirements. One could argue that rescheduling occurs rather frequently in the sawmill and would therefore be an interesting study object to test and refine the method.

Further, as noted by several authors (*e.g.,* Colli et al. 2019; Holmström 2020; Schuh et al. 2020), is not the technological and connectivity dimensions the only dimensions that should be focused on to prepare for Industry 4.0. Competences and culture could also be seen as important dimensions where improvements are needed. It should therefore be of interest to further in these dimensions in the context of sawmill.

Noteworthy is the need for further studies surrounding technologies fitted to Industry 4.0 in the sawmill and forest sector. Several new technologies are now seeing their first light, *e.g.* wood-pattern fingerprints, and advanced optimization programs. However, should increased focus be on not only innovating this type of technologies but also implementing them into the real world.

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Appendicies

Appendix 1

			Tools								
				Manuell							
Time	Place	Event	Computer system	Verbally	E-mail	Other	Source	Type	Receiver	Decision	Note

Appendix 2: Interview protocol

Decision probe

Descion number:

1. Describe the decision with your own words.
2. What was the root-cause for this decision?
3. What information did you use to make this decision? And what source did you retrieve it from?
4. Do you judge that you have sufficient information to make this decision?
5. Would information regarding this in an earlier stage ease your workload?
6. What knowledge did you use to make this decision?
7. To which degree of difficulty would you evaluate this decision? Between easy and complex?
8. Are there any standardized procedure for these type of decision?
9. Is it a common decision you have to make?

Appendix 3

Process: Mall				
	Technology		Connectivity	
	Digital capability	Adaptability	Vertical integration	Horizontal integration
Integrated	▨	The process autonomously adapts to changes in the supply chain with no human intervention	The process are integrated through the entire supply chain, allowing for fast communication	▨
Autonomous	▨	The process can autonomously adapt to changes in the internal value chain and act accordingly after an analytical process.	The process is fully integrated with the other processes in the internal value chain, allowing for optimization of the value chain	▨
Aware	There are tools that make possible to process and analyze the data from the process and is sufficiently communicated to the user.	▨	The process is integrated with some of the processes on sight	▨
Transparent	There are interfaces at place that makes the data easy accessible and visualized	▨	The process IT-system is not integrated, however could the process communicate with all other processes on the sight	Horizontal integration exists between the scheduler and the process
Basic	Digital data are generated, collected and handled locally.	▨	The process IT-system is segregated, allowing for only local communication and some information is shared manually to other processes	Horizontal communication exists between the scheduler and the process
None	Data is only collected manually	▨	There exists no IT-system allowing for digital communication	No information is digitally communicated

Example of analysis:

Process: Disjointing				
	Technology		Connectivity	
	Digital capability	Adaptability	Integration	Information sharing
Integrated	0	The process autonomously adapts to changes in the supply chain with no human intervention	The process are integrated through the entire supply chain, allowing for fast communication	0
Autonomous	0	The process can autonomously adapt to changes in the internal value chain and act accordingly after an analytical process.	The process is fully integrated with the other processes in the internal value chain, allowing for optimization of the value chain	0
Aware	There are tools that make possible to process and analyze the data from the process and is sufficiently communicated to the user.		The process is integrated with some of the processes on sight	0
Transparent	There are interfaces at place that makes the data easy accessible and visualized		The process IT-system is not integrated, however could the process communicate with all other processes on the sight	Horizontal integration exists between the scheduler and the process
Basic	Digital data are generated, collected and handled locally.		The process IT-system is segregated, allowing for only local communication and some information is shared manually to other processes	Horizontal communication exists between the scheduler and the process
None	Data is only collected manually		There exists no IT-system allowing for digital communication	No information is communicated

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