# Investigating Production Planning and Scheduling Approaches in Sawmill Operations

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# Abstract

This thesis addresses production planning and scheduling in sawmill operations, which involve a unique production flow characterized by both divergence and convergence. The study is conducted in collaboration with Södra Skogsägarna ekonomisk förening. Its objective is to identify existing production planning and scheduling approaches from the academic literature and to select the most suitable approach based on performance measurement.

The study employs an operations research framework that began with defining the problem. Next, it established a framework for existing production planning and scheduling approaches relevant to sawmill processes. Then, a simulation model is developed to analyze production performance for the selected planning and scheduling approach. Four different scenarios were created, each reflecting various decoupling point positions.

The findings of this thesis apply to sawmill operations in general. The first key finding identifies the existing production planning and scheduling approaches in sawmill production, which can be classified into integrated and decomposition techniques. Based on an analysis of the benefits and drawbacks of each approach, the agent-based planning and scheduling method is chosen for its ability to break down complex problems into smaller sub-problems, thereby reducing computational complexity. Among the coordination mechanisms for agent-based planning and scheduling, the hybrid push-pull method with a decoupling point is chosen due to its suitability in reflecting the operational characteristics of the sawmill production system. The second key finding involves analyzing the impact of various decoupling points on performance measurement. This study specifically focused on how these decoupling positions affect average inventory levels. The decoupling positions are placed between three stages in the sawmill process: sawing, drying, and after-treatment. The results indicate that placing the decoupling point before the after-treatment stage yields the best performance regarding average inventory levels. This configuration employs two distinct production strategies: a push strategy before the decoupling point and a pull strategy afterward. The push strategy allows the agents to push the logs without considering demand, while the agent after the decoupling point processes the product according to customer demand. Placing the decoupling point before after-treatment enables higher average inventory levels, providing greater production flexibility by making more inventory available to adapt to varying customer demands.

**Keywords:** Production planning and scheduling, divergent production flow, convergent production flow, agent-based planning, simulation, decoupling points, sawmill planning

# Preface

This master's thesis represents the culmination of our two-year journey studying Logistics and Supply Chain Management at the Faculty of Engineering at Lund University. Conducted over four months within the Division of Production Management, this thesis was completed in collaboration with Södra Skogsägarna during the Spring of 2026. Our objective was to explore production planning and scheduling approaches that are suitable for the sawmill. Throughout this study, we gained valuable insights and practical knowledge specific to planning and scheduling in the sawmill industry.

The completion of this thesis would not have been possible without the support of several individuals. We extend our deepest gratitude to our academic supervisor, Danja Sonntag, for her invaluable guidance and support throughout this journey. Her expertise greatly assisted us in overcoming challenges and significantly contributed to the quality of our final work. We would also like to express our thanks to our supervisor at Södra, Tinh Sjökvist, for her valuable input, cooperation, and genuine interest in our thesis, which made this experience both meaningful and exciting.

Finally, we would like to extend heartfelt thanks to our families and friends for their unwavering support and encouragement throughout this journey. Additionally, I am (Zavira Ramadhanti) very grateful for the assistance provided by the Indonesia Endowment Fund for Education Agency (LPDP) throughout my academic endeavors.

Sincerely, Haoyang Wu and Zavira Ramadhanti

# List of Figures

# List of Tables



# Abbreviations

| | |
|---|---|
| DES | Discrete Event Simulation |
| DP | Decoupling Point |
| FGI | Finished Goods Inventory |
| FIFO | First In First Out |
| OR | Operations Research |
| RMI | Raw Material Inventory |
| WIP | Work in Progress |

# Table of Content

# 1. Introduction

*This section provides an overview of the research context and introduces Södra Skogsägarna and the sawmill operations. It then presents the background and the problem formulation of this thesis. The problem formulation section concludes the purpose of this study, along with the research questions that guide this study.*

## 1.1 Background

Forests cover approximately 70% of Sweden's land area (Swedish forest industries, n.d.). The Swedish forestry industry is one of the country's most important economic sectors, contributing significantly to both employment and exports. One of the largest forest-owner associations in Sweden is Södra Skogsägarna, founded in 1938, which manages the full value chain, from sustainable forestry to the production of a wide range of forest-based products. Södra's operations are based on the long-term profitability of forest estates and have a strategic focus on making more from every tree and finding sustainable solutions from the forest.

Södra is a cooperative owned and controlled by more than 50,000 family forest owners who sell and deliver wood to Södra. Due to the cooperative structure, Södra receives fluctuating volumes of raw materials depending on when the cooperative members sell the wood. This creates a dynamic inflow with variations in volume, log diameters, and quality of raw materials, which significantly increases supply uncertainty on a short-term basis. Supply uncertainty is a common challenge for the sawmill industry, particularly regarding log availability. This limitation makes effective production planning and scheduling difficult for sawmills. In practice, planning determines which logs to process and what products to produce in order to meet the customer demand, while scheduling involves determining which log stacks should be processed, the sequence in which logs are sawn, how the resulting timber products are allocated to the available drying capacity, and the sequence in which the dried timber products are sent to the after-treatment. The variability in log arrivals, therefore, complicates coordination between production stages and the efficient utilization of the drying process.

In sawmill operations, timber is processed into wood products for construction and other industries. Efficient management of sawmill operations is essential to maintain productivity, ensure product quality, and minimize waste. The sawmill production process can be broadly divided into several main stages: arrival, sorting, debarking, sawing, drying, after-treatment (such as planing), wrapping and packaging, and dispatching, as shown in Figure 1. A detailed description of these stages is provided in Section 2.

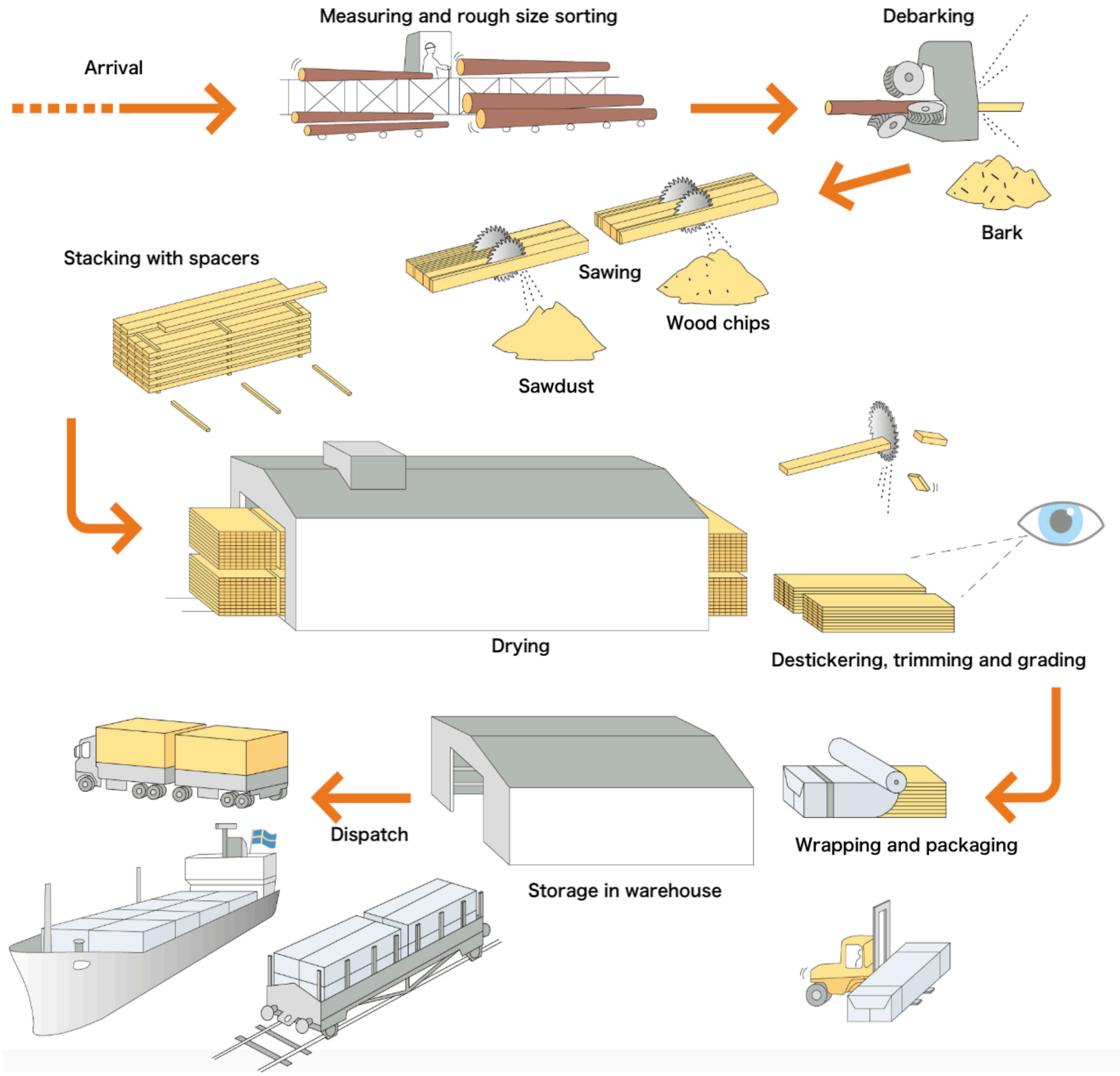


***Figure 1.*** *Overview of the sawmill production process*
*(Svenskt trä, 2021. Translated by the authors)*

## 1.2 Problem formulation and purpose

Production planning and scheduling in sawmill operations is highly complex due to fluctuating raw material inflows, co-production effects, and the coexistence of divergent and convergent production flows within a continuous material flow system. Inventory is maintained at several stages of the process, including log stacks containing logs with similar dimensions before sawing, timber buffers before and after drying, and storage after the after-treatment process. In the sawing stage, predefined sawing patterns cause a single log to generate multiple product types simultaneously, meaning that products cannot be produced independently. Consequently, producing one desired product inevitably results in additional co-products, making it difficult to align upstream production decisions with downstream customer demand, which varies across product types. As a result, production planning and scheduling must balance the need to satisfy demand for high-demand products while avoiding overproduction of lower-demand products and maintaining an appropriate distribution of finished goods inventory over the planning horizon. In addition, operational constraints such as limited drying capacity, kiln batching requirements, inventory accumulation, and the need to maintain buffer capacity for uncertain demand further complicate coordination across production stages. These production characteristics and constraints are discussed in more detail in Section 4, while production planning and scheduling is further elaborated in Section 4.3.

The objective is to explore existing production planning and scheduling approaches in sawmill operations from the academic literature and to select the most suitable approach based on performance measurement.

To fulfill the objective, the following research questions guide this study:

1. To better understand a sawmill's planning and scheduling challenges and complexities, what is the structure and material flow of a sawmill production system?

2. Which production planning and scheduling approaches from the literature would be suitable for implementation in sawmill production?

## 1.3 Report outline

The remainder of this thesis is structured as follows: Section 2 provides an overview of the sawmill production process. Section 3 presents the general and applied methodology adopted in this study. Section 4 further elaborates on the production process and also focuses on production planning and scheduling. Section 5 summarizes the existing production planning and scheduling approaches into a conceptual framework. Section 6 focuses on the agent-based planning and scheduling approach and analyzes the hybrid push–pull approach with a decoupling point in a simulation model using ExtendSim. Finally, Section 7 concludes the thesis and outlines directions for future research.

# 2. Sawmill Process

*This section describes the sawmill production process in detail, covering all major stages. It explains how logs are sorted, sawn, dried, and further processed. This section also introduces the roles of production planning and scheduling. Together, these sections provide the foundation for understanding the sawmill production process on which the subsequent sections are based.*

## 2.1 Before sawing

The harvested logs are collected by logging trucks and transported to the sawmill. Upon arrival, the logs are screened with a metal detector to identify any metal objects that could damage the sawing equipment. Next, the logs move through the sorting area, where they are placed on a conveyor belt for categorization based on their dimensions into specific sawing classes. Logs belonging to the same sawing class, which is referred to as LogID, will later be processed together. Along the conveyor belt, there are compartments to temporarily store the logs that have been sorted. During this sorting process, log loaders transfer the logs from the compartments to the stacking area, where they are stored temporarily before being sawn. It is crucial not to leave the logs in the stacking area for too long, as this can adversely affect their quality. To prevent wood degradation, it is essential to process logs promptly. After a tree is felled, logs begin to dry naturally, and the rate of natural drying depends on several factors, such as ambient temperature, humidity, tree species and log size (Pettersson and Nordfjell, 2007). Sending logs with varying moisture content into the same kiln can result in distortion, which negatively affects the quality of the final product (Tarvainen, 2005). Furthermore, biological degradation of wood may occur due to bacteria, insects and fungi (Reinprecht, 2016). Hence, it is essential to process logs promptly. To address this issue, a requirement has been established that once a class of logs is selected for processing, all logs in the corresponding stack are removed. The logs are then transported from the log stacks to the sawing house, where the sawing process begins.

## 2.2 Sawing

Logs enter the sawing house via a conveyor belt. If the logs have not been debarked in a previous step, the debarking process is performed now. The sawing process transforms the logs into products based on the different sawing patterns. Each log can have different sawing patterns based on the final products that are specified by the customer. During this phase, a single log is processed to produce multiple products. The aim is to optimize the yield from each log by using the most efficient sawing patterns to generate high-value products for the market. The sawing pattern determines how the log is divided into a certain number of boards with different dimensions. One board product type has its own product identity number, which is called ProdID. At the end of the sawing line, sawn timbers of the same size are palletized together for the drying process. Each pallet has a predefined maximum capacity, which varies depending on the width and thickness of the boards. To facilitate proper air circulation during drying, spacers are placed between each layer of timber. This ensures uniform drying and consistent moisture content across the entire batch.

These palletized timbers await their scheduled time in front of the drying area. These pallets should not wait for too long, as delays can lead to quality issues.

## 2.3 Drying

Pallets containing timber of the same dimensions and characteristics (e.g., spruce or pine) are organized into same drying groups, defined by a DryingID, an identifier used to group timber products that share identical drying requirements, which determines the drying duration in kilns. The drying time largely depends on the timber's specifications, i.e., thicker pieces require longer drying times. If timbers with significantly different dimensions are dried together, thinner pieces risk being over-dried while thicker ones may not reach the desired moisture content. To prevent this, only pallets with the same DryingID are grouped into a drying batch, ensuring uniform drying and consistent final quality. Once a full batch is ready, it is sent to the kiln, where drying typically takes several days. Two types of kilns are used for drying: continuous kilns and chamber kilns, as shown in Figure 2, respectively.

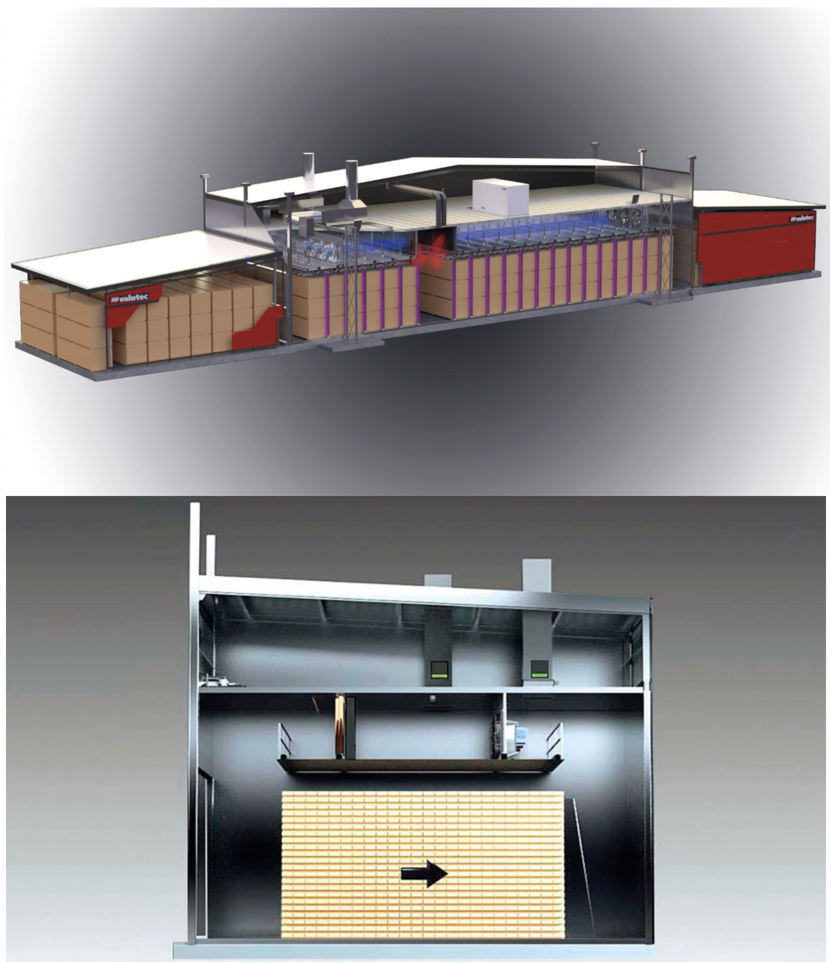

***Figure 2.*** *Continuous drying kiln versus chamber drying kiln (Sahateollisuuskirja, n.d.)*

Continuous kilns operate as automated systems, where wagons gradually move through a tunnel-like structure, supporting high throughput. Each wagon carries pallets, and the system must be kept in constant motion to maintain drying quality. Idle time must be avoided, as it can compromise the consistency of product quality. Interruptions in the continuous movement of wagons disturb the designed airflow and temperature conditions inside the kiln, leading to uneven air circulation and potentially inconsistent moisture content in the timber. Continuous kilns are less flexible and require adjustments, such as temperature changes, when switching between different log types. Therefore, minimizing switches of DryingID within each continuous kiln is crucial from a product quality perspective. Every time switching to a different DryingID in the same kiln, the drying conditions cannot be optimized for the coming batch. This may result in uneven drying and inconsistent moisture content, which should be strictly avoided.

In contrast, chamber kilns provide greater flexibility and can accommodate timber of different sizes and species in separate batches. A complete batch also consists of several pallets. Drying begins only when a full batch is loaded because if kilns are not fully loaded, the incomplete batches lead to uneven drying. Once drying is complete, the chamber is emptied and reloaded with the next batch. Although chamber kilns are more adaptable, they are also more labor-intensive due to the need for manual loading and unloading, whereas the drying itself continues automatically once the kiln is sealed.

## 2.4 After-treatment

After the drying process, the timber enters the after-treatment stage, beginning with processing steps such as trimming and planing. Larger timber pieces may also be split into smaller dimensions based on inventory levels and customer demands. Following these steps, the timber undergoes a quality inspection. It passes through a quality control machine and is visually examined for defects. The timber is then graded and sorted into different quality categories. Once all processing is complete, the timbers are palletized again and secured with straps for transport. The finished products are stored in the sawmill's finished goods inventory, awaiting dispatch.

# 3. Methodology

*This section describes the methodology of this thesis. Section 3.1 describes the general approach for the thesis. Then Section 3.2 explains the general overview of operations research methodology. Finally, Section 3.3 details the adopted methodology for this study.*

## 3.1 Research approach

There are three types of research approaches based on a thesis's purpose and objectives: descriptive, explanatory, and problem-solving. According to Höst et al. (2006), a descriptive approach enables researchers to understand current practices by providing a structured overview of a specific subject. In contrast, an explanatory approach goes beyond mere description; it aims to explain, through hypotheses, how certain patterns occur. Lastly, a problem-solving approach concentrates on developing solutions to specific issues.

The research approach for this thesis is centered on problem-solving. The objective of this study is to identify an appropriate approach for the sawmill's planning and scheduling system. According to Höst et al. (2006), the most suitable research method for a problem-solving approach is Operations Research (OR).

## 3.2 Research methodology

This section provides a general overview of the operations research methodology and discusses its application in alignment with this thesis. According to Hillier and Lieberman (2010), there are six steps to conducting operational research, which are detailed below:

**Step 1. Define the problem and gather relevant data**

The first step in an operations research study is to analyze the relevant system and clearly define the problem. In this phase, the objectives are established, along with any constraints that may impact the project, such as time limitations and the relationship between the area being studied and other areas within the organization. Specifically, the current conditions of the sawmill production are mapped to address the research question regarding the structure and material flow of its production system. This involves examining the production system and the material flow that contributes to the complexities of the operation. The next step is to gather the necessary data. A significant amount of information is needed to thoroughly understand the problem and provide the inputs required for the mathematical model that will be developed in the subsequent stage.

**Step 2. Formulate a mathematical model that represents the problem**

The second step is to formulate a mathematical model representing the problem. A mathematical model includes decision variables, an objective function, constraints, and parameters. The goal of the mathematical model is to choose values for the decision variables in order to maximize or minimize the objective function while adhering to the specified constraints. It's best to start with a simple version of the model and then gradually develop more complex versions that better reflect the intricacies of the problem. When creating the mathematical model, there is a trade-off between precision and tractability; the model should be both accurate and solvable.

**Step 3. Obtain the solutions to the problem from a computer-based model**

The third step involves obtaining the solution to the mathematical model formulated in the second step. In this step, procedures are developed to derive solutions from the mathematical model. Typically, these procedures are computer-based and utilize available software packages. The solutions produced from the model may not be optimal in real-world terms, but they are optimal in the context of the mathematical model, which represents an idealized version of the system rather than an exact depiction of reality. If the model is well-formulated and tested, though, the derived solution can serve as a good approximation for addressing the real problem. Additionally, post-optimality analysis can be performed after obtaining the optimal solution. This analysis involves conducting a sensitivity analysis to identify which parameters in the model are most critical in influencing the solution. The analysis of the model is conducted by using Python with the solver package and with the data that has been collected in the previous step. Then, the sensitivity analysis is conducted to test the robustness of the model using software

**Step 4. Test and refine the model**

This step is known as model validation. Due to the complexity of real-world problems, oversights and errors can occur during the model formulation phase, such as incorrect assumptions and the omission of key factors. Therefore, it is advisable to begin this step by checking for inconsistencies in the mathematical model and conducting trial-and-error procedures to better understand the results and refine the model. This process of testing and improving the model enhances its reliability. A systematic approach to testing involves conducting a retrospective test to compare the results of the model to actual historical outcomes to assess the performance of the model. In this research, a simulation model is employed to evaluate the performance of the proposed solutions.

**Step 5. Prepare for the ongoing application of the model**

Once the model has been validated and is ready for use, the next step is to establish a well-documented system outlining how the model should be utilized. This documentation should include the model itself, the solution procedures, and the operating procedures for its implementation. Such a system ensures consistency in the use of the model, even in the event of personnel changes. Additionally, a continuous monitoring procedure should be included to allow for adjustments to the model if it becomes irrelevant. Typically, this system is computer-based.

**Step 6. Implement the model**

The last phase of an OR study involves putting the system into action and achieving the expected benefits. The research team must stay engaged during this stage to make sure that the solutions from the model are properly integrated into the operating procedures and to address any issues that may arise in the solution. Additionally, continuing to gather feedback during this stage is essential to evaluate the effectiveness of the system and to confirm whether the model's assumptions still hold true.

## 3.3 Applied research methodology

The operations research methodology described by Hillier and Lieberman (2010) offers a general framework for conducting operations research studies. Its application can vary based on the specifics of each study. In this research, we utilized the first three steps of the original operations research framework and made adjustments to better align with the objectives of this study. Additionally, the remaining steps are outside the scope of this thesis. The adapted methodology, consisting of four steps based on Hillier and Lieberman's general framework, is outlined below:

**Step 1. Define the problem**

The problem is being formulated in collaboration with Södra. During this phase, regular meetings and discussions were held to gain a clearer understanding of the issue, define the boundaries of this study, and clarify the objective. The aim is to develop a comprehensive planning and scheduling strategy for sawmill production. As a result, these meetings primarily focused on understanding the sawmill production system, identifying the complexities of its operations, and exploring available planning and scheduling approaches within the scientific field, specifically related to sawmill production processes.

**Step 2. Develop the conceptual framework and gather relevant data**

This step addresses the second research question and serves as the initial phase in determining which production planning and scheduling approaches are suitable for the sawmill production. During this stage, an extensive literature review is conducted, focusing on production planning and scheduling, particularly as it relates to the sawmill production process. A conceptual model is developed to visually represent and outline the benefits and drawbacks of different production planning and scheduling approaches applicable to the sawmill production. Following this, the next step involves gathering relevant data that will be utilized to build a simulation model. The pertinent data collected from Södra's ERP system includes machine speed, working hours, and inventory levels of raw materials and work-in-progress (WIP) items.

**Step 3. Build the simulation model and derive the solution**

In this step, a discrete-event simulation is built to represent the sawmill production system. The simulation includes the main production stages, such as sawing, drying, and after-treatment, along with the flow of logs and timber products between these stages. The model is used to incorporate the production planning and scheduling approaches identified in the previous step. Its primary purpose is to analyze and identify an efficient and practical method for developing the production schedule. The simulation is built using Extendsim software. During this phase, multiple scenarios are tested to understand the impact on one key evaluation parameter. The output from the simulation model will be used to determine the most suitable production planning and scheduling approach.

# 4. Sawmill Production Characteristics

*This section provides an overview of the sawmill production system, focusing on the general definitions of production planning and scheduling and the structure of material flow. Overall, this section corresponds to Step 1 of the applied research methodology, namely defining and formulating the problem. Section 4.1 defines production planning and scheduling and explores their relationship with the sawmill. Section 4.2 presents a general explanation of the flow structures within the sawmill production system. Section 4.3 offers a detailed explanation of the material flow structure in sawmills, along with the planning and scheduling practices in the sawmill production system.*

## 4.1 Production planning and scheduling

Production planning determines what should be produced, while production scheduling focuses on when it should be produced. Production planning estimates the aggregate production target for a specific time period but does not specify when to produce each type of product. Production scheduling determines which product goes to which machine and at what time. Both production planning and scheduling address the challenge of allocating available resources over time to perform various tasks. Although the distinction between the two is not always clear-cut, the primary difference lies in their time horizons (Dumetz et al., 2021). Production planning typically focuses on a longer time frame, such as yearly or monthly periods, and emphasizes high-level decisions, including production levels and investments in new facilities. In contrast, scheduling operates on a shorter time frame, often weekly or daily, and concentrates on more granular decisions, such as determining the operations sequence on machines.

Determining the operations sequence on machines is closely related to production systems. Production systems describe how jobs move through machines during the manufacturing process. Two common production systems are flow shop and job shop, which differ in job routing and machine organization. In a flow shop, all jobs follow the same sequence of processing stages. In contrast, a job shop allows each job to follow its own routing, visiting machines in different orders (Thonemann, 2015). Flow shop typically enables more standardized and predictable scheduling, whereas job shop systems require more flexible and adaptive scheduling approaches due to their variability.

The sawmill production system is classified as having a hybrid flow shop. The hybrid flow shop combines the classical flow shop, which has the sequential processing stages, with parallel machines at one or more stages (Pinedo, 2016). In such systems, jobs must not only be sequenced but also assigned to specific machines. All jobs follow the same sequence of stages: sawing, drying, and after-treatment, characteristic of flow production. Figure 3 illustrates the hybrid flow shop of a sawmill production system. Machines are denoted by $M_{ij}$, where i indicates the production stage and j denotes the machine number within that stage. For example, $M_{11}$ represents the sawing machine in Stage 1, while $M_{21}$, $M_{22}$, $M_{23}$, and $M_{24}$ represent parallel drying machines in Stage 2. Each sawmill may have a different number of machines at each stage of the process. The specific number of machines in each stage depends on the actual setup of a sawmill and can vary significantly. While one sawmill might utilize multiple machines at some stages, another may allocate several machines at others. The distribution of machines depends on the specific requirements of each sawmill.

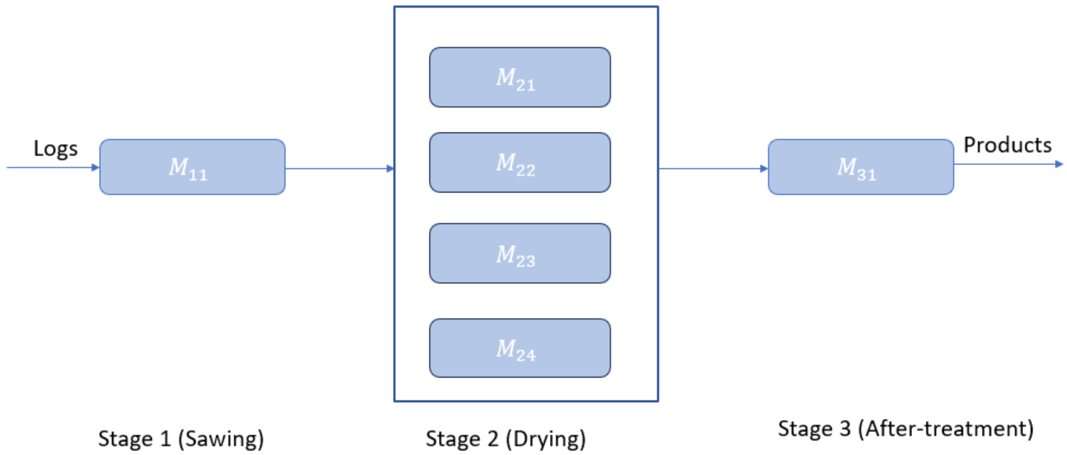


***Figure 3.*** *The hybrid flow shop of the sawmill production system*

This type of production system presents several challenges for scheduling. In a hybrid flow shop, scheduling involves not only determining the sequence of jobs but also assigning jobs to specific machines. This added complexity arises from the presence of parallel machines. On the other hand, within a hybrid flow shop, any machine can become a bottleneck due to the multiple machines and processing stages involved. Therefore, it is crucial to balance capacity effectively to prevent machines from becoming either overloaded or underutilized.

In addition, the presence of bottleneck machines significantly affects planning and scheduling decisions. Bottleneck resources require careful coordination throughout the production process because they constrain the available capacity of the entire sawmill system. By considering bottleneck machines during scheduling, more feasible and efficient production plans can be achieved. For instance, properly sequencing production can help balance operations and utilize limited capacity more effectively. Ultimately, scheduling decisions aim to optimize resource utilization, reduce idle time, minimize waiting times, and increase the overall throughput of the production system.

## 4.2 Divergent and convergent production flow

Production flows can generally be classified into three categories: (1) divergent production flow, (2) convergent production flow, and (3) divergent production flow at the assembly point. Each production flow has its own plant type. These three production flows can be classified according to the plant types, which are plant types V, A, and T (Umble, 1992). The A-plant is characterized by having a convergent production flow, the V-plant is characterized by having a divergent production flow, while the T-plant is characterized by having a divergent production flow at the assembly point. In a T-plant, the initial manufacturing stages are linear and highly standardized. A small number of raw inputs are processed into standard components, and the divergence occurs only at the very final stage, which is the assembly point. At the assembly point, the uniform components are combined into a wide variety of customized finished goods, which reflects the divergent flow. The focus of this study will be solely on the divergent and convergent production flows to give an idea of how these two production flows are related to the sawmill.

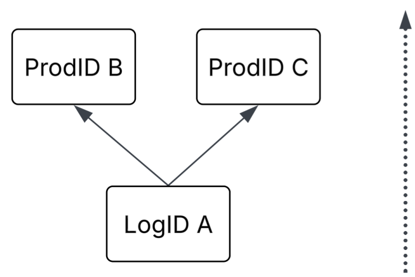


***Figure 4.*** *Divergent production flow*

Divergent production flows have a V-Plant structure, meaning that a single material can be transformed into a wide variety of distinct end products. This type of product flow is characterized by a large number of end items compared to the number of raw materials. All end items undergo the same processing method (the same routing), and the equipment used is highly specialized and capital-intensive (Umble, 1992). A clear example of this product flow can be found in sawmill production, particularly during the sawing process. Figure 4 illustrates the divergent production system of the sawing process. This process produces multiple products, including main products and co-products, from a single raw material. However, prioritizing efficiency for this type of production system might lead to a large batch size, resulting in surplus WIP and finished goods inventories (FGI), as well as inflated lead times (Umble, 1992).

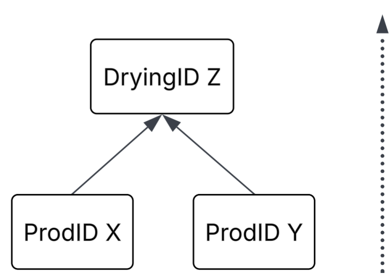


***Figure 5.*** *Convergent production flow*

A convergent production flow refers to an A-Plant structure where a large number of components or materials are assembled to create unique end products. This type of product flow is characterized by having fewer end products than components, with each component being largely specific to certain end items. The equipment used in this process can serve different functions, and the routing of components is often quite varied (Umble, 1992). This flow is commonly seen in the automotive industry, where an assembly point is necessary for producing the final product. Additionally, convergent product flow can also occur in the drying process within the sawmill industry, where different products that share the same DryingID can be grouped together into a single drying batch. Figure 5 presents the convergent production system of the drying process. One significant challenge associated with convergent product flows is resource misallocation. Because the divergent process can only begin once all components are available, it requires careful synchronization between the various production processes.

The sawmill production system, characterized by a combination of divergent and convergent production flows, is presented as follows.

## 4.3 The sawmill production system

The material flow of the sawmill production process is illustrated in Figure 6, which consists of three main stages: sawing, drying, and after-treatment. The figure does not represent the exact production environment but rather serves as a simplified model to illustrate the general material flow within the sawmill system. WIP inventory exists primarily in four forms within the process: logs stored in log stacks prior to sawing (Position A), palletized timber waiting before the drying process (Position B), dried products waiting for the after-treatment stage (Position C), and finished goods (Position D).

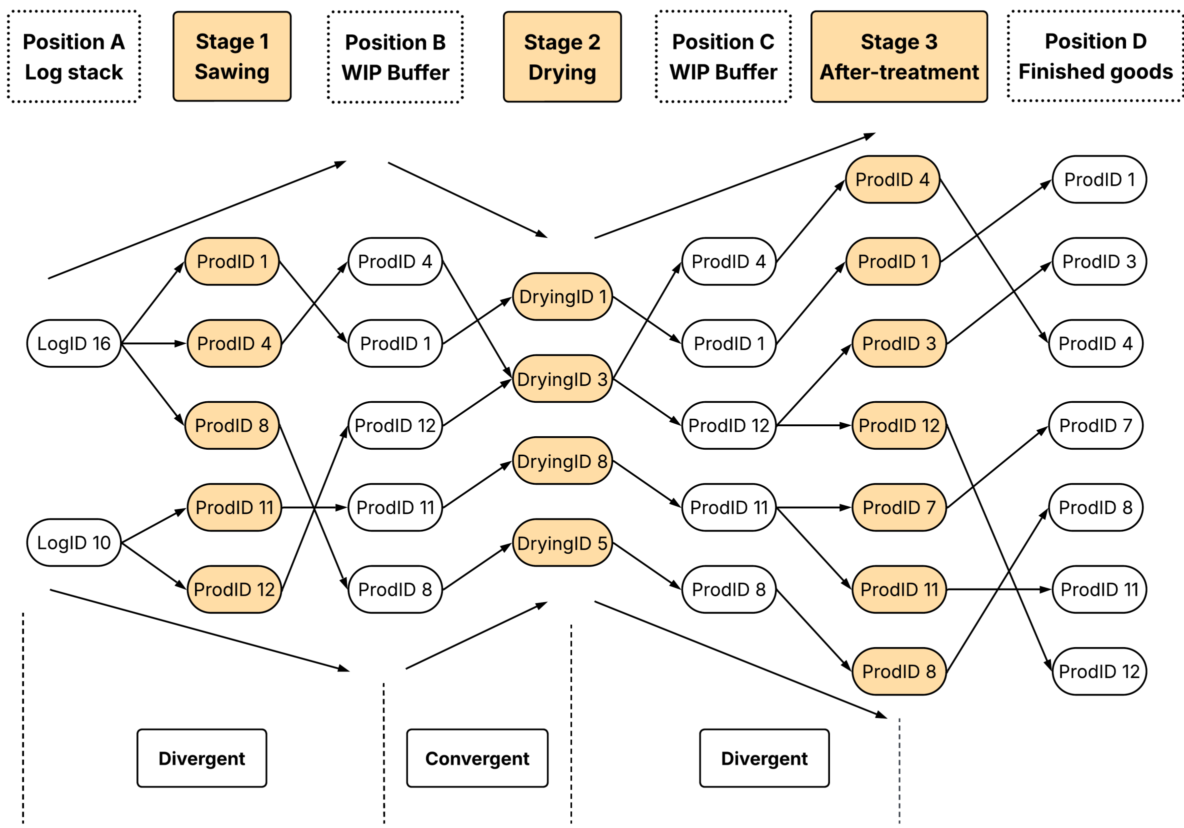


*__Figure 6.__ The material flow of the sawmill production process*

After arrival, logs are first sorted according to their dimensions and categorized into predefined log classes. They are then temporarily stored in their corresponding log stacks. When a particular log stack is selected for processing, the entire stack is emptied and sent to the sawing stage.

During the sawing stage, a single log is transformed into multiple products. Each log class (LogID) has one or several predefined sawing patterns. The sawing pattern is designed based on the cross-sectional shape of the log and the desired product dimensions. Logs are typically approximated as having a circular cross-section. Each board product has specific width and thickness requirements, which determine the feasible sawing patterns within the log cross-section. For each log class, the feasible sawing patterns define the number of boards of each product type (ProdID) that can be produced.

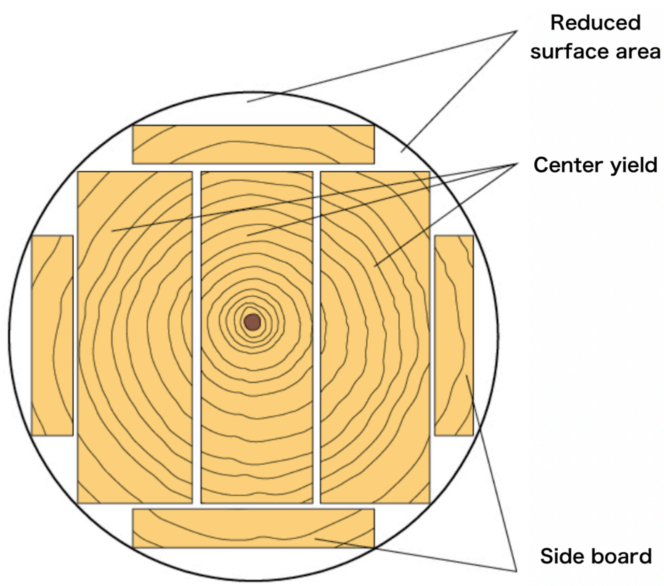


***Figure 7.** The log cross-section (Svenskt trä, 2021)*

Figure 7 demonstrates how a log is processed using a specific sawing pattern, which produces several center boards (main products) and side boards (co-products). Different sawing patterns yield different product mixes. For simplification, Figure 7 illustrates only one sawing pattern for a single log. It is also possible to adjust the sawing pattern to align with the product mixes requested by customers. Even if only the center board products are required, sideboards are inevitably produced at the same time. This phenomenon is referred to as co-production, where multiple product types are generated simultaneously from a single log. As a result, the sawing process creates the first divergent material flow, in which one log is transformed into several different product types, where the product flow becomes more complex. Producing one type of product automatically generates the production of other products. Therefore, products cannot be scheduled independently. Ignoring this relationship may lead to overproduction of unwanted products, which could cause congestion in downstream processes. The remaining material from the reduced surface area does not produce board products but can still be utilized as by-products, such as wood chips or sawdust, which are often used in pulp mills or other industrial applications.

The second stage, drying, involves grouping multiple ProdIDs into the same DryingID. Different product types might share the same DryingID. Batching is critical in this stage because not all products can be dried together. Only products with the same drying requirements can be processed in the same batch. This batching process creates dependencies between products originating from the sawing stage. If one product within a batch is delayed, the entire batch is affected, which in turn influences the completion time of the production system. Consequently, the drying stage represents a convergent production process with batching requirements, which increases the complexity of planning and scheduling.

After drying, products leave the kilns and are unbatched before temporarily being stored according to their ProdID. The after-treatment stage represents the final stage where product dimensions can still be modified. For instance, a board may be cut into several smaller pieces, thereby creating new product types with different ProdIDs. As a result, both the unbatching process after drying and the after-treatment stage introduce the second divergent material flow. The divergence in this stage depends on customer requirements and the quality of the dried products, as some boards may be trimmed into smaller dimensions while others remain unchanged.

In summary, the sawmill production system exhibits a combination of divergent and convergent material flows. Material flows split during the sawing stage, merge during the drying stage, and split again during after-treatment. The initial divergence creates joint production constraints, since output volumes for multiple product types are determined simultaneously by the chosen sawing pattern. The convergent drying stage introduces batch synchronization requirements and bottleneck-driven behavior. These structural dependencies propagate downstream, reducing scheduling flexibility and increasing the need for coordination. Consequently, this production structure generates significant operational complexity and poses substantial challenges for planning and scheduling.

# 5. The Framework of The Production Planning and Scheduling Approaches

*This section introduces different existing production planning and scheduling approaches identified in the literature review, particularly those relevant to the sawmill production process, and summarizes them in a conceptual framework. In the context of the applied research methodology, this section corresponds to Step 2, namely the development of the conceptual framework.*

To better understand the different ways production planning and scheduling can be structured, it is useful to organize the existing approaches into a unified framework. Figure 8 presents a framework that provides an overview of production planning and scheduling approaches. At the highest level, these approaches are classified into integrated and decomposition-based approaches. While integrated approaches solve planning and scheduling simultaneously, decomposition techniques divide the problem into sub-problems. Decomposition can be structured either by agents (agent-based) or by decision levels (hierarchical). Within the agent-based category, five main approaches are identified: pull, push, hybrid push–pull with the decoupling point positioning at different places, two-phase planning, and bottleneck-driven approaches. Each approach represents a different way of coordinating decisions and managing material and information flows within the system. The following section provides the explanation of these approaches along with their advantages and limitations.

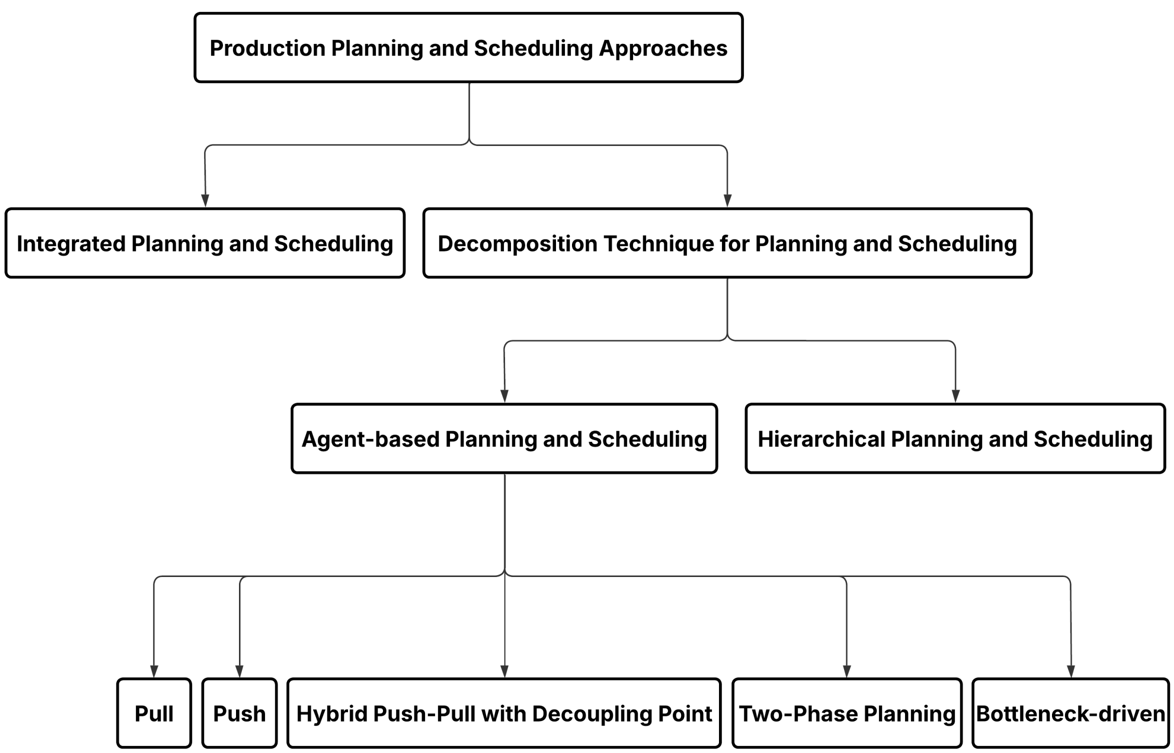


***Figure 8.*** *The framework of production planning and scheduling approaches*

## 5.1 The integrated planning and scheduling approach

Integrated planning and scheduling, often described as a centralized optimization approach, provides a unified and comprehensive view of production. It typically employs optimization models to obtain near-optimal production plans (Forget et al., 2009). In contrast to decomposition approaches, integrated approaches do not treat process planning and operations scheduling as separate, sequential tasks. Instead, both are addressed simultaneously within a single model. Gaudreault et al. (2011) highlight the strong interdependence between process planning and operations scheduling decisions. The feasibility of planning depends on machine availability and capabilities, while the effectiveness of scheduling relies on planning that avoids bottlenecks and ensures balanced resource usage. As a result, the integrated approach aims to determine, within one single model, what should be produced, when it should be produced, and which resources should be allocated.

However, the integrated planning and scheduling approach presents several practical challenges. The resulting production plans can quickly become infeasible when system conditions change. Disturbances such as delivery delays, supply shortages, machine breakdowns, or demand variability can make production plans obsolete on a short notice (Forget et al., 2008). Moreover, the approach is computationally intensive and complex. Therefore, although an integrated planning and scheduling approach offers a theoretically robust solution, it is not further considered in this study. Instead, decomposition-based approaches are adopted due to their greater flexibility and suitability for dynamic and real-world production environments.

## 5.2 The decomposition planning and scheduling approach

The decomposition planning and scheduling approach divides a complex process planning and operations scheduling problem sequentially and independently in order to reduce computational complexity. Instead of solving the entire system in a single model, the problem can be decomposed based on different perspectives.

Two main types of decomposition can be distinguished. The first is agent-based, where the system is divided across different agents or process stages. Each agent is responsible for solving its own local sub-problem and makes its own decisions. The coordination between agents is achieved through the exchange of information such as demand and supply plans. The second is hierarchical, where the problem is separated according to decision levels, typically the tactical level and the operational level. Decisions at the tactical level define targets and constraints such as the production volume and the available production capacity, while the operational level focuses on detailed scheduling.

### 5.2.1 The agent-based planning and scheduling approach

Agent-based planning is a method of decomposing planning and scheduling where decisions are made by multiple entities known as agents. In the context of a sawmill production system, there are three primary agents: sawing, drying, and after-treatment. Each agent is responsible for a specific part of the system and makes its own decisions instead of relying on a single centralized model. This decentralized approach is particularly beneficial when the centralized approach becomes too complex. In this strategy, the original problem is divided into smaller sub-problems, each assigned to a different agent. These agents act as independent decision-makers, each with its own data, constraints, objectives, and planning model. While they operate autonomously, effective communication and coordination among them are essential to ensure the overall efficiency of the system.

Each agent has three main functions: (1) to produce an operations plan, (2) to allocate demand to upstream agents, and (3) to allocate production to downstream agents. According to Table 1 from Frayret et al. (2007), each agent has different objectives, inputs, processes, and outputs. The sawing agent utilizes log class data as input to determine the optimal sawing pattern that maximizes production value or minimizes cost. The output from the sawing agent, which is the lumber size distribution, serves as input for the drying agent to create its production plan. The information shared from the sawing agent to the drying agent is referred to as "internal supply". Then the drying agent takes the lumber size distribution provided by the sawing agent and assigns the drying process sequence to achieve its objectives of minimizing tardiness or maximizing production value. The output from the drying agent, which consists of the quality distribution of dried sawtimber, is then used by the final agent, the after-treatment agent, to develop its production plan.

***Table 1.*** *Agent-based planning and scheduling process for each agent*

| | **Sawing** | **Drying** | **After-treatment** |
|---|---|---|---|
| Objectives | 1. Min. tardiness (upstream and downstream phases)<br>2. Max. production value (downstream phase)<br>3. Min. costs | 1. Min. tardiness (upstream and downstream phases)<br>2. Max. production value (downstream phase) | 1. Min. tardiness (upstream and downstream phases<br>2. Max. production value (downstream phase)<br>3. Min. costs<br>4. Min. resource utilization rate |
| Processes model (supply type, process type, and output type) | Log class, sawing pattern, lumber size distribution | Lumber size, drying sub-process, moisture content, and quality distribution | Lumber size and lumber size distribution |
| Process Features | Divergent | Convergent | Divergent |

A key feature of agent-based planning and scheduling is that each agent may pursue its own objectives, which can differ from the overall system objective. Thus, strong coordination among agents is crucial. Without a centralized planner, each agent has a limited view of the problem, making coordination more challenging (Gaudreault et al., 2009; Gaudreault et al., 2010). The main challenge in agent-based planning and scheduling is facilitating effective coordination among these autonomous agents to meet external customer demand. To overcome this challenge, agents continuously exchange information, adjust their plans, and respond dynamically to changes in demand or supply.

According to Gaudreault et al. (2010) and Dumetz et al. (2019), there are five types of coordination mechanisms for the agent-based approach: (1) the pull planning and scheduling, (2) the push planning and scheduling, (3) the hybrid push-pull planning and scheduling with the decoupling point, (4) the two-phase planning and scheduling, and (5) the bottleneck-driven planning and scheduling. These coordination mechanisms will be explained in the following section.

#### 5.2.1.1 The pull planning and scheduling

The pull planning and scheduling is initiated based on actual customer orders or forecasted demand. In this approach, production quantities are determined according to demand requirements, with the primary objective of fulfilling customer orders by their due dates. Consequently, the system aims to achieve a high service level by producing the right products in the required quantities. Service level refers to the ability of a system to meet customer demand successfully. For instance, a 95% service level indicates that 95% of customer demand is satisfied without experiencing stockouts.

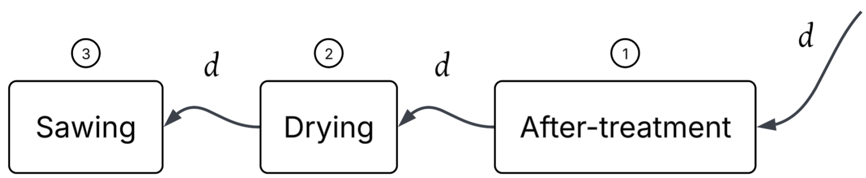


***Figure 9.*** *Pull planning and scheduling*
*(adapted from Gaudreault et al., 2010, p.181)*

Figure 9 illustrates the pull planning and scheduling approach. Customer demand, which is notated as “d”, is first received by the after-treatment agent, which is positioned closer to the customer. This agent generates its own production plan based on the customer's demand and existing capacity constraints. This plan is then communicated to the drying agent as "internal demand". The internal demand differs from the initial customer demand because it has been adjusted according to the capabilities of the after-treatment process. Subsequently, the drying agent sends its production plan to the sawing agent.

Another important aspect is the divergent production structure of the sawing process. When a log is sawn, multiple co-products are typically produced simultaneously. Therefore, producing only one specific product type according to demand may not always be possible. To address this issue, the production planner must select suitable sawing patterns that maximize the production of the required products while considering the unavoidable co-products. In addition, switching between sawing patterns to meet different customer demands requires setup time, such as changing the saw blade configuration. These setups reduce the effective production time and therefore influence the total available capacity of the sawing process. The planner must account for these factors to avoid overestimating the achievable production rate.

An advantage of pull planning and scheduling is that it typically results in lower inventory levels for finished products and work-in-process items waiting before the drying agent. However, a potential drawback is that the log stack may not be emptied regularly, as production focuses only on the products in demand. This may lead to quality degradation of logs that remain stored for long periods.

### 5.2.1.2 The push planning and scheduling

The push planning and scheduling are triggered by the availability of logs in the inventory. In this approach, production quantities are determined primarily by the amount of raw material available in the log stack. The main objective is to process as many logs as possible, subject to the capacity limitations of the sawmill production system. Under this approach, the planner schedules production based on the current inventory level of logs. As long as logs are available, production continues to be pushed through the system. Customer demand is therefore not the primary driver of production decisions. For instance, if a large number of pine logs are available in the inventory, the planner may choose sawing patterns that process these logs immediately, even if the resulting products exceed current customer demand.

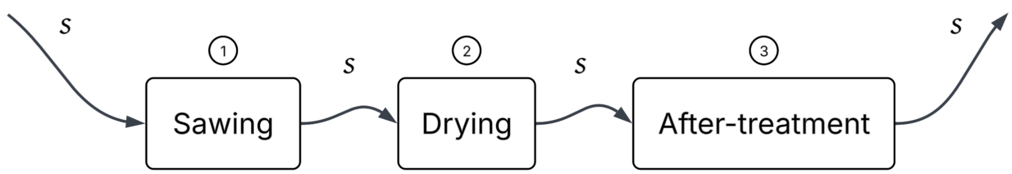


***Figure 10.*** *Push planning and scheduling*
*(adapted from Dumetz et al., 2019, p.266)*

Figure 10 illustrates the push planning and scheduling approach. The sawing agent receives information about the supply of logs, which is notated as "s", and generates its production plan based on this information, considering its capacity and objectives. This plan is then communicated to the next agent, which is the drying agent, as "internal supply" information. This internal supply differs from the original supply received by the sawing agent because it has been adjusted according to the sawing agent's capacity. Finally, the production plan from the drying agent is sent to the after-treatment agent, which will then generate its own production plan based on the information received from the previous agent.

Because production is driven by supply rather than demand, this approach may lead to inventory buildup of finished goods and WIP, such as pallets of products waiting in front of the kilns. Excessive waiting times before drying may lead to quality degradation of the products. In addition, due to the divergent production structure of sawmills, sawing a log typically generates multiple co-products simultaneously. As the planner aims to maximize the utilization of available logs, sawing patterns that yield higher product value or larger quantities may be preferred. However, this can result in the overproduction of certain products that are not immediately required by customer demand. Despite these drawbacks, push planning and scheduling ensures that the log stack is regularly processed and prevents long storage times of logs, which could otherwise lead to raw material quality deterioration.

#### 5.2.1.3 The hybrid push-pull system planning and scheduling with the decoupling point

There are four possible locations for placing the decoupling point (DP) within the production system, as illustrated in Figure 11. The decoupling point defines the inventory management (where should the inventory be positioned) and the changes of the production strategy (from push to pull system). At one extreme, when the decoupling point is positioned at the very downstream end, the system operates as a pure push system. In this configuration, production decisions are triggered by supply-side factors such as raw material availability or production capacity. Products are continuously processed and pushed downstream regardless of demand. This resembles the push planning and scheduling, as discussed earlier. At the opposite extreme, when the decoupling point is located at the most upstream stage, the system behaves as a pure pull system, which is referred to as the pull planning and scheduling. In this case, production is entirely driven by actual customer demand. Downstream stages initiate production requests, which propagate upstream through the system.

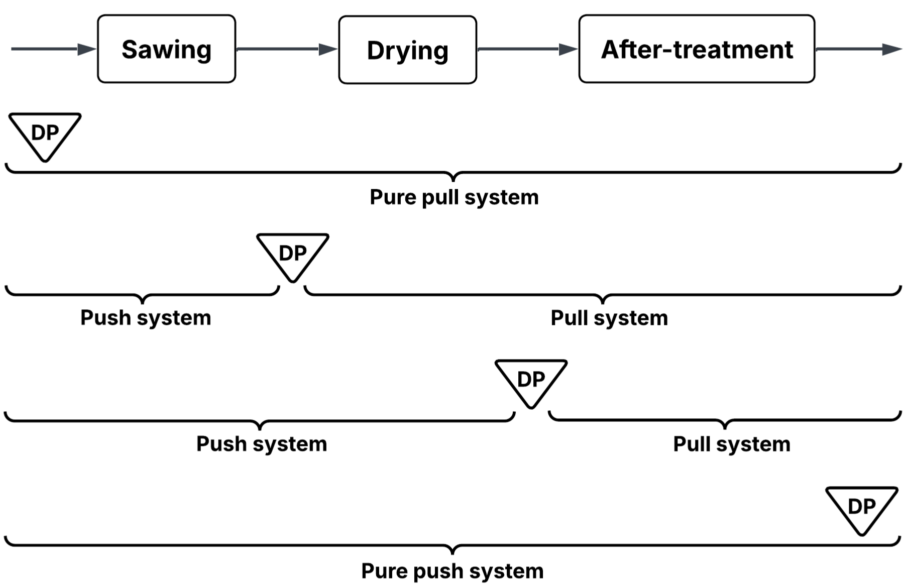


***Figure 11.*** *The four alternatives for positioning the decoupling point*

Cid Yáñez (2009) highlights that in a hybrid push–pull strategy, upstream stages operate under a push strategy to push materials into the system and ensure stable utilization of capacities, while downstream stages operate under a pull strategy to pull materials out in order to maintain responsiveness to customer demand. The transition between these two production strategies is defined by the decoupling point, which acts as a buffer separating supply-driven and demand-driven operations. The positioning of the decoupling point has significant implications for system performance, influencing inventory levels, responsiveness, and resource utilization. A detailed analysis of the hybrid push–pull strategy is provided in Section 6.

### 5.2.1.4 The two-phase planning and scheduling

The two-phase planning approach consists of two sequential planning phases: an upstream phase and a downstream phase, as shown in Figure 12.

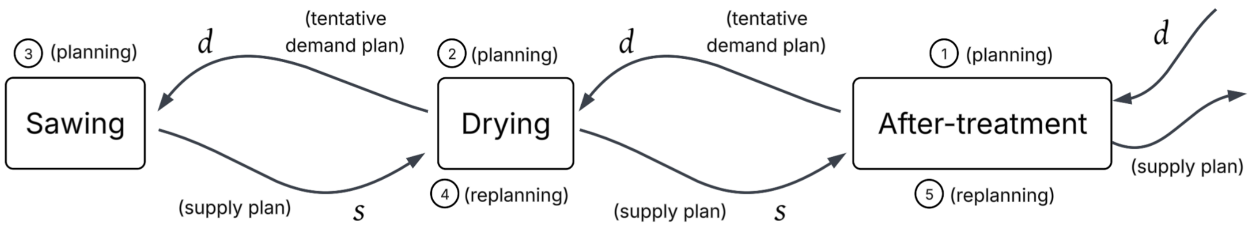


***Figure 12.*** *Two-phase planning and scheduling (adapted from Gaudreault et al., 2010, p.182)*

In the upstream phase, an infinite capacity planning step is performed. During this stage, agents ignore production capacity and supply constraints and generate a tentative production plan solely based on the demand requirements. Each agent computes its demand for upstream resources and sends this information to its upstream supplier. The purpose of the upstream phase is to estimate the required supply quantities.

In the downstream phase, a finite capacity planning is carried out, where real production constraints are taken into account. Upstream agents evaluate whether they can meet the requested demand given the actual supply availability and production capacity. Additionally, the co-production introduces additional constraints on feasible production outcomes. Instead of fully satisfying the demand, each supplier generates a feasible supply plan and sends it to its downstream agent. As a result, downstream agents receive the updated feasible supply information and revise its production plans accordingly.

This process forms a coordination loop between upstream and downstream agents. In the first phase, demand information propagates upstream in a tentative manner, while in the second phase, actual supply information propagates downstream. Through this coordination mechanism, the iterative exchange of information, a coordinated and feasible production plan is generated. This approach supports local optimization, as each agent considers its own constraints and objectives. However, some limitations remain. Since the process is primarily driven by demand, certain logs available in inventory may not be selected for processing if they do not match current product requirements, potentially leading to quality degradation over time. On the other hand, this approach has the advantage of maintaining relatively low inventory levels between stages, as only the selected logs are processed.

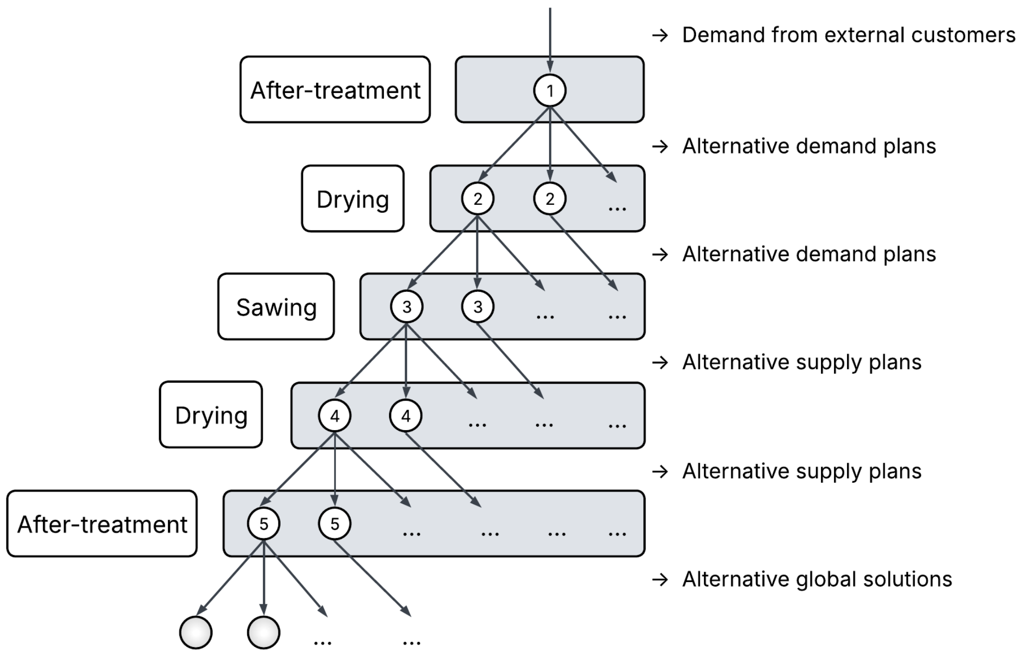


***Figure 13.*** *Tree for two-phase planning and scheduling (adapted from Gaudreault et al., 2009, p.443)*

In addition to the coordination mechanism explained above, Gaudreault et al. (2009) propose a new coordination mechanism as a tree structure, as illustrated in Figure 13. This enables each local agent to generate multiple alternative solutions instead of a single demand plan or a single supply plan. Each alternative is then considered as a possible input for the subsequent agent, leading to the construction of the coordination mechanism in the form of a tree. Each level of tree corresponds to an agent in the system. A node at each level represents a solution to the sub-problem. The arcs connecting nodes represent that there are different feasible solutions proposed by agents. At the final level, each leaf node of the tree corresponds to a complete and feasible solution to the overall problem.

The main distinction between the traditional structure and the tree structure of two-phase planning lies in the exploration of alternatives. Traditional structure generates only one plan at each agent and does not consider any other options, which may result in possibly better solutions. In contrast, the tree structure systematically explores multiple paths, creating a decision tree of possible production plans. The final solution is selected from these alternatives based on criteria, such as minimizing makespan or total tardiness.

#### 5.2.1.5 The bottleneck-driven planning and scheduling

Bottleneck-first planning and scheduling are driven by the capacity of the bottleneck machine in the production system. In this approach, production quantities are determined based on the feasible capacity of the bottleneck resource. Since the bottleneck limits the overall throughput of the system, it becomes the primary reference point for production planning and scheduling.

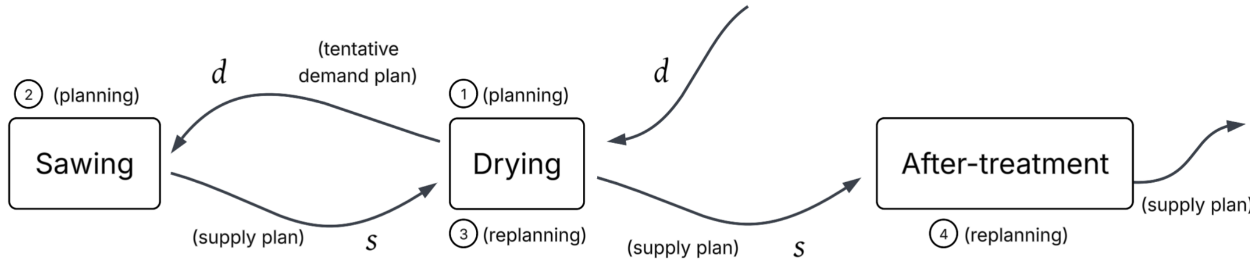


***Figure 14.*** *The bottleneck-driven planning*
*(adapted from Gaudreault et al., 2010, p.182)*

Figure 14 illustrates the bottleneck-driven planning and scheduling approach, which is used as an example to support the explanation. The customer's demand is received by the bottleneck machine, represented here by the drying stage. The bottleneck may shift depending on the production conditions. The coordination process is the same as in Section 5.2.1.4. The difference is that the demand is transmitted to the bottleneck machine, instead of the after-treatment. According to Gaudreault et al. (2010), the drying production center often becomes the bottleneck because of the heavy investment needed to increase the capacity of the kilns.

The main objective of this approach is to ensure that the bottleneck machine is neither starved nor overloaded. In other words, the bottleneck should always have enough work to process, while the incoming flow of work should not exceed its processing capacity. For example, if customer demand is 150 logs per day but the capacity of the kilns is only 100 logs per day, the planner will adjust the daily production plan to match the kiln capacity of 100 logs per day.

Because the throughput of the entire production system is constrained by the bottleneck machine, other processes, such as sawing and finishing, must adjust their production rates accordingly. As a result, these processes may not operate at full capacity. However, this approach ensures that the bottleneck resource is utilized as efficiently as possible.

Another advantage of bottleneck-driven planning is that WIP inventory can be reduced since upstream production is regulated to match the bottleneck capacity, excessive accumulation of products waiting before the kilns can be avoided. On the other hand, because the overall production rate is limited by the bottleneck, longer lead times may be required to satisfy customer demand.

## 5.3 The hierarchical planning and scheduling approach

In the hierarchical planning approach, the overall problem is decomposed into different decision-making levels. Santa-Eulalia et al. (2011) identify three main levels within this structure: strategic, tactical, and operational planning. At the strategic level, long-term decisions are made to support the organization's mission and vision. The tactical level focuses on production planning, where decisions are made regarding what to produce, how much to produce, safety stock, production capacity, and staffing. These decisions define the intermediate goals and overall constraints for the system. At the operational level, detailed decisions are made, such as detailed scheduling. Based on the production planning at the tactical level, specific schedules are determined to execute it effectively. Consequently, rather than relying on fully integrated planning and scheduling, the hierarchical approach decomposes the problem into smaller sub-problems, typically separating tactical planning from detailed scheduling. The interaction between these two models follows a hierarchical structure.

First, the production planning phase represents the tactical level, where aggregate production decisions are determined over an intermediate horizon, e.g. two-week horizon. Specifically, the model decides the number of logs to be processed and the resulting production quantities of different products. The objective of the production planning in a sawmill can be defined either in terms of maximizing production volume or maximizing revenue. Maximizing volume focuses on increasing the number of timber pieces produced. However, higher production volume does not necessarily lead to higher revenue, as different timber products generate different profit margins, and some products are significantly more valuable per piece than others. In order to handle this situation, product-specific coefficients are introduced to represent the profit across products, allowing the company to easily translate volume-based results into profit-based decision-making when implementing the model in practice. This approach provides flexibility while keeping the model structure adaptable. In addition, the constraints are the production capacity of sawing, drying, and after-treatment stages. Besides that, inventory bounds (the upper and lower bounds of the finished goods inventory level) are imposed to avoid overproduction and satisfy demand requirements.

Subsequently, based on the aggregate planning, the scheduling phase represents the operational levels and translates these aggregate production targets into detailed, time-based decisions. Using the outputs of the planning models as input parameters, such as batch sizes, target quantities for each kiln, the scheduling model determines the exact timing of operations, including when each batch starts, how products are assigned to kilns, and how resources are utilized over time. It explicitly considers operational constraints such as kiln non-overlap, loading and unloading time windows in chamber kilns, batch compatibility, and inventory balance at each time step. The objective of the scheduling model is to minimize the makespan, ensuring that the planning production targets are achieved as early as possible.

# 6. Analysis

*This chapter presents the analysis of an agent-based planning and scheduling approach with a focus on the hybrid push-pull planning and scheduling approach with the decoupling point. Section 6.1 first identifies the key production decisions to be made by each agent within the sawmill production. Section 6.2 then analyzes different scenarios by positioning the decoupling point at various positions. The decoupling point divides the system into upstream and downstream segments, thereby influencing the decision-making responsibilities of each agent. In Section 6.3, a simulation model is developed using ExtendSim, in which different scenarios are implemented and analyzed. Finally, Section 6.4 presents the simulation results, followed by critical discussions in Section 6.5.*

## 6.1 Agent-based decision-making

Various production planning and scheduling approaches are introduced in Section 5, among which the agent-based approach is selected for further analysis in this section. This approach is selected due to its ability to decompose complex problems into smaller, more manageable sub-problems, thereby addressing computational complexity and improving scheduling flexibility compared to other approaches. An agent-based production system consists of multiple interdependent agents. Collectively, these agents are responsible for production planning decisions, such as what and how much to produce, while individually handling scheduling decisions, including job sequencing, resource allocation, and timing. Each agent receives planning information from its upstream agent and makes local decisions on how to execute the assigned tasks. The agent-based approach is therefore selected for further analysis. In this study, there are three agents in the production process: sawing, drying, and after-treatment agents. The local decisions made by each agent are discussed as follows.

**Decisions made by sawing**

At the sawing stage, the sawing agent determines a saw plan, specifically the sequence in which logs are processed. Additional decisions could include selecting sawing patterns to maximize yield or profit and determining production quantities. For the sake of simplicity, several assumptions are made in this thesis: each log type is assumed to have only one sawing pattern and to generate only one product type. As a result, co-production is not considered in the analysis. Furthermore, the number of logs to be processed is not treated as a decision variable, due to the operational restriction to empty log stacks. Consequently, this thesis only focuses on how to better decide the sequence of processing logs in the saw plan. The sequence for the saw plan is influenced by the production strategy employed by the agent, which is linked to the position of the decoupling point. As a result, the objectives of the saw plan will vary depending on the production strategy used. This topic will be discussed further in Section 6.2.

**Decisions made by drying**

The drying agent is responsible for deciding the drying sequence of timber batches and to which kiln they are assigned. Since the drying process follows a first-in-first-out (FIFO) rule, the sequence is therefore predetermined. As a result, the drying agent's role is primarily focused on kiln allocation.

When determining the kiln allocation, it is important to distribute logs evenly across all kilns in operations. If too many logs are assigned to the same kiln, they will accumulate in the queue, while other kilns remain idle. Repeatedly alternating log assignments among all kilns helps prevent imbalance and kiln starvation, maintains a steady flow, and improves overall drying capacity utilization.

Next, to further maximize throughput, not only the number of pallets that exit the drying process, but also the number of pallets waiting before drying should be taken into consideration. Grouping compatible products improves batching efficiency. For instance, Logs that generate products which may or may not share the same ProdID but do share the same DryingID should be assigned to the same kiln. Sawing them together allows them to be palletized together, and their pallets to be grouped more easily. This results in fuller pallets and fuller drying batches, which improves drying throughput.

Continuous kilns should be prioritized for utilization, as idle time in continuous kilns should be minimized. When a continuous kiln runs idle, interruptions in the continuous movement of wagons disrupt the designed airflow and temperature conditions, resulting in poor air circulation and uneven drying. Therefore, the DryingID with the largest amount of drying demand, measured in number of pallets, should preferably be assigned to a continuous kiln in order to keep it operating continuously. When the inventory in front of a continuous kiln is low, another DryingID may be assigned if necessary. However, switching between DryingID should be strictly minimized, as it disrupts temperature conditions. Since limiting changes in DryingID is essential to maintain consistent drying quality and avoid uneven moisture content, a different DryingID should only be assigned to a continuous kiln when inventory becomes critically low and only in exceptional situations. Conversely, if a log type is for a continuous kiln but has a very high volume, it may be reassigned to a chamber kiln in order to reduce excessive waiting time before drying.

The remaining logs, which differ in height or log characteristics and are therefore less suitable for grouping in continuous kilns, can be allocated to the chamber kilns. These logs are generally more heterogeneous, making chamber kilns a more appropriate and flexible drying option.

**Decisions made by after-treatment**

Finally, at the after-treatment stage, the after-treatment agent determines the processing sequence for converting semi-finished products into final goods, with an after-treatment plan specifying the processing sequence of the ProdIDs. The existence of an after-treatment plan thus provides greater flexibility, enabling production to better respond to external customer demand and match the required product specifications more accurately.

## 6.2 The analysis of the positions of the decoupling point

Among the agent-based production planning and scheduling approaches (see Figure 8), the hybrid push–pull system with the decoupling point is identified as a practical approach that does not require intensive computation while still providing effective solutions within a short time frame. Although this approach does not guarantee optimal solutions, it offers solutions that are sufficiently good and operationally feasible. Hopp and Spearman (2004) argue that real-world production systems rarely operate under purely push or pull strategies, particularly in environments characterized by divergent material flows and co-production. In the hybrid push-pull system, the push system helps manage the variability caused by co-production and the diverse nature of sawmill production, while the pull system provides greater responsiveness to customer demand (Gaudreault et al., 2010). Although co-production was not considered in this study, the objective is to analyze a model that can effectively address both divergence and co-production in the sawmill production system. Therefore, the hybrid push–pull planning and scheduling approach is selected for further analysis.

The positions of the decoupling points (DP) have significant implications for system performance. In this study, different scenarios are analyzed by positioning the DP at various locations within the production process. The position of the DP determines how far demand information is propagated upstream across the agents. By varying the extent of demand information flow, different production strategies can be established within the system. For instance, if demand information is not propagated to the sawing agent, this agent operates under a push-oriented planning strategy, where decisions are based solely on supply conditions. In contrast, agents that receive demand information adopt a pull-oriented planning strategy, where decisions are driven by customer requirements. As illustrated in Figure 11, the DP separates the upstream push-oriented production strategy from the downstream pull-oriented production strategy. Each agent makes decisions based on the production strategy of the system in which it operates and the corresponding production strategy.

Different production strategies can be adopted, either aiming to push more materials into the system or to pull only the required materials. Accordingly, different sequencing rules can be applied. For push-oriented sequencing rules, examples include the largest-stack-first rule or prioritizing logs based on their expected profit contribution or volume. In contrast, pull-oriented sequencing rules can be driven by customer demand. Logs can also be pulled and prioritized based on their ability to generate timber dimensions urgently needed in the kilns, thereby preventing kiln idleness, or based on their ability to generate products with low inventory levels before after-treatment or in the FGI. Such alternative strategies have the potential to improve both economic performance and operational efficiency.

In this study, the upstream push-oriented production strategy is implemented using the largest-stack-first sequencing rule. Under this rule, log stacks are processed in descending order based on their inventory levels, beginning with the largest available log stack and continuing with the next largest. This sequencing logic is applied to the agents positioned upstream of the DP. The purpose of the upstream push-oriented strategy is to push logs into the system and maintain a high utilization rate of machines while simultaneously reducing the risk of raw material quality degradation caused by prolonged storage times. In contrast, the downstream pull-oriented production strategy is implemented using the urgent-customer-order-first rule. Under this rule, products associated with the most urgent customer demand are prioritized, followed by products with the next highest levels of urgency. This sequencing logic is applied to the agents positioned downstream of the DP. The purpose of the downstream pull-oriented strategy is to improve responsiveness to customer demand. Therefore, only one upstream push-oriented production strategy and only one downstream pull-oriented production strategy are chosen as a proof of concept, intended to demonstrate the effect of the decoupling point on agent decision-making and the system performance.

Therefore, the introduction of a decoupling point enables the stage downstream of the DP to alter the processing sequence of materials, independent of the sequence determined in the upstream stages. In this study, four different decoupling point locations are analyzed: (1) before sawing, (2) after sawing but before drying, (3) after drying but before after-treatment, and (4) after after-treatment. Each of these configurations is examined in the following sections.

### 6.2.1 The decoupling point before sawing

First, the DP is positioned upstream, before the sawing stage, as shown in Figure 15. In this configuration, demand information is integrated into the planning and scheduling decisions for all agents involved. Consequently, each agent operates under a pull-oriented planning strategy, where decisions are driven by downstream demand. Since the DP is located before the sawing stage, a single production strategy is applied across all agents, which is the pull-oriented strategy. This enables the coordination of operations from sawing through drying to after-treatment in alignment with customer demand.

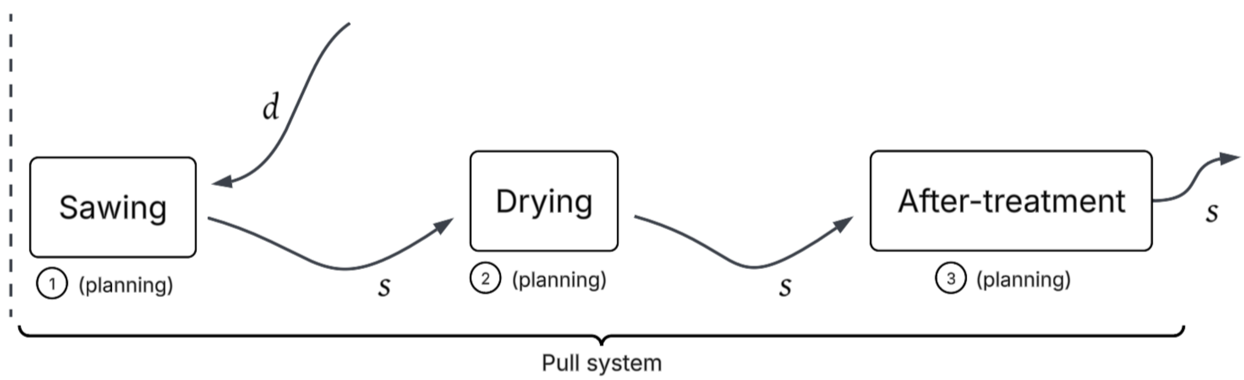


***Figure 15.*** *The hybrid push-pull system planning with the decoupling point before sawing*

The pull-oriented strategy is driven by customer demand, meaning that all agents share the common objective of fulfilling downstream requirements. In this configuration, both the saw plan and the after-treatment plan are generated based on demand-driven decision rules. Specifically, the after-treatment plan follows the urgent customer orders first rule, ensuring that products are processed according to demand priority. Similarly, the sawing plan prioritizes log types that are more likely to produce products required by customers, thereby aligning upstream production with downstream needs.

However, the pull strategy implemented in this study differs from a traditional pure pull system. In a conventional pull system, decisions regarding raw material procurement and production quantities are directly determined by external demand. In contrast, “empty the stack” is required, which constrains the ability to fully control input selection and production volumes. As a result, even under a pull-oriented strategy, the system may generate excess products due to the need to process available raw materials. At the same time, it also helps to prevent quality degradation.

Placing the decoupling point before the sawing process increases the responsiveness of the production system by allowing all agents to utilize demand information in their planning. This reduces the likelihood of producing unnecessary products and limits the accumulation of intermediate inventory between stages. Consequently, production capacity can be directed toward fulfilling actual demand. However, this configuration may lead to lower resource utilization across agents, as operations are triggered by demand rather than continuous processing of available materials.

### 6.2.2 The decoupling point after sawing before drying

The DP is then positioned between the sawing and drying stages, as illustrated in Figure 16. In this configuration, demand information is propagated to the drying and after-treatment agents, while the sawing agent operates without direct access to demand information. As a result, a hybrid production strategy is established, where the sawing agent follows a push-oriented planning strategy, and the drying and after-treatment agents operate under a pull-oriented planning strategy.

Upstream of the DP, the sawing agent applies the largest log stack first sequencing rule, which prioritizes processing based on available inventory and supports efficient utilization of raw materials. Downstream of the DP, the drying and after-treatment agents follow demand-driven planning logic, where operations are aligned with customer requirements. A dry plan, whose main role would be to define a new drying sequence, follows the urgent customer orders first rule, the same as the after-treatment plan.

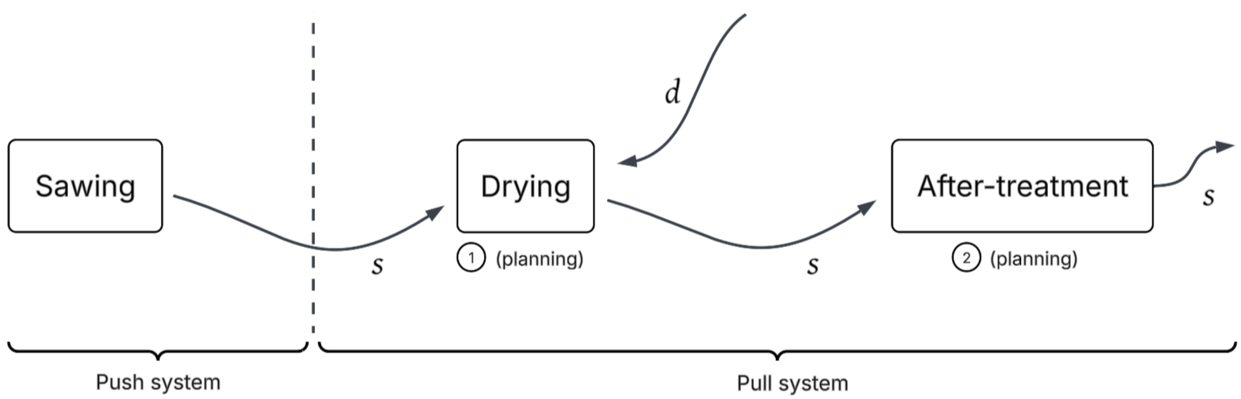


***Figure 16.*** *The hybrid push-pull system planning with the decoupling point after sawing and before drying (adapted from Dumetz et al., 2019, p.268)*

Positioning the DP before the drying stage allows demand information to directly influence drying decisions. As a result, sawn timber is prioritized for drying based on the external customer demand, improving alignment between production and customer requirements. However, this creates a problem. Some timbers may be sawn because they originate from large log stacks selected by the upstream strategy in the saw plan, yet they may remain undried for an extended period before entering the kilns if there is no immediate downstream demand for them. Freshly sawn timber begins to dry naturally after sawing. If it is stored for a long time before drying, it becomes vulnerable to quality deterioration, which can significantly reduce the value of the final products. Therefore, a DP configuration that encourages the accumulation of sawn but undried timber is considered impractical in the lumber production context. This also explains why it is meaningless to develop a dry plan in general. If such decoupling is undesirable in practice, then a separate dry plan will not be developed. Consequently, this decoupling point configuration is not explored further in this study.

### 6.2.3 The decoupling point after drying before after-treatment

The DP is positioned downstream, following the drying process but preceding the after-treatment, as illustrated in Figure 17. In this configuration, the demand information is received by the after-treatment agent but is not communicated back to the upstream agents (sawing and drying). This leads to a difference in production strategy between the upstream and downstream agents. Consequently, the DP is placed after the drying process and before the after-treatment.

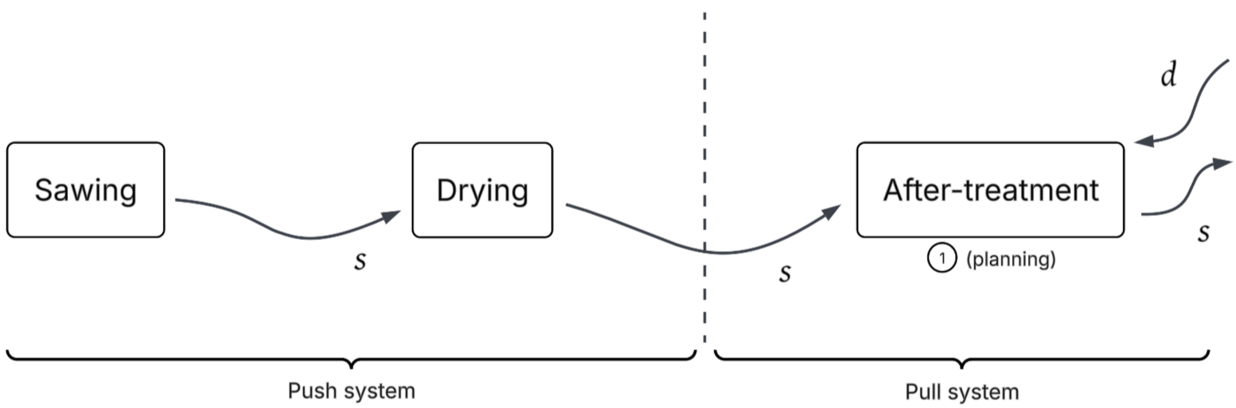


***Figure 17.*** *The hybrid push-pull system planning with the decoupling point after drying and before after-treatment*

The sawing and drying agents, which are located before the DP, operate under the push-oriented strategy. While the after-treatment agent, which is located after the DP, operates the pull-oriented strategy. Within this configuration, the sawing and drying agents prioritize maximizing production based on the push-oriented strategy, regardless of the current demand. In contrast, the after-treatment agent focuses on fulfilling the customer's demand. It means that the after-treatment agent only produces the product required by the customers.

In this configuration, the saw plan is generated based on the largest log stack rule. This means that the sawing agent prioritizes logs with the highest supply first and processes them according to their supply condition. The drying agent follows the same principle, adhering to a FIFO approach. As a result, the first WIP produced by the sawing agent will be processed first by the drying agent. On the other hand, the after-treatment plan, implemented by the after-treatment agent, prioritizes urgent customer orders. Unlike the sawing and drying processes, which focus on supply conditions, the after-treatment process centers on fulfilling customer demand.

This decoupling after the drying process allows for boards to be produced independently, with the after-treatment responding specifically to demand. This setup enables efficient production in the upstream processes while providing the flexibility needed in the downstream response. As a result, the upstream processes can operate at their optimal capacity while ensuring that there is a surplus of finished goods.

### 6.2.4 The decoupling point after the after-treatment

Finally, the DP can be moved all the way downstream and positioned after the after-treatment stage, as illustrated in Figure 18. In this configuration, demand information is no longer incorporated into the planning and scheduling decisions of any agent. Instead, only upstream supply information is considered, making this configuration conceptually equivalent to a pure push system. Since all production stages are located upstream of the DP, all agents operate under a push-oriented production strategy. As a result, materials flow continuously through the system from sawing to drying and then to after-treatment without being selectively held back in response to downstream demand.

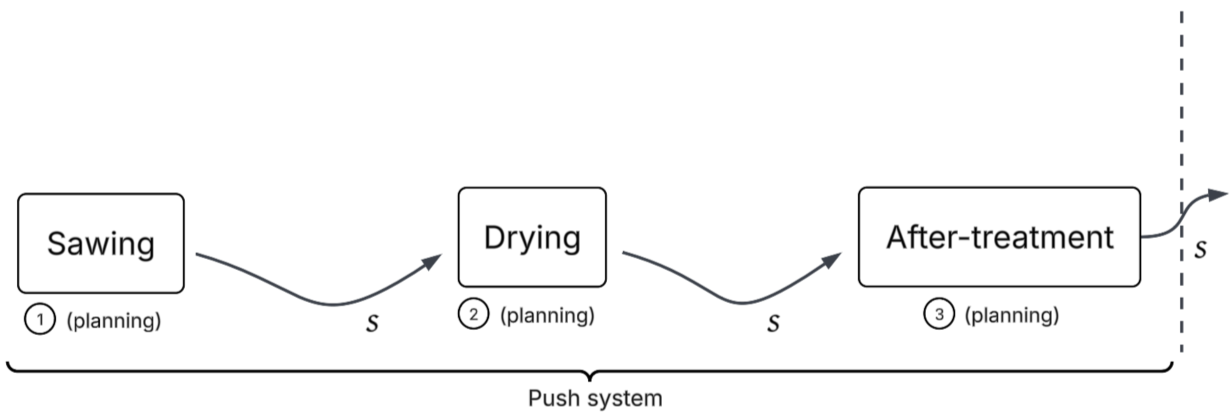


***Figure 18.*** *The hybrid push-pull system planning with the decoupling point after after-treatment*

Compared with configurations in which the DP is positioned between agents as discussed above, this configuration leads to a smoother and more uninterrupted material flow. All materials are pushed through the production system according to the upstream production strategy and continue toward the final stage. In this sense, only one main scheduling sequence needs to be determined, namely the sequence imposed at the very upstream stage. Accordingly, the saw plan is sequenced from the largest log stack to the smallest. A corresponding sequence is then followed in the after-treatment plan, ensuring consistency across stages and preserving a continuous push flow throughout the system. This configuration is operationally simple and reduces the need for frequent replanning or coordination between stages.

In this configuration, there is no point at which the processing sequence is adjusted in response to demand signals, and no products are held back at any stage to prioritize others based on demand. As a result, all products, including those not required by demand, can move through the system without additional waiting time between stages. However, as a push-oriented system, this configuration tends to produce more than necessary and may produce and process materials that are not immediately required, which can lead to a mismatch with the customer demand.

To better capture these system dynamics and assess the performance of different configurations, a simulation model is developed in the following section to analyze the impact of different decoupling point positions.

## 6.3 Building the simulation model

Simulation is used to model the sawmill production process, which encompasses sawing, drying, and after-treatment processes, as shown in Figure 19. WIP inventory exists in four forms within the process: logs stored in the raw material inventory (RMI) before sawing, palletized timber waiting before the drying process, dried products waiting for the after-treatment stage, and finished goods in the finished goods inventory (FGI). The detailed production process has been discussed in Section 2. A simulation model is chosen due to the stochastic nature of the sawmill production system, characterized by uncertain log arrivals and potential machine breakdowns. Additionally, the complexity of these production processes, discussed in Section 4.3, exacerbates the challenges of analyzing operations using traditional analytical models. Therefore, a simulation model is preferred for its capability to manage both complexity and variability. This modeling aims to assess the effectiveness of the hybrid push-pull approach with the decoupling point positioned at different positions.

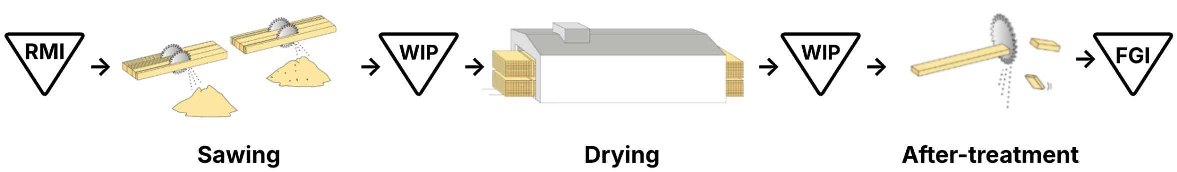


***Figure 19.*** *The recap of the sawmill production process*

The simulation model is a powerful tool for understanding and evaluating processes, particularly due to its ability to incorporate variability. This capability is crucial for analyzing business processes that exhibit complex structures and patterns of variability. Simulation models can be classified based on three key attributes: (1) static or dynamic, (2) deterministic or stochastic, and (3) discrete or continuous (Laguna & Marklund, 2025, pp. 259–261).

A static simulation model represents a system at a single point in time and does not track changes over time. In contrast, a dynamic simulation model captures the evolution of a system over time, such as monitoring changes in inventory levels, which is the objective of this study. Deterministic models are created without accounting for variability in input variables, while stochastic models do incorporate this variability, leading to different outcomes. In the sawmill production process, stochastic factors can be observed in machine breakdowns and the arrival of logs, both of which can directly affect inventory levels. Discrete models change only at specific points in time and describe how a system evolves through a sequence of distinct events. In the sawmill production process, these discrete events include truck arrivals and the completion of production processes (with the next event commencing once new input is received). On the other hand, continuous models show smooth changes over time. Therefore, the production process is best characterized as dynamic, stochastic, and discrete.

To model the sawmill production process, a discrete-event simulation model (DES) is utilized. DES is a modeling technique that describes how a system evolves over time by focusing on specific moments when changes occur, known as events. These events are the only points at which the state of the system is updated. Between events, the system is assumed to remain unchanged. In the context of the sawmill production process, the example of the events includes the arrival of logs and the completion of the sawing process. This means that the simulation remains static until new logs arrive or the next processing stage begins. In DES, entities represent the items moving through the process, such as logs or sawn timber. Each entity has specific attributes that capture its characteristics, such as the distribution function of the logs. The simulation operates through a repetitive cycle, starting with initialization, where the initial state of the system and the event list are defined. Key events within the sawmill system include the arrival of logs, the start of processing, and the completion of processing at each stage. The sawmill system is characterized by variability in both arrival times and processing downtimes. The simulation captures changes in the system's state, such as inventory length and resource utilization, only when these discrete events occur. The ExtendSim software was used to model the DES for the production process.

The purpose of the simulation experiment is to evaluate how different positions of the decoupling points impact system performance. The study specifically focuses on analyzing inventory levels at four distinct locations as discussed in Section 6.2. A scenario-based experimental design was employed, creating four scenarios based on the location of the decoupling point, each reflecting a different allocation along the production stages. To ensure comparability across scenarios, all experiments were conducted under identical stochastic conditions. In this simulation model, the co-productions involved in the sawing process were not included in order to simplify the model. However, the simulation still effectively captures the mix of convergent and divergent elements within the sawmill production system, as discussed in Section 4.3.

The simulation model analyzes different scenarios, with the upstream and downstream applying production strategies discussed in Section 6.2. These strategies dictate the sequences for processing materials. The simulation operates according to these predefined sequences, making the results closely aligned with the planned strategies. Each scenario runs for a duration of 14 days. To minimize variability in the results due to the stochastic nature of the input data, each scenario is executed 10 times. The logic of the simulation model, along with its detailed settings, will be explained in the next section.

### 6.3.1 Simulation logic for arrival

The arrival process involves trucks delivering logs to the sawmill. Each truck carries various types of logs. The logs delivered consist of multiple log types and are measured in $m^3$to (cubic meter “toppmatt”). This unit is commonly used in the sawmill industry to estimate the volume of sawn timber, as the toppmatt is the narrowest part of the log that determines how much sawn product can be extracted. The volume is calculated by measuring the length of the log and its diameter at the top, which allows for determining the volume of a right cylinder. As each log is unloaded, it is classified, receives a LogID and is then stacked according to its log class.

### 6.3.2 Simulation logic for sawing

The sawing process is a crucial component of the sawmill simulation, primarily aimed at converting each log into sawn timber and estimating the quantity of products generated. In this simulation model, each log follows a single sawing pattern, and one log produces only one type of product. Logs are transported along a conveyor while they are being sawn. During the sawing process, each log is sawn into several identical pieces. After sawing, the products are grouped into pallets based on their ProdID. If the product type remains consistent and the pallet has not yet reached its maximum capacity, the product is added to the current pallet.In reality, only full pallets are sent to kilns to preserve air circulation and maintain drying quality. However, in the simulation, if a different product type arrives or the pallet becomes full, the current pallet is released and sent to the drying stage, even if it is not full. This differs from reality, but the effect is very minor.

### 6.3.3 Simulation logic for drying

The drying process simulates how pallets are dried using two types of kilns: a continuous kiln, which follows a continuous flow process, and a chamber kiln, which operates as a batch drying system. Each pallet is assigned to a specific kiln. A specific number of pallets are required in each drying batch for both continuous kilns and chamber kilns. The continuous kilns operate continuously. The chamber kilns can only be loaded and unloaded during working hours. Once pallets are loaded in chamber kilns, the drying process automatically starts without manual intervention until unloading.

### 6.3.4 Simulation logic for after-treatment

The after-treatment process serves as the final stage of production. The primary purpose of this model is to convert dried products into finished goods. After drying, the timber is depalletized into individual pieces. These pieces are then temporarily stored based on their respective ProdID and wait for the after-treatment plan to determine when they should enter the process. When a ProdID is selected as a new batch, each piece in the batch is planned one by one. Each piece is transported forward along a conveyor, where it is planed by a planing tool positioned above the conveyor. Once planned, the pieces become finished goods and are sent to the FGI, where they are categorized by ProdID together with finished goods already waiting for dispatch.

Finally, the external demand data are customer orders. Orders are placed on a daily basis, typically involving several different product types in varying quantities each day. Therefore, the order dataset is assumed as a predefined sequence of the external customer demand. In the simulation, customer demand is set to be deterministic, and the demand data is deducted from the FGI, representing fulfilled and dispatched orders.

## 6.4 Results

To gain an initial understanding of the effect of different decoupling point positions. The key evaluation parameter analyzed in this study is the inventory level, as it is preferable to minimize quality degradation caused by excessive WIP or high inventory levels between production stages. Table 2 presents the average inventory levels at four different inventory locations under the different DP configurations. As shown in the table, the differences between scenarios are substantial. The simulation was run 10 times, and the adequacy of the number of simulation replications was evaluated using the relative half-width of the 95% confidence intervals. For all evaluated scenarios with different inventory locations, the relative half-widths were below 1% of their corresponding sample means. This indicates low variability between simulation runs and a high level of precision in the estimated results. Therefore, 10 simulation replications were considered sufficient to obtain statistically reliable and stable performance estimates for the analyzed scenarios.

***Table 2.*** *The comparison of the average inventory level in different scenarios*

| **Average Inventory Level (10 runs)** | | | | |
|---|---|---|---|---|
| Inventory location | Log stacks (RMI) | After sawing before drying | After drying before after-treatment | After after-treatment (FGI) |
| Inventory form | Logs (unit) | Undried products (pallet) | Dried products (piece) \| (pallet) | Finished products (piece) \| (pallet) |
| Scenario 1 with DP before sawing | **40479** | 47 | 192088 \| 364 | 149985 \| 284 |
| Scenario 3 with DP after drying before after-treatment | 28321 | 53 | **201650 \| 382** | 150002 \| 284 |
| Scenario 4 with DP after after-treatment | 28186 | 53 | 197429 \| 374 | **154163 \| 292** |

The position of the DP has a clear effect on the inventory distribution because it changes the production strategy and, consequently, the sequencing of material flow. When a DP is introduced between stages, the system is no longer governed by one uninterrupted sequence. Instead, the production flow is split into two parts, and the downstream stage may reorder processing priorities according to demand. As a result, some materials are held back and must wait while other materials are allowed to proceed first. This resetting of the sequence tends to increase intermediate inventory at the DP location, which can be concluded from Table 2.

From a practical perspective, it is preferable to keep inventory either in the form of raw logs in the RMI or in the form of dried products, rather than as sawn but undried timber after sawing and before drying. Logs stored in the stack remain in raw material form and are less exposed to quality deterioration than freshly sawn timber. Once timber is sawn, its newly exposed surfaces come into direct contact with air, making it more susceptible to natural drying and associated quality defects. Similarly, inventories after drying are already dried, so the risk of quality degradation is much lower. By contrast, a high inventory of sawn but undried timber is undesirable because freshly sawn timber begins to dry naturally and may deteriorate if it waits too long before entering the kilns. This is the main reason why Scenario 2, in which the DP is positioned after sawing and before drying, is excluded from further analysis.

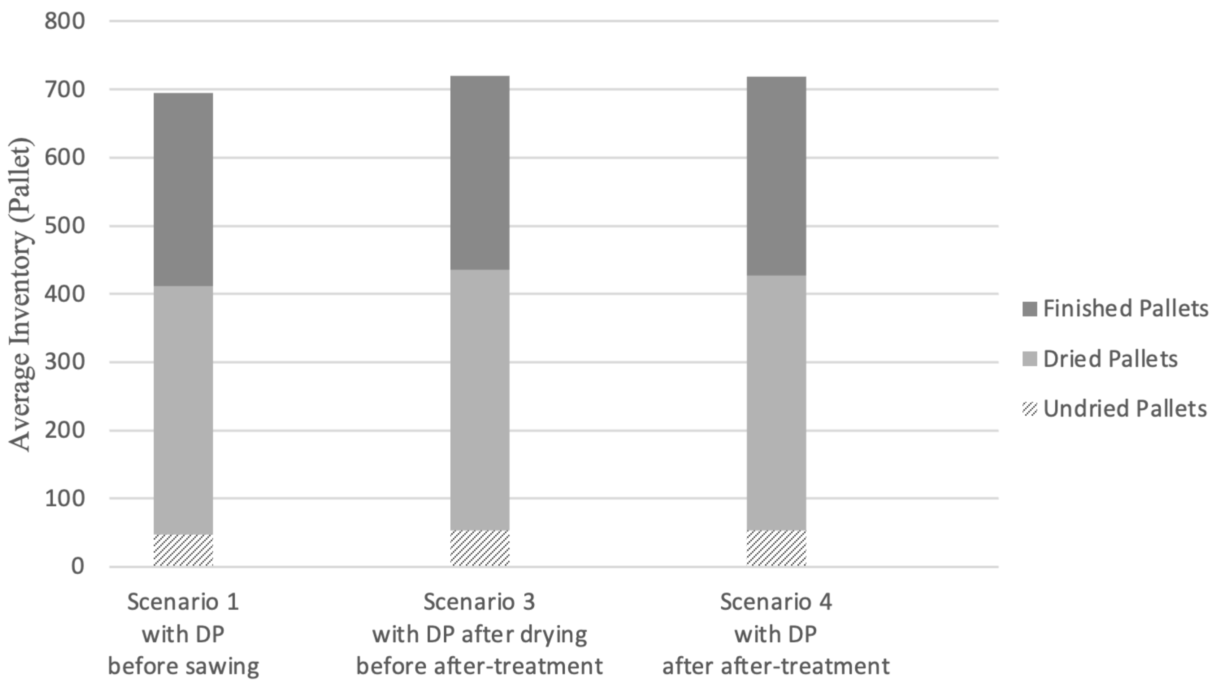


***Figure 20.*** *The average inventory levels for each scenario of undried pallets, dried pallets, and pallets of finished goods*

Figure 20 compares the average inventory levels of pallets for Scenarios 1, 3, and 4 at different inventory locations after sawing. In Scenario 1, demand information reaches all the agents until the sawing stage. As a result, production follows demand more closely. As shown in Figure 20, in Scenario 1, the number of undried pallets and the number of dried pallets downstream (the combined inventory before and after after-treatment) are reduced. At the same time, as is immediately evident from Table 2, more logs remain in the log stacks compared with Scenarios 3 and 4, since fewer logs are sawn unless they are required by demand. This indicates better demand alignment, but it also means that the upstream production capacity is not fully utilized. In other words, the system could have produced more under a push-oriented configuration. Therefore, the pull planning and scheduling approach in Scenario 1 likely reduces the revenue potential of the system. Since production is constrained by demand signals, the system cannot fully exploit available capacity to maximize throughput. Additional inventory should be held in the form of dried products so that the uncertain demand can be fulfilled. Although monetary throughput is not explicitly quantified in this thesis, it is reasonable to infer that the pull configuration in Scenario 1 has lower revenue potential than the more push-oriented configurations in Scenarios 3 and 4, where products are moved downstream more aggressively. Higher inventory levels increase the potential to satisfy uncertain future demand and may therefore result in higher revenue potential. However, since Scenarios 3 and 4 push logs into the system without taking external customer demand into account, there is also a risk that the products generated in these scenarios will not match actual demand.

With regard to Scenarios 3 and 4, Table 2 shows that the combined inventory after drying before after-treatment and after the after-treatment (FGI) is almost the same in both cases. This is expected, since both scenarios are based on the same saw plan sequence and therefore push material downstream in a similar manner. However, the internal distribution between these two positions differs. Scenario 3 has a higher inventory after drying before after-treatment, while Scenario 4 has a slightly higher inventory in the FGI. This can be explained by the location of the DP. In Scenario 3, the DP resets the sequence before after-treatment, which means that some materials must wait before after-treatment while others are prioritized according to downstream requirements. In Scenario 4, by contrast, the entire system operates more like a continuous push flow, allowing more material to reach the FGI.

This distinction is important from an operational perspective. In the after-treatment stage, products are planned and then sorted into different quality classes. It is also the final stage at which product dimensions can still be adjusted. If the inventory after drying before after-treatment is too low, the system loses flexibility to adapt dimensions and qualities in order to satisfy demand or maintain the minimum required finished goods stock. On the other hand, if inventory in FGI is too low, the company risks failing to meet customer expectations, since it is important to dispatch finished goods as soon as possible. Therefore, the key managerial implication is not simply to minimize inventory everywhere, but rather to maintain inventories at these two inventory locations within appropriate ranges. The inventory after drying before after-treatment provides operational flexibility for final adjustments, while the FGI ensures service responsiveness and customer satisfaction.

To determine which configuration performs better, Scenario 3 is considered overall superior to Scenario 4. In both scenarios, if dried products are stored for extended periods in inventory, either before or after the after-treatment stage, there is still a risk of quality degradation. However, after-treatment represents the final opportunity to trim and plane products. Therefore, it is preferable to maintain higher inventory levels after drying before after-treatment rather than in the FGI.

Furthermore, the key difference between these two scenarios lies in the presence or absence of the after-treatment plan. When the inventory of a specific ProdID in the FGI becomes low, or when urgent customer demand arises, these products can be prioritized in the after-treatment sequence. The existence of an after-treatment plan thus provides greater flexibility, enabling production to better respond to external customer demand and match the required product specifications more accurately.

## 6.5 Critical discussions

This thesis analyzes the hybrid push–pull production planning and scheduling approach with the decoupling point located at different positions within the production process. The DP divides the system into upstream and downstream segments and thereby determines the decision-making responsibilities of each agent. In a hybrid push–pull system, the DP separates the upstream control strategy from the downstream control strategy. As a result, introducing a decoupling point allows different stages of the system to follow different sequencing logics, with decisions being made locally by the agents themselves. Since the strategies applied before and after the DP are based on heuristics, the resulting solutions are not guaranteed to be optimal. However, they provide practical and computationally efficient solutions that are relatively easy to obtain.

In this study, various scenarios were analyzed using a simulation model that represents the production system, which combines divergent and convergent production flows. However, the simulation model did not account for co-production in the sawing process, which is characteristic of the divergent production system. This simplification affects the simulation results, as co-production increases the complexity of production planning and scheduling. Because in this type of production system, it is essential to consider not only the main products but also the co-products that need to be processed.

Although the largest-stack-first rule and the urgent-customer-order-first rule are examined in this thesis, other push- and pull-oriented sequencing rules could also be considered, as discussed earlier. In addition, kiln allocation should be considered together with the choice of production strategy. For example, in the pull configuration, the number of logs sawn and pushed into the system is lower than in Scenarios 3 and 4. In that case, kiln allocation should not remain unchanged. Instead of operating all available chamber kilns, fewer chamber kilns may be used in order to save energy and increase kiln utilization. Similarly, the assignment of logs to specific kilns may need to be reconsidered depending on the production strategy and operating conditions. In other words, changes in production strategy should always be evaluated jointly with kiln allocation decisions.

Finally, since the study considers only one push-oriented sequencing rule and one pull-oriented sequencing rule, it is fully acknowledged that the identification of the best-performing scenario is sensitive to these choices. The relative performance of the scenarios may vary under different sequencing rules and different supply and demand patterns. However, this is not the primary purpose of this thesis. Rather, the simplified setup serves as a starting point and a proof of concept, intended to demonstrate the effect of the decoupling point on agent decision-making and overall production behavior.

# 7. Conclusions and Future Work

*This chapter summarizes the conclusions drawn from this study and outlines potential future work to enhance its findings. Section 7.1 presents the conclusions based on two research questions. Section 7.2 discusses future research opportunities that could address the study's limitations and further improve its outcomes.*

## 7.1 Conclusions

This study evaluates various decoupling points within the agent-based production planning and scheduling approach. It is structured around two research questions:

1. To better understand a sawmill's planning and scheduling challenges and complexities, what is the structure and material flow of a sawmill production system?

2. Which production planning and scheduling approaches from the literature would be suitable for implementation in sawmill production?

Regarding Research Question 1, the sawmill's production process is identified as having a combination of divergent and convergent flows as discussed in Section 4.3. The sawing process exhibits a divergent production flow, while the drying process presents a convergent flow. Additionally, the after-treatment process also demonstrates a divergent flow. The initial divergent flow leads to joint production constraints, as one input generates multiple outputs simultaneously. This means that producing the main product will also yield co-products concurrently. In the drying stage, the convergent flow requires batch synchronization, since timber products must be grouped according to the same drying requirements. The second divergent flow further divides the output into multiple products. This production flow indicates that the output from the upstream processes significantly impacts the performance of the downstream production processes. The simultaneous production of both the main products and co-products places stress on the subsequent production stages, which must be capable of processing both types of products according to their capacity. This flow introduces complexity to the planning and scheduling by requiring strong coordination between upstream and downstream operations.

To address Research Question 2, a framework was developed that categorizes various production planning and scheduling approaches suitable for sawmill production. From this framework, one approach was selected: the agent-based planning and scheduling approach. This method was chosen due to its ability to decompose complex problems into smaller, more manageable sub-problems, effectively addressing computational complexity and enhancing scheduling flexibility compared to other methods. This approach is particularly suitable for the production processes, given its various coordination mechanisms. The study focuses on a hybrid push-pull strategy with decoupling points.

To find a suitable production planning and scheduling approach, a simulation model was created to test four different decoupling points and assess their effects on average inventory levels. The simulation model encompasses the arrival, sawing, drying, and after-treatment processes. The results indicate that Scenario 3, which has the decoupling point positioned before after-treatment, demonstrates the best performance in terms of average inventory levels. In this scenario, materials are pushed to the decoupling point without considering demand, and thereafter, production is adjusted to meet actual demand. The shift from a push to a pull strategy resulted in an increased average inventory level before after-treatment, providing greater production flexibility due to the higher inventory level available to adapt to varying customer demands.

From a practical perspective, this study provides insights into the impact of different decoupling points. This approach highlights the advantages of employing two different production strategies: push and pull. These strategies are outlined in two plans: the saw plan and the after-treatment plan. The saw plan varies depending on the production strategies used by the sawing agent. In this, it's recommended to have a push strategy for the saw plan, which focuses on emptying the log stack by prioritizing the log type with the highest inventory level. Conversely, the after-treatment plan employs a pull strategy that is driven by customer demand. Production decisions made after the decoupling point aim to fulfill specific customer needs. Having an after-treatment plan increases flexibility, allowing production to respond to changes in customer demand and improving the ability to fulfill those demands. Managing two distinct plans within a single production system requires effective coordination between upstream and downstream agents.

## 7.2 Future work

The current thesis presents several existing approaches to production planning and scheduling in Section 5, which outlines different ways of organizing production planning and scheduling and discusses their respective advantages and disadvantages. Building on this theoretical overview, Section 6 focuses on analyzing the hybrid push-pull system with the decoupling point approach. Although this approach does not guarantee optimal solutions for production planning and scheduling, it provides reasonably good solutions that are relatively simple to obtain.

As stated earlier in the simplifications, one product type is assumed to generate from one log type, and each log type is assumed to have only one sawing pattern. Therefore, one important area for future research is to include co-production explicitly in the analysis. For some log types that have more than one sawing pattern, multiple sawing patterns could also be incorporated to better reflect the complexity of real production systems. Consequently, introducing co-production also increases the complexity of the saw plan and kiln allocation. The drying agent must make more complex decisions regarding how to group products into batches, which pallets to prioritize, and how to allocate them efficiently across kilns, with the existence of the co-products.

In addition, the analysis in this thesis is limited mainly to the inventory level as the key evaluation parameter. Future studies could expand the analysis by including other performance dimensions. For the kiln, relevant measures could include idle time or utilization rate, which would provide insight into how effectively drying capacity is used. From an economic perspective, profit or monetary throughput could be analyzed to evaluate the financial performance of different planning and scheduling approaches. Another important measure is fill rate, which indicates the extent to which customer demand can be satisfied directly from available inventory without delay. Including such additional performance indicators would provide a more comprehensive evaluation of different production planning and scheduling strategies.

Finally, simulation makes it possible to incorporate supply variability (log arrivals) into the analysis that has already been conducted in this thesis. Future research could also include demand variability. By analyzing scenarios with different levels of demand intensity, defined as the volume of demand over a given period, it would be possible to assess how demand intensity influences different key evaluation parameters. Such an approach would provide a more comprehensive understanding of demand dynamics and their effects on system performance.

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