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Agent-Based Simulation and Analysis of Demand-Driven Production Strategies in the Lumber Industry

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Abstract. This paper addresses the generic problem of production planning in a divergent lumber production environment. It aims at analyzing the performance of various demand-driven production strategies a lumber production system. This analysis is performed using a simulation platform built on an agent-based advanced planning and scheduling system. Nine production strategies configurations are evaluated under six scenarios in order to carry out a complete mixed level design of 54 simulation runs. Each of these configurations is a combination of a decoupling point position and a level of capacity that is committed to contracts with customers. Accordingly, the six scenarios are designed as a combination of raw material mix (i.e., log diameter distribution) and lumber market prices. Production processes and co-production yields are based on a real manufacturing system from eastern Canada. Performance is evaluated from the logistic and economic points of view. Results demonstrate that demand-driven planning approaches that propagate demand information upstream the supply chain have the potential to improve planned customer service and reduce planned inventories. Results also show that lumber companies need to receive a premium from their customers in order to compensate from the loss of potential value resulting from a more constrained planning environment.

Keywords. Demand-driven production strategies, push, pull, decoupling point, agent-based simulation, process industry.

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Introduction

The forest products industry is an important business sector in Quebec, Canada. It plays a central role in its economy, providing over 115.000 direct employments and contributing about 4% of the GDP (QFIC, 2005). Despite its importance, the lumber industry is facing serious difficulties. Timber has become scarce in quantity and quality in public forests, especially in eastern Canada. Furthermore, the combination of longer hauling distances and higher gas price result in constantly increasing supply costs due to higher transportation cost. Moreover, the increased concurrence in the US market, due to the emergence of low cost fiber producers, has also affected Quebec's lumber industry directly or indirectly because of its business relationship with the pulp and paper industry. Finally, the Canadian lumber industry is facing strong protectionism measures in the US market, as well as a strong Canadian dollar that impairs exports in general.

In order to face these issues, lumber producers have focused their efforts on cost reduction and potential market value recovery (i.e., price-based optimization with 3D scanning and curve sawing). The use of such push-oriented strategies also finds justification in a highly standardized and commoditized North American softwood lumber market. On the one hand, Quebec sawmills have become highly productive machines, in spite of the small diameter of the available logs (Bédard, 2002; Lévesque 2005). On the other hand, they have become inflexible to adapt to changing market needs.

Even though these make-to-stock strategies served the industry rather well when market prices were higher and competition inexistent, new market conditions are reshaping the way lumber is demanded. Value-added wood based industries, such as engineered wood products and prefabricated houses have been experiencing a sustained development for a few years and ask for more collaborative relationships with lumber producers. Instead of ordering large volume of commodity, engineered wood producers expect high quality products on demand, because they do not hold large inventory of raw material. A similar kind of pressure is emerging from the home center industry. Vendor Managed Inventory (VMI) is becoming extensively used, forcing lumber producers to learn how to manage consigned inventories and replenish their customers with the right quantities of the right product at the right time. Contracts that enforce the delivery of certain volumes of products are also more frequently used with large retailers. Even if these contracts are profitable, they put pressure on lumber producers as they must pay important penalties, or even may lose their contract, if stores become out-of-stock.

Similar challenges have already been addressed by other industries, such as the food processing industry (Soman *et al*., 2004). In this industry, customer centric strategies let demand information guides production decisions. Conversely, the Quebec lumber production strategy is still mainly driven by potential value recovery and market prices. The adoption of such strategies is a difficult task for lumber producers who strongly believe that cost reduction is still the main driver in the lumber business. Although low production cost remains a barrier to access the lumber market, it becomes more and more necessary for lumber producers to adopt new strategies to improve their ability to meet market needs. The challenge is thus to find solutions to overcome the price-based push strategy that is widely accepted in the industry.

This paper provides an exploratory analysis of the introduction of demand-driven (pulled by demand information) strategies in the lumber production process. In order to do this, a series of simulation experiments that exploit an agent-based advanced planning and scheduling system have been carried out. The objective is to provide managerial insights concerning the design of a mix marketing strategy (i.e., contract and/or spot market) that is closely related to the production and procurement specificities of softwood sawmills.

1. Research context

1.1 Characterization of the lumber production process

The lumber industry is a process industry characterized by three main elements. First, the process routing is fixed (i.e., sawing, drying, planing and sorting). Second, raw materials (i.e., log diameter distribution and quality) play a central role in constraining the volumes and mix of product types that can be produced. Third, lumber is produced through a set of successive divergent processes with co-production (i.e., several product types are produced simultaneously) best described by recipes rather than bills of material (Crama *et al.* 2001).

Lumber is thus co-produced according to multiple input-process combinations that produce several pieces of lumber from each single log. At the sawing level, the combination of input (i.e., the size, diameter and shape of a log to be processed) and sawing process (i.e., a set of log breakdown sub-processes) defines the distribution of output to expect. In practice, a price list defining the value of each co-product guides the selection of the sawing process to breakdown each log independently. This price-based optimization process is a typical local optimization, as each log is broken down independently without regards to customer demand. Some control system take past production volume into account to select the next sawing processes, which improve output production control, and thus, demand satisfaction.

With pure price-based production control systems, the only two possible ways to influence the output is to control the mix of input logs and to adjust the price list that is fed directly into the production control optimizers. In other words, the same production control decisions apply simultaneously to all input logs and products. Consequently, the adjustment of the price list to force the production of a certain type of lumber, let's say [t×w; gd; l], where ***t*** is his thickness***, w*** the width, ***gd*** the grading and ***l*** the length, will automatically push the flow of other co-products. This production control strategy limits the company's ability to commit with customer to deliver specific product types. Contracts are thus usually based on the mill's historical production data used to identify the reasonable volume that can be promised and delivered on time. This strategy tends to increase inventory levels due to limited control of output mix. The remaining products with less rotation are then pushed to market at a generally lower price.

The drying process is a batch-oriented production process. It can be modeled as a set of more or less independent sub-processes (i.e., air-drying, kiln drying and equalizing) that together define a drying process. Air-drying and equalizing are usually carried out in the log yard. However, kiln drying is a long and energy consuming process. A batch of pieces of lumber of similar thickness and moisture content level is loaded into the dry kiln. Although the nominal dimension of lumber is not changed during this process, the output quality (i.e., twist, internal stress, surface defaults, etc.) depends upon the combination of drying sub-processes. The careful definition of the overall drying process influences the lumber grade, which can be controlled to improve response to market needs (Gaudreault *et al*., 2006).

Finally, the planing and sorting processes produce several grades of various dimensions of lumber. A visual inspection of each piece of lumber enables the operator to cut the piece at the most valuable length, eliminating defaults such as flash (i.e., pieces of bark at the end of a plank).

Production planning of planing and sorting operations is likewise a difficult task, mainly due to the complexity arising from the co-production and the limited sorting capacity constraints (i.e., limited number of sorting bins vs. the number of end product types). Furthermore, sawmills in Québec generally limit the number of output end products in order to produce enough volume of each single product to be sold as commodities on the spot markets.

1.2 Production planning and control in the lumber industry

The lumber industry is also characterized by production control principles specific to process industries. Fransoo (1993) proposes a definition of production control in this context that emphasizes profit maximization rather than cost minimization. Indeed, the author explains that a process production system is more likely to influence the profitability of the company because it is the bottleneck that defines the company's capacity to satisfy customers demand. Crama *et al*. (2001) go further and explain that the characteristics of process industries, such as the availability of raw materials, the simultaneous production of several products, and the use of expensive equipments (which is not necessarily the case in the lumber industry), limits the flexibility of production control so that demand satisfaction cannot be enforced. Consequently, it is here necessary to allocate capacity to customer demand in order to maximize profit.

Similarly, the Quebec lumber industry is first constrained by supply availability. It is controlled, to some extent, to meet orders allocated to mills and market conditions perceived by the sales force. Although, production planning seems to be triggered by market needs, planning and control is in practice not geared up with advanced planning tools that can simultaneously consider both actual market orders and a forecast of aggregated market needs. Orders are usually allocated by corporate sales offices to mills according to their ability to produce certain types of products and according to their relative proximity to the customers. In turn, these orders influence production planning in a myopic way. In other words, the mills' production planner decides the mix of log types to transform daily, and sometimes (i.e., from once a week to once every 6 month), adjust the price list in the log sawing optimizer in order to influence output mix. It is indeed largely believed in the industry that the variability of the sawmilling process is too unpredictable to be triggered by orders or demand forecast information. However, a large part of this variability is due to poor raw material characterization and mills' poor capability to deal with divergence. Thus, the most important task of the mills' planner is to forecast output product mix and volumes based on supply availability and to communicate these production forecasts to the sales to push products (i.e., forecasted available-to-promise and on-hand inventory) to the market. De Toni *et al*. (1998) classify this type of production control approach as a process with a look back rather than look-ahead criterion, which means that it is less responsive to market fluctuations.

Furthermore, these practices are greatly encouraged by the performance measurement system metrics commonly used in the industry and indirectly validated by government policies. In such system, metrics are only concerned with lumber recovery factors (i.e., volume of lumber produced per unit volume of raw material) and productivity indicators (i.e., volume of lumber produced per shift). Consequently, it is usual for sawmills production planners not to pay attention to customer's satisfaction key performance indicators (KPI). Inventory costs are also often neglected and inventory buffers build-up to push products to the market hiding organizational inefficiencies.

Therefore, the introduction of demand information upstream in production planning is a challenge for both, companies and designers of advanced planning systems. Demand-driven planning is indeed made even more complicated because each stage of the routing is divergent. Consequently, the ability to improve customer satisfaction seems directly related to the ability to control the output mix of each production stage.

1.3 Decoupling point strategies

Push and pull are two production strategies used to trigger production decisions whether at the planning or execution levels. On the one hand, push refers to the production of items according to upstream signals from input products flow, such as material release or demand forecast information. On the other hand, pull refers to the release of production orders/authorization triggered by downstream signals, such as sales orders or kanbans. Both push and pull strategies offers advantages depending on the operational environment in which they are deployed (Olhager, 2003). The pull logic implies market information flowing and driving decisions upstream the supply chain in order to improve operations coordination. This strategy contributes to reducing the inefficiencies generated by information asymmetry, such as the bullwhip effect. It is often implemented through the use of information systems to share point-of-sale data.

Hopp and Sperman (2004) highlight that no systems operate under pure push or pull strategies (*i. e.*, moving materials according to only one pure logic). In fact, the question is where to establish the best push/pull interface (i.e., decoupling point) in the supply chain. In a multi-stage production process, it is possible to apply simultaneously both logics in order to reduce inventory and meet market response expectations. This leads to the positioning of a decoupling point within the production process. Several authors have studied this problem (Lampbel and Mintzberg, 1996; Garg and Tang, 1997; Adan and Wal, 1998; Olhager, 2003; Gupta and Benjafaar, 2004). The operations upstream the decoupling point are planned and controlled in order to push products to the next stage (i.e., make-to-stock, MTS). Downstream this point, operations are planned and controlled in order to pull products from the previous stage, except for the first operations that uses material from a buffer inventory (i.e., make-to-order, MTO; or assemble-to-order, ATO). The positioning of the decoupling point is strategically equivalent to minimizing inventory holding costs subject to response time constraints. On the one hand, the closer the decoupling point to the market, the shorter the response time and the higher the inventory levels. Production is, in this case, not differentiated to match market needs. On the other hand, the further the decoupling point from the market, the longer the response time and the lower the inventory levels. This approach enables to customize production to match customer needs.

In a divergent production process, co-products are simultaneously produced, which makes it impossible to plan and control the production system with a single strategy. Some products are indeed automatically pushed through and offered. Here, productions managers must balance the production capacity used to satisfy demand and the production capacity used to process co-products in order to avoid building-up work-in-process inventories. This is particularly the case in the lumber industry. In order to address this issue, Maness and Norton (2002) propose a production planning model that allows setting a sales target for every products as well as inventory and penalty costs for over or under achieving the sales targets. Such a model allows finding a trade-off between inventory cost and customer satisfaction. However, the lumber production process model is aggregated. The details of sawing, drying and finishing are omitted and only general yields are considered. Differently, Todoroki and Rönnqvist (2002) propose an optimization model that considers demand information to control production execution. Here, the sawing of each log is optimized in order to maximize the volume or the value produced, taking into account the volume of each lumber grade that remains to be produced to meet demand (i.e., the difference between previous production and demand). This approach only takes into account the detailed sawing process. Consequently, none of these approaches can be used to model a variety of production planning strategies with various decoupling point positions.

The experimentation platform used in this study models the operations planning of each production stages separately. Consequently, it is possible to configure this platform in order to model different strategies and compare their respective potential to meet demand. In the context of the lumber industry, the tested strategies are outlined in Figure 1.

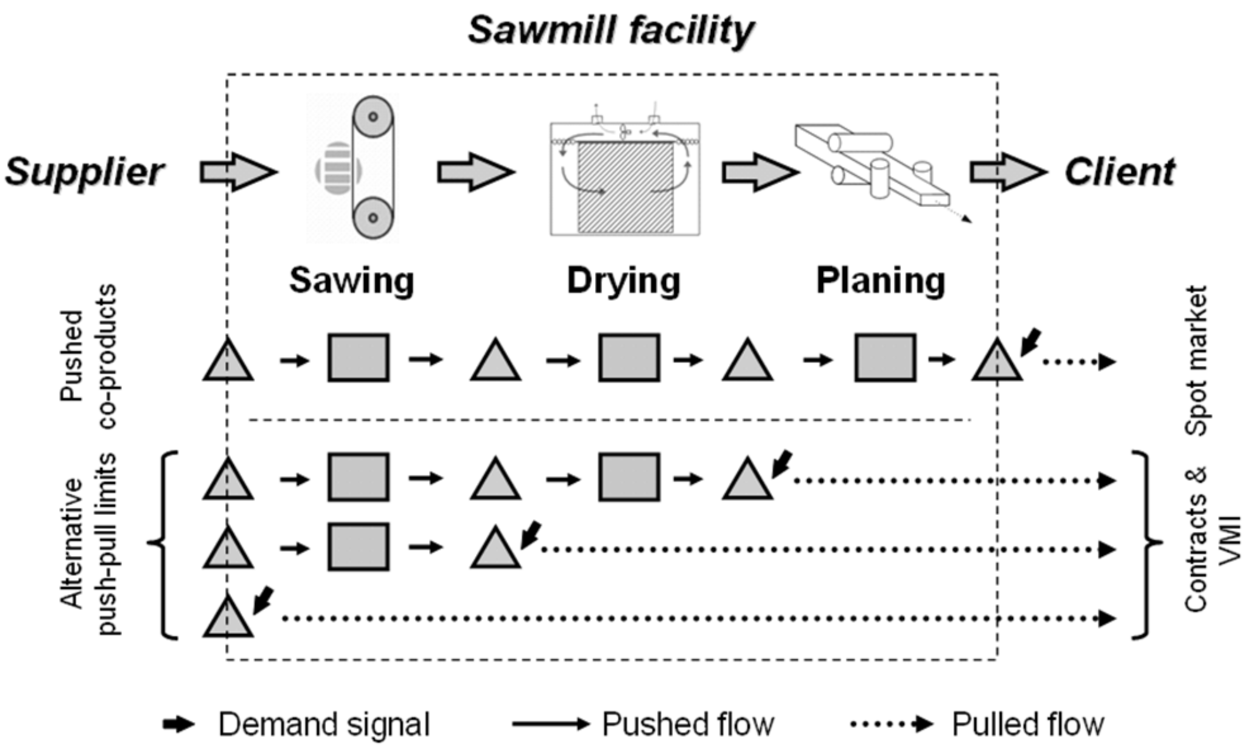

Figure 1: Tested decoupling point positions

2. Research objective, method, and tools

This section first presents an introduction to supply chain simulation techniques and applications. Next, the research objectives and method are described. Finally, the experimentation platform used to carry out this study is presented.

2.1 Introduction to supply chain simulation

The field of supply chain simulation is growing in interest and several studies demonstrate the usefulness of such practices in various situations. For instance, simulation is used to evaluate the value of information sharing in supply chain (Zhang and Zhang, 2007), to analyze the performance of business practices, such as VMI (Disney and Towill, 2003) or collaboration (Moyaux *et al*., 2004)), or to assess the usefulness of technologies such as EDI (Machuca and Barajas, 2004).

Kleijnen (2005) explained that there are four main approaches to supply chain simulation: (1) spreadsheet simulation; (2) systems dynamics; (3) discrete-event dynamic system (DEDS) simulation; and (4) business games, such as the beer game and wood supply game (Van Horne and Marier, 2005).

Along with this growing interest for supply chain simulation, the field of agent-based supply chain management is similarly growing in importance. This interest includes two main research initiatives. The first, initiated in the early 1990s, addresses the synchronization of supply chain operations through the coordination of distributed decision-making activities. Several approaches have been developed and proposed in the literature (Frayret *et al*., 2005). The challenge with these approaches deals with the modeling and implementation of supply chain decision-support tools and interaction mechanisms used to coordinate decision-making activities. Agents are sometimes geared up with advanced planning tools based on OR technology. These systems are referred to as *agent-based supply chain planning systems*.

Next, the conjunction of agent-based supply chain management and DEDS has created the field of *agent-based supply chain simulation systems* (Parunak, 1998; Swaminathan *et al*., 1998; Strader *et al*., 1998; Labarthe *et al*., 2007). This field aims to study supply chain performance in stochastic environments through the design and simulation of supply chain models based on agent technology. These technologies focus on the development of modeling and simulation environments, including modeling methods and software architectures and protocols (Umeda and Jones, 1998; Chatfield *et al*., 2006; Iannone *et al*., 2007). The goal is to support decision makers to design models of their supply chain operations and decision-making processes in order to simulate and study their collective and dynamic behavior.

In a context where supply chain members use advanced planning and scheduling systems to plan their operations, it is difficult to design accurate simulation models of such complex decision-making behaviors. Consequently, some authors have undertaken the design of simulation environments that include such optimization tools (Lendermann *et al*., 2001; Baumgaertel and John 2003). Along this stream of research, the FOR@C Research Consortium has developed an agent-based experimentation platform, which aims at optimizing supply chain operations planning and simulates operations execution in the context of the forest products industry (Frayret *et al*., 2005). This study exploits this platform.

2.2 Research objective and method overview

The first objective of this research is to study the introduction of demand information at various points in the planning process of lumber production and analyze its impacts on work-in-process inventories, delivery and business performance. In order to do so, a case study was designed based on a real manufacturing sawmill. The production system and processes of this sawmill were already modeled with a commercial simulation software called Optitek® from Forintek. Optitek allows simulating the yields of any configuration of sawmill in order to evaluate a new design or modifications of a lumber production system. Optitek also simulates the optimization process of the production controllers that optimize log breakdown. The production processes and yields respectively modeled and calculated with Optitek were then used to configure the FORAC experimentation platform specifically designed to optimize production planning in sawmills. In order to achieve the objective, an experimental design was implemented to set all the parameters of the simulation environments and scenarios. Once all scenarios and configurations of the platform were implemented, the platform was used to plan production within each context. The plans resulting from these planning runs were then studied using statistical analysis software.

2.3 Experimentation platform

The general modeling architecture that was used to carry out this study was set up to model typical softwood sawmill. The main software components include three types of agents. Downstream the supply chain, the *Deliver agent* is responsible for managing the relationship with customers through the exchange of demand information. Upstream the supply chain, the *Source agent* is responsible for managing the procurement of logs. Next, the central part of the application is a series of three *Make agents* responsible for operations planning and for the coordination of their decision-making activities. These *Make agents* are respectively responsible for the planning of sawing, drying and finishing (i.e., planing and sorting) operations. Similarly, another Make agent referred to as the *Warehouse agent,* is responsible for making products available to customers, was used. Each agent was designed with specialized optimization tools (Frayret *et al*., 2005; Gaudreault *et al*., 2006). They were also configured in order to model various planning strategies from push to pull (Figure 2).

In order to be able to simulate the lumber supply chain, agents can propagate upstream and downstream information concerning demand and supply decisions. Through the propagation of this information, it is possible to configure various planning strategies by changing the point up to where demand information flows (Figure 2). For instance, if no demand information is passed from the Deliver agent to the Make agents, then production will be made-to-stock with the goal of maximizing the potential value recovery at each stage of production. On the contrary, if demand information is passed up to the Make agent responsible for sawing, then production is made-to-order by minimizing tardiness (i.e., late customer deliveries) at each stage of production.

In order to plan their respective operations, each Make agent is geared up with advanced planning tools. Table 1 presents the main features of these tools. First, each agent is geared up with alternative planning models that they use during the various phases and steps of the planning coordination protocol they use to coordinate their planning decisions (see next section). These tools are either mix integer models solved directly with Cplex® (Ilog), or constraint programs solved with Solver® (Ilog). Because they have been specifically designed for each planning domain, these models accurately represent their planning contexts, especially with regard to their production constraints. Although they model sub-problems of the entire production system, they include specific details in order to ensure plans feasibility. Furthermore, once instantiated, each model represents thousands of decision variables tat must be solved together.

In the context of this study, only planning decisions were simulated. In other words, the simulation of the execution of operations was not carried not. This experimental study was indeed only designed to test various configuration of planning strategies. The next section details the experimental case designed to carry out this study.

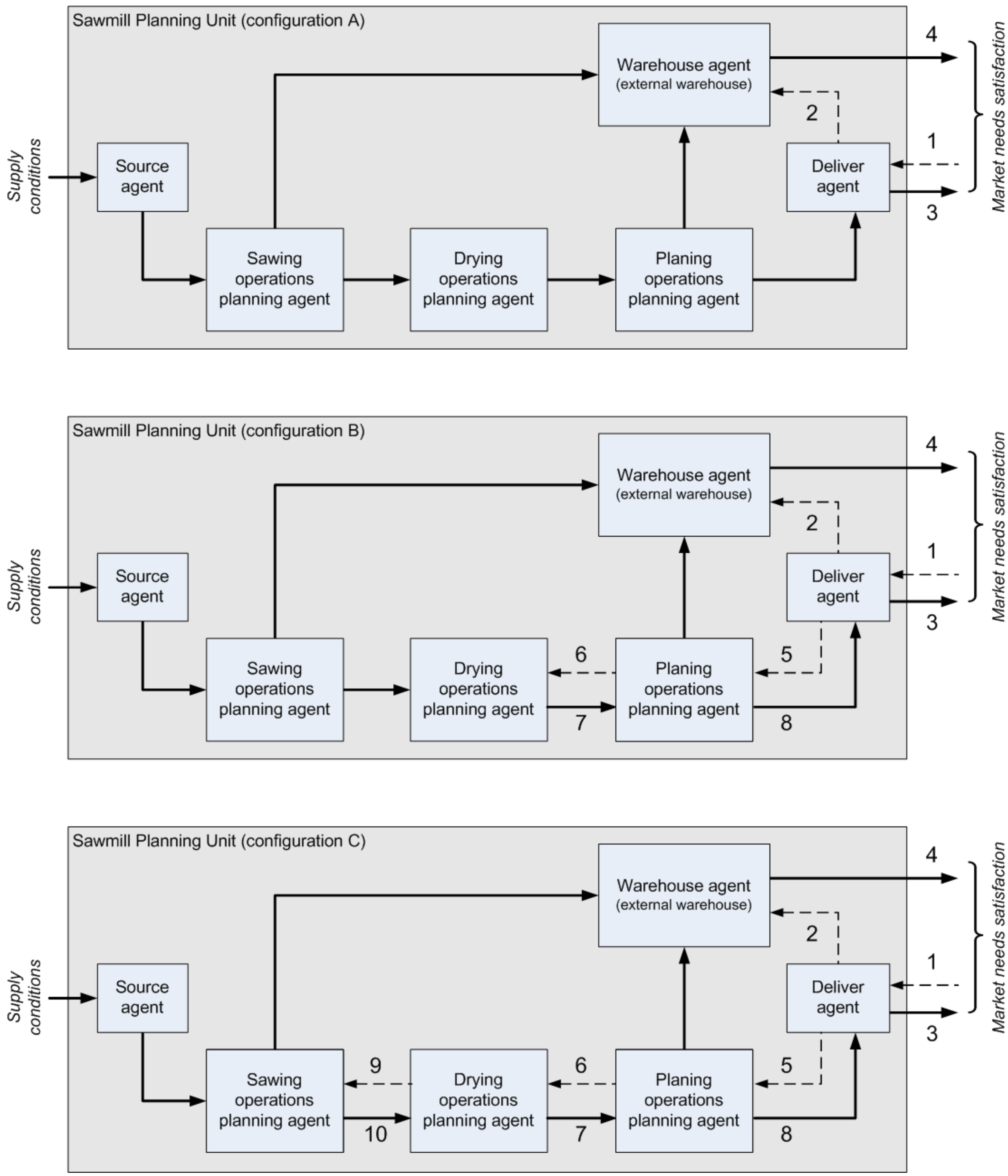

Figure 2: Modeling of the decoupling point strategies

Table 1: Advanced planning tools features

	Sawing agent	Drying agent	Finishing agent
Objectives	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase) 3. Min. costs	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase)	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase) 3. Min. costs 4. Max. resource utilization rate
Parameters	Machines capacity calendar Frozen jobs Maximum sales per product Inventory cost Raw product cost	Machines capacity calendar Frozen jobs Operations costs	Machines capacity Frozen jobs Maximum sales per product Expedition windows Inventory, raw material and Setup cost
Method	MIP solved with Cplex	Constraint programming solved with Solver	MIP solved with Cplex

3. Experimental case definition

3.1 Sawmill case study modeling

The sawmill case study is inspired by a Quebec based forest company which owns a medium sized and stud oriented sawmill. The sawmill case study is similar to the real sawmill in terms of capacity and production processes. Its annual lumber production can rise up to 120 Million Board Feet (MMbf) or 283,000 m^3, from spruce, pine and fir trees (SPF), although spruce represents more than 60% of its total raw logs inputs. Nevertheless, because the real sawmill is not geared up to pull production, some adjustments to the overall planning process were made. For instance, in the real sawmill, there is no log classification and all logs are sawn in a bulk process. This generates a wide range of green lumber types without real control over the output mix and volumes. Production is thus pushed through sawing by maximizing value recovery according to a price list. Green lumber is then loaded in kilns for drying, or stacked for air drying or even sold green. The sawmill has two kilns of 244 Mbf capacity and the drying time range from 40 to 70 hours depending on the species and season. Once dried and equilibrated, lumber is planed and graded in a single line and then packed, sold and shipped mainly by train.

In order to create different planning strategies, each alternative production processes have first been modeled in order to configure the advanced planning tools of the experimentation platform.

Data from a random sample of 600 3D scans of real logs and Optitek were used to model the real sawmill and its typical procurement. Next, using Optitek, the sawing of each log was simulated using actual and manipulated price lists in order to obtain the production yields of each output product. This approach also allowed us to define log classes based on output mix distribution similarities. For kiln drying, several feasible loading patterns were developed for each thickness of lumber from actual kiln drying operations. A loading pattern may include various lengths of lumber, but thickness must be the same for all pieces of lumber. Air drying, planing and sorting operations were modeled similarly. All configurations were then translated into a XML format and fed into the platform. Table 2 presents the general elements of the case study configurations.

Table 2: Case study general characteristics

	Structure	**Assumptions**
Logs	• m^3 of bulk raw logs 4.8 m (16') long. Logs are classified in 7 classes.	The randomly generated sample is used in each configuration.
Sawing	• 1 sawing line. • 47 sawing patterns. • fixed sawing speed.	Sawdust and chips produced are sent to the warehouse.
Green Lumber	• 30 products based on dimensions.	Only 2×3, 2×4, 2×6 and 2×8 in their five different lengths will go through drying. Small boards, 1×3 and 1×4 in their five lengths are transferred to warehouse as is.
Drying	• 2 kiln dryers of 576 m^3 (244 Mbf) capacity plus 8 air drying locations. • 237 alternative loading patterns for kiln drying, plus the same number for air drying.	One fixed time duration for all loading patters regardless of green lumber dimensions.
Dry lumber	• 20 products based on dimensions	2×3, 2×4, 2×6 and 2×8 in their five different lengths will go through planing and sorting.
Finishing	• One planing and sorting line • Fixed input/output relationship based on actual recovery yield.	Changeover of thickness during a shift is penalized.
Planed Lumber	• 60 products according to dimension and grading.	From these 60 products demand is placed on five of them, namely 2×4 12 RL.
Operation conditions	• Sawing and finishing have operation's schedules of 16 hours per day. Drying operates 24/7 for the sixty days planning horizon.	No downtime. Demand is visible from time zero.

3.2 Modeling of the decoupling point positions

This study aims at evaluating and comparing the performance of three decoupling point positions within a lumber production system. In order to do this, the experimentation platform discussed in the previous section was configured to represent these three strategies of demand propagation. Figure 6 summarizes these strategies.

In configuration A, demand information is not propagated at all within the system. Consequently, each agent plan its operations in order to maximize value recovery subject to the supply constraint propagated downstream by their direct supplier. This represents the pure push strategy. In configuration B, demand information is propagated up to the drying agent. Consequently, both drying and finishing agents plan their operations in order to minimize the overall weighted tardiness (i.e., delay x volume demanded) subject to the supply constraint propagated downstream by their direct supplier. In this configuration, only the sawing agent plans its operations in order to maximize value recovery. Finally, in configuration C, all agents plan their operations in order to minimize the overall weighted tardiness.

Given that lumber production is a divergent process with co-production, the production generates simultaneously different volumes of several types of lumber, only part of which is actually required to fulfill orders. The remaining volumes of lumber are thus pushed to the spot market. In such a multi-stage production process, increasing the control of co-production requires, among others, to coordinate all production stages. Consequently, a coordination protocol controlling the behavior of each agent has been designed and implemented. According to this protocol, an agent that receives demand information first plans its operations in order to minimize tardiness with no supply constraints. From its plan, and if it is configured to propagate demand information, it derives and expresses its own dependant demand to its supplier(s). This upstream planning phase continues until demand information is sent to an agent that is not configured to propagate demand information. This agent then plans its operations in order to minimize tardiness subject to the supply constraint of the agent upstream, which is configured to propagate supply information. During this downstream planning phase, the agents that receive both supply and demand information plan their operations in two steps. In the first step, they minimize tardiness considering demand information and subject to supply constraints. Then, in the second step, they plan their operations in order to maximize value recovery using the current product price list, subject to a constraint that limits the maximum overall weighted tardiness (for the same demand) to the tardiness calculated in the first step. From this operations plan, they derive and send the supply information required by their client(s). During the experiment, the production planning horizon was fixed to 60 days and one planning cycle was simulated for each simulation run.

4. Experimental design and simulation

4.1 Experimental design

In order to plan the experiment, a mixed level design approach was used. This kind of design, yet simple, is well suited for combining factors that can be controlled through structured decision-making processes (such as the decoupling point position and the level of capacity committed to contracts) and noise factors that can only be controlled within the experiment (such as supply quality and availability and market prices). Table 3 describes these factors and their various levels as they were set in the simulation experiments. The controllable factors represent the inner array, in other words, a complete factorial design with nine configurations. Noise factors represent the outer array, which is a complete factorial design with six scenarios. The experimental design, which comprises 54 runs, was developed using mixed levels designs.

In these configurations, the level of capacity allocated to contracts is included in the definition of a configuration in order to study the effect of production/sales commitments on performance. This level is expressed as the percentage of the maximum production capacity (i.e., total volume of production over the planning horizon) of the product sold in these contracts. In order to estimate this maximum capacity, a pure push configuration of the sawmill was set, giving a zero value to all products except this product. In the experiments, orders were simulated as a periodical set of the same quantity of products per week.

The two levels of supply factor were introduced in the definition of the supply chain configuration in order to study the influence of a small increase of the proportion of logs with smaller diameter in the procurement distribution. Furthermore, concerning the market price, we consider three levels of variations for the product sold by contracts, and so, according to 2004 average price range variations.

Table 3: Configuration and scenario elements

Factor	Description	Levels	
Decoupling point position (Planning configuration)	The point upstream in the lumber supply chain up to where demand information is incorporated in production planning decisions	3 levels	Between deliver and finishing: (configuration A)
			Between drying and sawing: (configuration B)
			Between sawing and source: (configuration C)
Level of contract (demand configuration)	The percentage of the maximum capacity for producing 2×4 12 R/L allocated to contracts	3 levels	60 % of the maximum capacity
			80 % of the maximum capacity
			100 % of the maximum capacity
Supply type (Scenario)	The main type of logs present in supply	2 levels	SMALL: higher distribution of small logs
			NORMAL: Typical distribution
Market prices (Scenario)	Price lists with differences for 2×4 12 R/L with respect to Random Lengths® average price for 2004	3 levels	-10 %: The products have lost value
			0: Regular prices
			+10 %: The products have a better price than average

4.2 Performance measurement framework

In a traditional lumber production context, performance assessment is based on two main measures. The first measure concerns material throughput. This is the volume of production per work shift, measured in board feet per shift (bf/shift). This measure is an indirect representation of production costs per volume of lumber produced. Because lumber production is a capital intensive industry, production costs in sawmills can be considered as fixed. Consequently, the higher the throughput, the lower the production cost per board feet.

The second measure concerns the lumber recovery factor, which means the volume of lumber that is produced per unit volume of raw material. This indicator is measured in board feet per m^3 of logs. It is a function of raw material quality (i.e., log diameter and singularities). It is also an indirect representation of unit procurement cost, because the higher the recovery factor, the least the volume of raw material that is required per unit volume of lumber produced.

In the context of the customer-centered economy, the performance assessment framework considered in the study proposes to use other KPI as well. Figure 3 presents this framework.

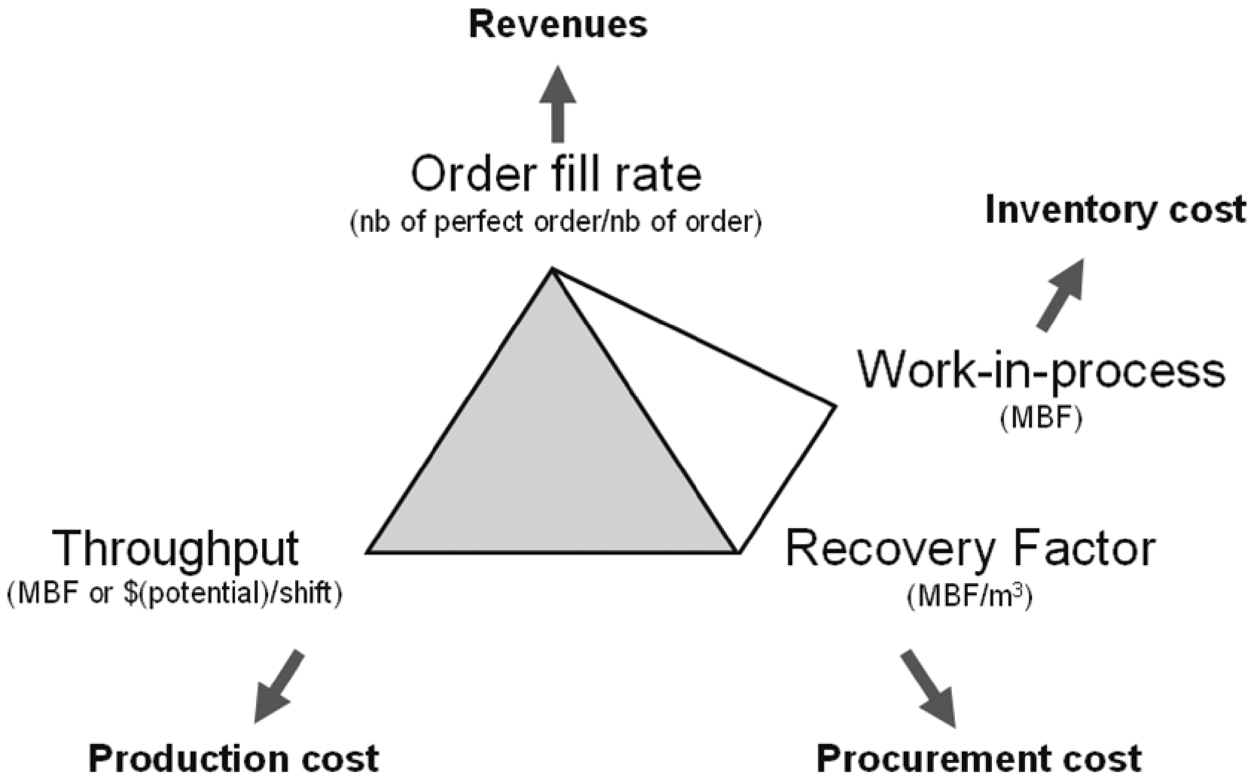

Figure 3: Performance assessment framework

In a context where customer satisfaction is gaining importance while resource is scarce, sawmill production managers must consider complementary measures to better represent the overall performance of a lumber production system. The first measure concerns the daily average inventory of work-in-process (i.e., DAWIP). It is a indicator that evaluates material flow streamlines and an indirect representation of work-in-process (WIP) inventory costs. In the context of this study, it is measured using the operation plans of each agent. In other words, the planned work-in-process is calculated directly as the daily average inventory of all non-finished products (green rough + dry rough), see equation [1].

$$\text{DAWIP (bf/day)} = \frac{\sum_{p^{\text{all non finished products}}} \text{Daily\_WIP}_p \text{ (bf)}}{\text{Horizon\_size (day)}} \qquad [1]$$

Additionally, business performance is evaluated through two other performance measures. The first is classic in supply chain management: the weighted fill rate (WFR). It is calculated once for each simulated production plan as the percentage of demanded quantities planned to be delivered on time, weighted by the total demanded quantity (see equation [2]). Once again, this measure only considers planned deliveries. Furthermore, demand is aggregated per product. Indeed, the planning tools have not been designed to consider individual orders. This measure is thus an lower bound of the actual fill rate because even if the aggregated daily demand is not fulfilled, individual orders may still be fulfilled on time.

$$\text{WFR (\%)} = \frac{\sum_{p^{\text{all sold products}}} \left[\text{Daily\_fulfilled\_demand}_p \times \text{Demand\_quantity (bf)}\right]}{\sum_{p^{\text{all sold products}}} \text{Daily\_demand\_quantity}_p \text{ (bf)}} \times 100 \qquad [2]$$

with

$$\text{Daily\_fulfilled\_demand}_p = \begin{cases} 1 \text{ if Daily\_demand}_p \text{ is fulfilled} \\ 0 \text{ if not} \end{cases}$$

The second measure, adapted from the theory of constraints (TOC) performance measurement framework (Goldratt and Fox, 1986), is used to compare the Potential Monetary Throughput (PMT) of the overall planned production in each simulation using referential lumber market prices. Although, it is based on the TOC throughput measure, this PMT assumes that the whole production can be sold, which is a common practice in this industry. Furthermore, it is calculated without subtracting raw material investment. This potential value is calculated for each simulation run using the planned output of finished products (including all products that can be sold) multiplied by the corresponding market price (see equation [3]).

$$\begin{aligned} PMT(\$) = & \sum_{p \in \text{finished lumber}} \text{daily production}_p (bf) \times \text{price}_p (\$/bf) + \\ & \sum_{p \in \text{non finished lumber}} \text{end inventory}_p (bf) \times \text{price}_p (\$/bf) \end{aligned} \qquad [3]$$

The difference between the potential values generated by the pure push strategy and any other strategy represents an upper bound of the cost of introducing this strategy. Indeed, this measure considers that the company is able to collect this value immediately. Unfortunately, this is rarely the case. Inventory costs should thus be assess as well because they also affect the company's profitability.

5. Results and discussion

5.1 Logistic performance

First, the Weighted Fill Rate (WFR) improves as the decoupling point is set upstream in the lumber production process. An analysis of variance (ANOVA) shows that this factor explains almost 40% of WFR variation alone, and 96% coupled with the contract level factor. Although this is intuitive, it indicates that lumber co-production can be controlled to a certain extent in order to match a specific demand pattern. Moreover, it also shows that the further upstream demand information is propagated, the more accurate the control of production and, thus, the better the customer service. In particular, Figure 4 confirms the importance of controlling the sawing process, which sets the dimension (i.e., width and thickness) of the lumber to be produced, in order to satisfy contracts. Indeed, setting the decoupling point upstream the sawing process has a more significant effect than setting it upstream the drying process, with an average of 122% increase in performance.

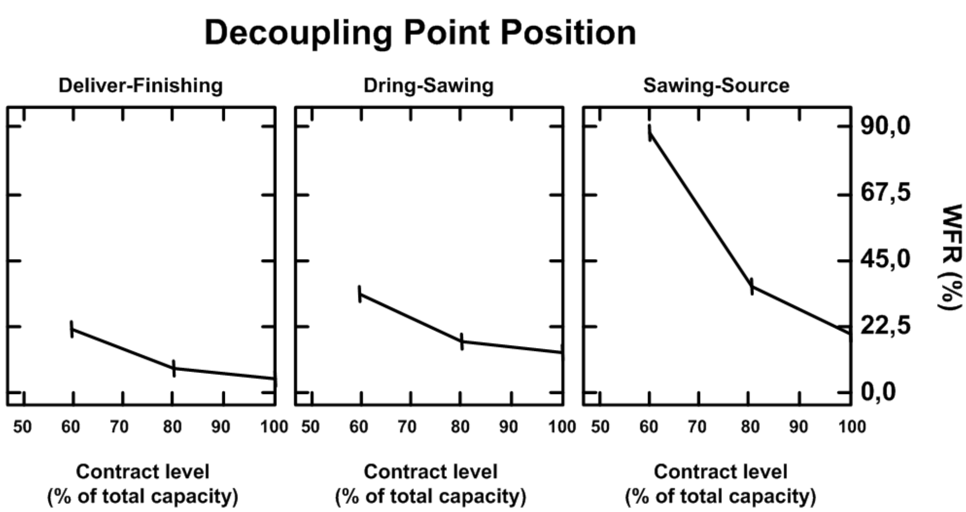

Figure 4: Weighted Fill Rate performance (%)

In addition, the level of the production capacity committed to contracts is negatively correlated with the WFR performance. Indeed, the lower the demand level that pulls production, the more likely it is that this demand can be fulfilled on time. It is particularly true in a divergent co-production context. In practice, the levels of production capacity that are committed are maintain rather low because lumber companies do not have a good control of their production output mix. Consequently, historical data about production reports is used to set a reasonable volume of production that can be committed to customers.

Finally, for given level of contracts, the coefficient of variation of the WFR decreases as the decoupling point goes upstream (Figure 5). In other words, positioning the decoupling point upstream de supply chain tends to decrease the negative effect of other contextual factors.

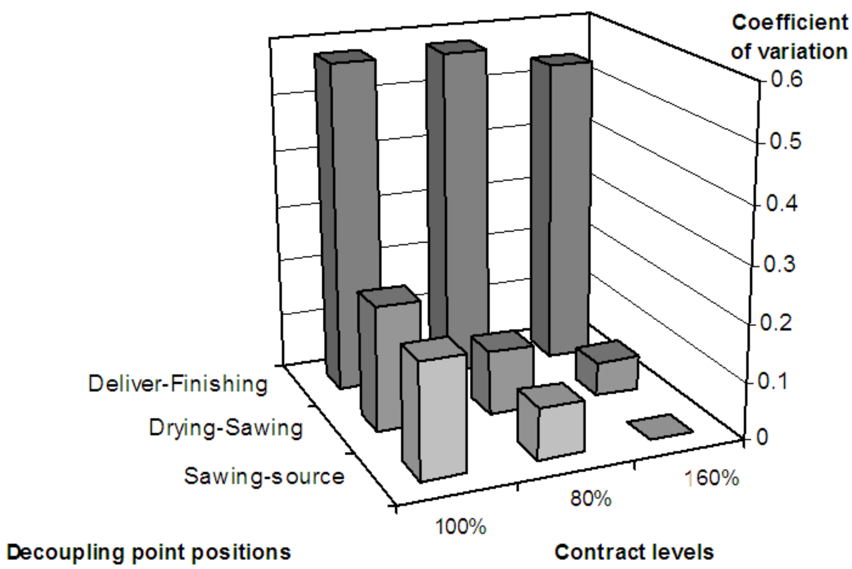

Figure 5: Coefficient of variation of the Weighted Fill Rate

Second, concerning the *Daily Average Work-in-Process* (Figure 6), planned WIP levels are reduced when the decoupling point is set upstream the sawing process. Demand-driven planning strategies thus seem to improve inventory levels in the context of a divergent process industry. However, the results are not conclusive when the decoupling point is set between drying and sawing. This may be explained, once again, by the nature of the sawing process that sets the main dimensions of lumber. Because demand is first specified in terms of width and thickness, once these dimensions are sawn based on price optimization, the lack of demand for these products will keep the work-in-process level high throughout the entire production system. Furthermore, compared to the pure push strategy, the impact of planning drying operations in a pull mode creates slightly more WIP of green lumber. This may be explained by the nature of the objective function of the drying agent, which is to minimize tardiness without regard to green lumber inventory. Consequently, inventory builds up because the sawing agent pushes whatever products have a good market value. This effect disappears when the sawing agent also minimizes tardiness (i.e., produce on time whatever the drying agent needs). This also demonstrates the importance of controlling the sawing process. Furthermore, work-in-process levels decrease when demand (i.e., contract level) is higher because a larger portion of unfinished products is pulled by demand.

Finally, log supply quality influences logistical performance. Indeed, an analysis of variance (ANOVA) shows that 45% of WIP variations can be explained by raw material quality variations. This shows the strong influence of log quality on the lumber production control. Although these findings tend to be in favor of a greater control of quality variations of raw material, more studies should be carried out in order to investigate the benefit of an improved characterization and classification of logs.

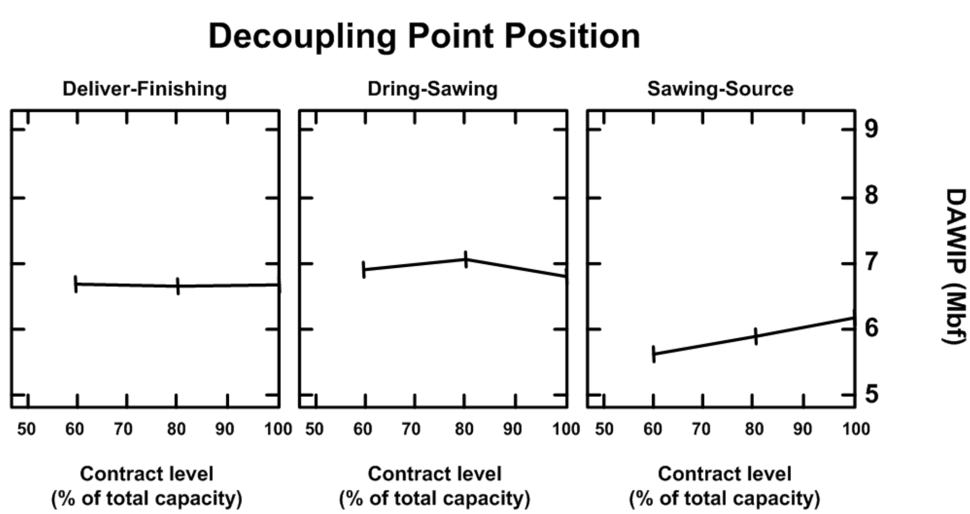

Figure 6: Daily Average Inventory performance

5.2 Financial performance

Improved service level and lower inventories are obtained by adding constraints to the production planning process and by changing the objective function so as to reduce tardiness. Consequently, one can expect a lower potential monetary throughput (*PMT*) compared with a pure push strategy that maximizes potential value recovery from every single log. This decrease is captured in Figure 7. As mentioned earlier, this potential value is calculated using the market price list, which, consequently, influences directly the *PMT*. Once again, an analysis of variance (ANOVA) shows that log characteristics explains up to 50% of the PMT variability. This highlights the strong influence of log quality (i.e., log diameter distribution) on the lumber companies' capacity to generate a profit. Furthermore, the importance of the control of the sawing process is, once again, demonstrated here. If controlling the drying process does not have a significant impact on the PMT, the control of sawing strongly affect negatively the PMT. Indeed, the production of the dimensions of lumber demanded by customers does not necessarily generate the volumes of lumber that have the most value (as set in the push mode price list). Consequently, there is a loss of potential value that arises directly from a more constrained production planning environment.

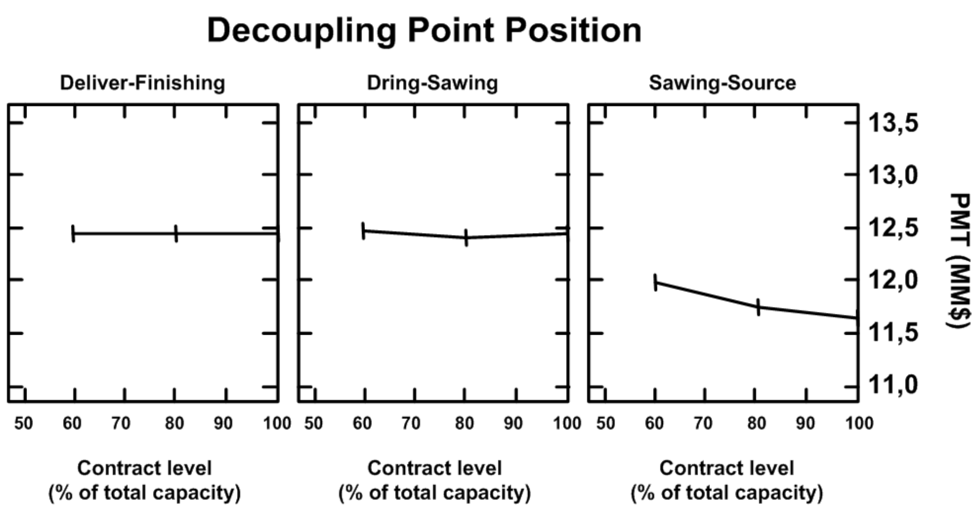

Figure 7: Potential Monetary Throughput (PMT)

In order to compensate for this loss of potential sales revenue, a higher sales price is generally applied in the industry using a premium added to the market price. This premium represents the price to be paid for the service of committing production capacity and minimizing supply risk for the customer. Table 4 summarizes the average losses for the pull strategy (the pure push strategy being the reference for calculations) and for each contract level. This table also presents the premium required to compensate for this loss. Potential value and loss are calculated from PMT in Figure 7. For each contract level (60%, 80% and 100%), this represents respectively a loss of

3,59%, 5,44% and 6,40%. The premium is calculated as a price increase applied on the part of the capacity that is committed to fulfill demand. In other words, the premium is calculated for each contract level configuration as follows:

$$\mathrm{Pr}\,emium_c(\%) = \frac{Loss_c(\$)}{(\alpha \times Contract\_level(\%) \times PMT_c(\$)} \times 100 \qquad [4]$$

with

$$Loss_c(\$) = \frac{\sum_{all\,scenarios} PMT_{push}}{S} - \frac{\sum_{all\,scenarios} PMT_c}{S} \qquad [5]$$

c $\in$ $\{$A,B,C$\}$, A, B and C being the 3 contract level configurations

α = 80%

S = Card($\{$scenario$\}$)

This approach to calculate the premium considers several hypotheses. First, the coefficient α represents an approximation of the maximum level of capacity that the sawmill can commit for contracts. In other words, due to divergence not all production capacity can be sold with a contract. Consequently, the contract level only concerns the products that can be sold like that, which represents 80% of all production in the pure push test simulation ran before experimenting. Second, it is also assumed that the potential value is equally generated by all products. This is not the case, because monetary throughput is primarily generated by the most valuable products, which are generally demanded by contracts. Consequently, this calculation is an upper bound of the break even premium. Finally, as mentioned earlier, the loss is calculated using the PMT of the pure strategy, which does not take into account inventory cost due the sales delay. Furthermore, this calculation of the premium does not include the savings from reduced inventory costs and reduced sell-off promotions as more production is pulled by demand. In practice, this value is between 5% and 10% of the current market price for a much lower contract level, which seems quite reasonable for lumber producers.

An additional interesting finding indicates that an optimal limit to the contract level must exist for every configuration, which includes the log supply availability and quality. Consequently, increasing the contract level does not necessarily improve profitability. For instance, in the context of this study, the 80% and 100% contract levels require a larger premium in order to compensate for a larger loss of potential value recovery. Over committing thus creates in this context more constraints on the production system than it generates revenues. Further study should be carried out in order to investigate more precisely this point in order to help lumber producers define the contract level that is most appropriate for their facility.

Table 4: Loss and premium calculations for 60 days of production

Contract level	Average Potential monetary Throughput ($)	Loss ($)	Loss (%)	Premium (%) (over market price)
Pure push strategy				
0%	$ 12 433 143	$0	0%	0%
Pure pull strategy (Configuration C)				
60%	$11 987 220	$ 445 924	3,59%	7,75%
80%	$11 756 677	$ 676 467	5,44%	8,99%
100%	$11 637 634	$ 795 509	6,40%	8,54%

6. Conclusion

This paper proposes an evaluation of various strategies to introduce of the pull strategy within a typical lumber production system. This exploratory study is done through simulation using several configurations of an advanced planning systems developed by the FOR@C Consortium. The main conclusions drawn from this study confirm the positive impact of the pull strategy to improve customer satisfaction and reduce overall inventory. However, due to the divergent nature of lumber production, this improvement impairs the ability of the production system to generate value based on market prices. Forcing the system to minimize tardiness creates indeed a pressure on the production system that limits its ability to maximize value recovery, which is generally the case in lumber production systems. Consequently, improved service level must be paid by customers through a premium which value can be evaluated through this kind of simulation. Future work includes the evaluation of the trade-off between the premium value and the contract level in a context of profit maximization.

Another interesting insight suggests that in order to introduce customer demand in the planning process of lumber production, a particular effort must be done on the planning of sawing operations. Hence, sawing, which is generally the most upstream transformation process in sawmills, seems to control the logistic performance of the entire production systems.

Finally, from a methodological point of view, this study demonstrates the capability of agent-based technology to provide the means to analyze specific industrial contexts and support decision makers to configure their production systems.

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