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Tactical-operational coordination of a divergent production systems with coproduction : the sawmilling challenge --Manuscript Draft--

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Tactical-operational coordination of a divergent production systems with coproduction : the sawmilling challenge

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Abstract

Various optimization tools have been used in industry to facilitate production planning at different levels of aggregation. Choosing the interoperability mechanisms of these systems, such as the planning frequencies, the information passed between them and the interpretation that other systems must make of them, has always been a challenge. This work focusses on production planning at the tactical and operational levels in North American sawmills, a commodity industry characterized by volatile prices and a divergent production process with coproduction. In this context, tactical planning produces aggregated plans, and information from these plans can be used as targets and / or constraints at the operational level (e.g. quantities to be produced / kept in stock per product and per period, sales targets, etc.). A simulation of this production system was therefore developed, encompassing the planning process and the market dynamic, to compare and evaluate the impact of different coordination approaches on business economic performance. Results showed that the type of information which should be shared from the tactical level to the operational level varies according to several factors, including the company's order acceptance policy, prices seasonality, and the presence or absence of overcapacity on the market.

Keywords: Tactical-operational coordination; Lumber production planning; Simulation; Forest industry; Divergent process; Coproduction.

1. INTRODUCTION

Production planning at the tactical and operational levels is a widely studied topic. The forest industry is not an exception and many optimization models exist to plan lumber production in order to meet demand (D'Amours et al., 2009). The forest industry operates in a particular context defined inter alia by a divergent flow of products (several finished products from the same raw material) with coproduction (production of several products at the same time).

1 The tactical planning of a sawmill aims to obtain an aggregated plan for a horizon of 12 months, which
2 will generally be updated once a month. It integrates the three main activities of the production process
3 which are the sawing, drying and finishing operations. This planning takes into account the company's
4 strategic objectives, available resources, available capacity, long-term commitments, forecasts of
5 demand and supply constraints. The tactical plan aims to maximize the expected income; it predicts how
6 resources will be used and acts as a guide for sales and production work. In fact, information from tactical
7 planning is used to determine the operational plan (which has a much shorter horizon of a few weeks) in
8 order to ensure income over a long period as well as a good operational performance. For example, the
9 tactical level might recommend keeping stocks of a particular product during certain periods in order to
10 be able to take advantage of an improvement in future prices, which the operational level alone cannot
11 anticipate.
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24 Since tactical models do not have the same level of accuracy as operational models, it is necessary to
25 communicate and / or disaggregate information from the tactical level in order to transfer it to the
26 operational level. This information can take the form of, for example, production targets (what to produce
27 at each period for each operation included in the timber production process), inventory targets (what
28 quantity to keep in stock at the end of a given period) or information about estimated monthly sales
29 prices.
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38 This study contributes to scientific literature by addressing the coordination issue between two planning
39 levels which have different time horizons. It proposes an approach to design the production planning
40 process incorporating both tactical and operational planning levels. Various information can be extracted
41 from the tactical plan to become constraints and / or targets that will be used at the operational level.
42 However, the type of information which should be transferred from the tactical level to the operational
43 level depends on various factors, such as the order acceptance policy used at the sales level (Available-
44 to-promise [ATP], Capable-to-promise [CTP]), the importance of price seasonality, or the presence of
45 overcapacity on the market. The evaluation of the different scenarios is carried out using simulation. The
46 simulation platform of Dumetz et al. (2016) is used to simulate the production system, the planning
47 process at the tactical and operational levels, as well as the market behavior, using a rolling horizon. This
48 simulation also implements a tactical planning model and three operational planning models (one for
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each production activity: sawing, drying and finishing operations) from Marier et al. (2014a, 2014b, 2016). The company's performance (i.e. sales volumes, revenues, inventories) is evaluated according to the planning system in place, the order acceptance policy used (ATP, CTP), and the context of the market (volume of demand, seasonality of prices). Results show that certain information / targets / constraints shared from the tactical level to the operational level can lead to performance improvement or degradation depending on the context. This is crucial information for industries as it has a direct impact on the performance of the company, in terms of generated income.

The article is organized as follows. Section 2 presents a brief literature review on hierarchical planning as well as on the peculiarities of tactical and operational planning in the North American lumber industry. Section 3 introduces the simulation model used to complete the experiments and Section 4 describes the experiments and the results obtained. Finally, Section 5 concludes the paper.

2. Preliminary concepts

2.1. Hierarchical planning

The planning process encompasses a large number of decisions at different hierarchical levels (Vollmann et al., 1997). At the strategic level, long-term decisions are made (business plan). At the tactical level, mid-term decisions, covering an average planning horizon of 6 to 18 months, involve defining the quantities to produce and to stock so as to meet the objectives defined at the strategic level and achieve the financial objectives defined in the budget. The operational level establishes a detailed plan. The horizon is very short, about a few weeks, usually reviewed weekly or more often depending on the business context.

There are many mathematical models for tactical and operational production planning in various industries (see for example Díaz-Madroñero et al., 2014). Nevertheless, it remains essential to ensure synergy between the two levels of planning. For example, all of the orders anticipated by the tactical level will not necessarily occur and the operational planning must take that fact into account.

It is difficult to design and validate a planning process that incorporates both tactical and operational levels while maintaining good consistency. The time scales used for planning (both the size of the

1 planning horizon and the review frequency) at these two levels are not the same, which implies some
2 form of disaggregation. Typically, monthly data is used for tactical planning while the operational level
3 needs daily data. In addition, the tactical level sometimes works with product families¹ while the
4 operational level works with individual products. The tactical level's "macro-vision" is sometimes
5 necessary for several reasons: on the one hand, there is not enough knowledge of the data and only
6 aggregated data is available or makes sense, and on the other hand, the problem has to be simplified to
7 be solved in its entirety (Simchi-Levi, 2003).
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16 For many years, much work has led to proposals for obtaining tactical plans and / or disaggregation of
17 these tactical plans into production plans for the operational level. The term Hierarchical Production
18 Planning (HPP) (see Bitran and Hax, 1977) is often used to describe the general planning process in
19 stages. A problem that is too complex to solve may be simplified and solved in an aggregated way and
20 the result may be used to solve the more detailed problem (Hax and Meal, 1984). McKay et al. (1995)
21 provided a review of the concept of HPP and highlighted different applications in the manufacturing
22 sector. Aghezzaf et al. (2011) used this approach to solve a planning problem in a two-level environment,
23 composed of semi-finished products (aggregate level) and finished products (disaggregated level), by
24 proposing a robust HPP model. Based on Genin's (2003) work on the stability and robustness of tactical
25 plans and Ortiz and Thomas's (2004) work on the disaggregation of tactical plans into master production
26 schedules through several optimization models, Thomas et al. (2012) proposed a methodology to
27 disaggregate a tactical plan. They showed, among other things, that this disaggregation allowed stability
28 of the operational plan under certain conditions (building stocks). The tactical plan provides aggregated
29 information, i.e. product family per month. A first model makes it possible to transform these quantities
30 of product families by month into a number of finished products per month. A heuristic is then used to
31 provide a stable operational plan (finished products per week). Ortiz and Albornoz (2012) developed a
32 methodology based on the concept of HPP allowing a disaggregation of a monthly plan of product
33 families into a weekly plan of finished products. The case studied concerned a company that produces
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56 ¹ In our experiments, the products were not aggregated into families, in accordance with current
57 practice of North American sawmills. The forecasts for these distinct convenience products are
58 generally available by product. Furthermore, aggregation into families did not greatly reduce the
59 planning model's complexity.
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reusable bags in Chile and Peru. The disaggregation is done using several optimization models imposing constraints to keep the coherence of the final production plan. Vogel et al. (2016) compared two approaches: hierarchical production planning versus integrated production planning. They assumed that (1) some of the reasons justifying the use of a hierarchical approach to plan production at different levels are not legitimate and (2) optimizing a series of subproblems can lead to sub-optimality of the general problem. They proposed two models, a hierarchical model taking into account an aggregate level and a disaggregated level, and an integrated model combining these different levels. In their context, they showed that the integrated approach delivers a better result and that the necessary computation time, although longer than for the hierarchical model, is acceptable. Even though this study is interesting, most of the practical cases require a hierarchical decomposition as well as the use of several specialized models at the operational level (e.g. several factories). In the case of sawmills, it is currently not possible to use a single model to plan sawing, drying and finishing operations (see Gaudreault et al (2010)).

2.2 Production planning for the North-America lumber industry

This study focuses on operations planning at the tactical and operational levels in North American sawmills. Lumber production consists of three sub-processes in almost independent facilities: sawing (turning logs into planks), drying (removing excess moisture from the wood), and finishing (to give parts the desired finish, then grading and trimming parts). Each operation is different and has its own constraints and characteristics (for more information, see Gaudreault et al., 2010). Production planning is a real challenge because of the particular characteristics of this industry. Indeed, from the same raw material, several finished products are obtained (divergent process) simultaneously (coproduction) (see Öner and Bilgiç, 2008). The impact of this divergent flow is very significant and affects the intermediate products at the sawing, drying and finishing operations, which multiplies the number of finished products originating from the same log. In addition, the market price for these products are highly susceptible to seasonality (Marier et al., 2011). The North American lumber market is a convenience market whose products must meet the National Lumber Grades Authority (NLGA) ² criteria. The price therefore

² The North American lumber system relies on a standardization process lead by the National Lumber Grades Authority (NLGA) that defines strict dimensions and qualities. This makes lumber a

fluctuates greatly depending on supply and demand.

In this context, planning at the tactical level aims to define objectives for the production of sawing, drying and finishing, by product and by period, taking into account that the coproduction phenomenon limits the options of the company (since producing one product entails the production of several, maybe unnecessary, coproducts). The tactical models used are therefore developed to take these constraints into account. They also make it possible to establish inventory targets (i.e. for which products to build stocks) and when these quantities should be sold to take advantage of the market prices. Again, storage constraints and costs need to be taken into account as well as contract constraints. Depending on the volume of demand and the price fluctuation, the strategy to be used may vary widely (Marier et al., 2014a). There are many planning models at the tactical level, including Singer and Donoso (2007) who proposed an optimization model for production planning in a Chilean sawmill, or Marier (2011) and Marier et al. (2014) who introduced a tactical MIP model integrating operations (sawing, drying and finishing) planning and sales.

Planning at the operational level defines the exact operations schedule by taking into account the actual demand and the information provided by the tactical level. The tactical level serves as a reference frame, allowing the operational level to carry out its short-term planning while taking into account future visions. Different models to plan for each of the three lumber production operations are also needed at this decision level. For the sawing operation, planning models generally include the selection of cutting patterns which generate either a better volume of sawn timber or a better material yield or aim to promote the cutting of a particular product. The cutting pattern represents how the log should be cut and which products will be obtained. There are a multitude of cutting patterns, taking into account the natural characteristics of the log. Maturana et al. (2010) listed some operational planning models such as the ones developed by Occeña & Schmoldt (1996), Todoroki & Rönnqvist (1999) and Winn et al. (2004). They also developed a deterministic planning model for sawing operations for a sawmill in Chile.

commodity market. The situation is different in Europe where most products are made to order according to specific characteristics.

1 However, in their model, they assume that all data are known. Varas et al. (2014) improved this model
2 by taking into account uncertainty in demand and raw material, using a robust optimization approach.
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4 For the drying operation, several models exist such as those of Yaghubian et al. (2001) who developed a
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6 planning model that takes into account the possibility of buying dry wood or drying it and Marier et al.
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8 (2016) who proposed a MIP model that dynamically generates loading patterns. A loading pattern
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10 indicates how a dryer should be filled, taking into account the different wood species (which do not dry
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12 at the same speed), wood dimensions and the characteristics of the dryer. For the finishing operation,
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14 Gaudreault et al. (2010) and Marier et al. (2014) proposed planning models that maximize the value
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16 produced by taking demand into account and minimizing delays.

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20 In forestry literature, tactical disaggregation and tactical / operational coordination approaches are also
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22 studied. As it is the case for other industries, the main challenges are to obtain a certain level of coherence
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24 between the decisions taken at the different levels.

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28 In forestry operations, Beaudoin et al. (2008) showed how to take into account the impact of decisions
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30 made at the tactical level on the feasibility of the operational plan. The authors propose an application of
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32 the Schneeweiss (2003) generic hierarchical model allowing for a better alignment between the different
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34 levels of planning. Their application is for the wood harvesting capacity, which determines the number
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36 of contractors to be hired during the year. For the sawing industry in Chile, Alvarez et al. (2015) used
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38 robust optimization to obtain tactical plans, generating robust solutions that ensure good operational
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40 feasibility. Recently, Lobos and Verra (2016) studied the problem of tactical and operational planning in
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42 a sawmill in Chile. Their study focuses on the use of aggregated and disaggregated models at the tactical
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44 level and their short- and long-term impact on storage costs, raw material purchase costs and production
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46 costs. In their context, a model is said to be disaggregated if it uses several flow patterns for sawing and
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48 a model is said aggregated if it uses an average of all these flow patterns. They used a "two-stage
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50 formulation" (Birge and Louveaux, 1997) to coordinate long-term decisions and short-term decisions
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52 and presented four models covering these two levels of planning (tactical and operational). In their study,
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54 only sawing is taken into account while in North America, sawmills also need to dry and finish their
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56 wood in order to meet NLGA standards, which complicates the coordination between tactical and
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58 operational levels.
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3. Simulation framework

This study uses proven planning models ensuring feasible production plans to evaluate the impact of different types of information shared from the tactical level to the operational level performance of a typical North American sawmill.

In order to compare and evaluate the impact of different coordination approaches between the tactical level and the operational level on business economic performance, both the decentralized planning process and production process (sawing, drying and finishing) are simulated. The simulation incorporates the physical production system, the planning process implemented, the market context as well as the company's order acceptance policy, whether it is ATP or CTP.

The production planning process incorporates tactical and operational planning levels. The information is shared from the tactical level to the operational level as constraints or targets to be respected (e.g. quantities to be produced / kept in stock per product and per period, sales targets, sales price forecasts, etc.).

3.1 Configuring the framework

The simulation framework proposed by Dumetz et al. (2016, 2018) was exploited and a tactical decision level was added (see Figure 1).

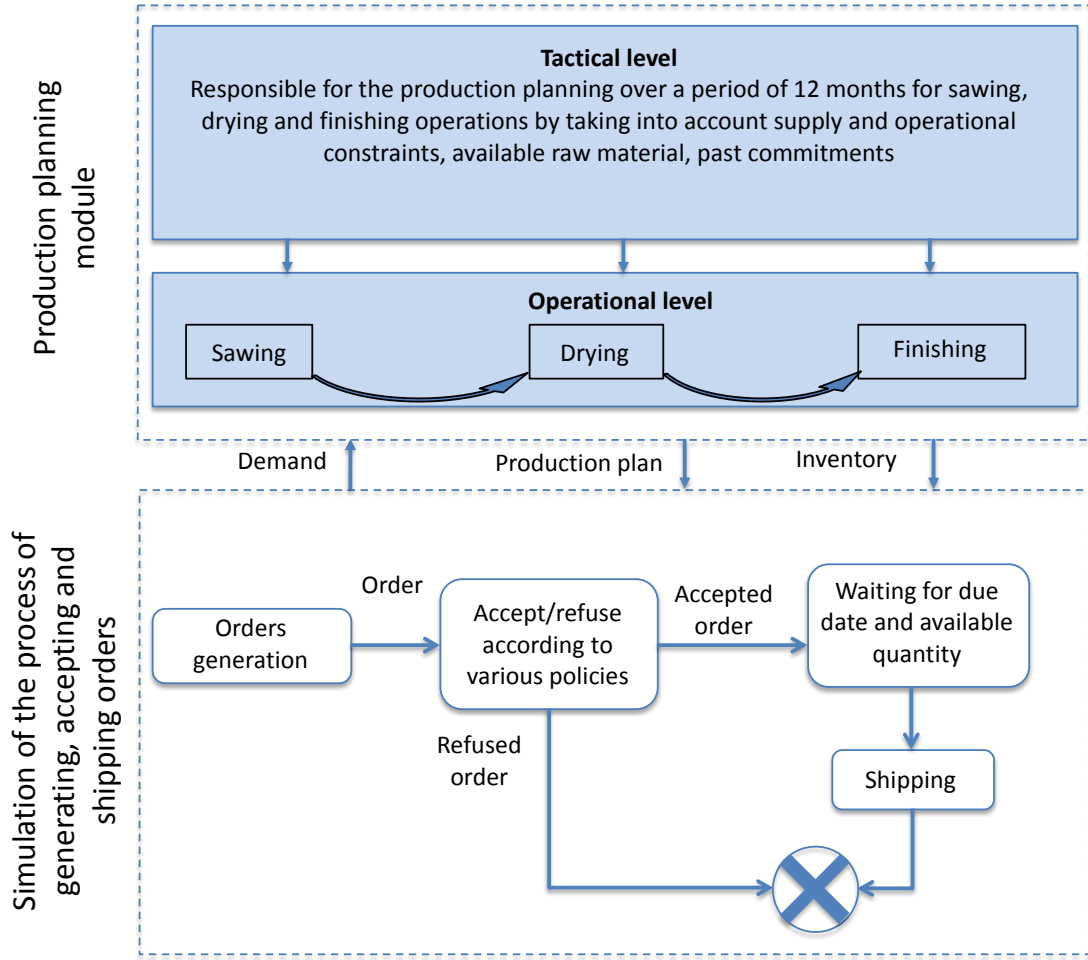


Figure 1: Conceptual representation of the simulation framework (adapted from Dumetz et al., 2016 and 2018)

The simulation framework was developed in the Simio environment, a discrete event simulation software. Orders are generated following a Poisson distribution as proposed by Ben Ali et al. (2014). These orders are then accepted or rejected based on an order acceptance policy (e.g. ATP or CTP). In particular, with the ATP policy (APICS, 2012), an order of size Q is accepted only if Q is smaller or equal to the expected stocks for each period of the planning horizon after the due date.

$$Q \leq I + \sum_{t=\text{now}}^{D-1} (P_t - E_t) - \max_{D \leq t \leq T} \{ \sum_{k=D}^t (E_k - P_k) \} \quad (1)$$

where D is the due date of the order, T is the simulation horizon, I is the current inventory, P_t is the production at period t and E_t are the commitments at period t .

The CTP policy (APICS, 2012) amounts to first attempting to accept an order with the ATP policy, as previously explained. If the order cannot be accepted using the ATP policy, a provisional production plan is drawn up, including this new order, to check if the order can be satisfied without compromising previous commitments. If the order cannot be made in time, the customer is notified, and it is assumed that he has withdrawn his request. When an order is accepted, the simulation model waits for the delivery date and the quantity available and the order is delivered.

The simulation framework incorporates a custom-built Enterprise Resource Planning (ERP) that is responsible for tactical and operational planning. This ERP was programmed in C # .net environment, which makes use of different specialized models and algorithms taken from the literature. At the tactical level, the Sales and Operations Planning model for the lumber industry published by Marier et al. (2014a) is used. This integrated model provides a production plan for sawing, drying and finishing over a one-year horizon. The constraints at different stages of production (raw material, dryer configuration, flow patterns, ...) are taken into account. Based on the assumed sales prices from forecasts, a production plan is generated with the aim of maximizing income and reducing costs. Figure 2 shows the inputs and outputs used in this model.

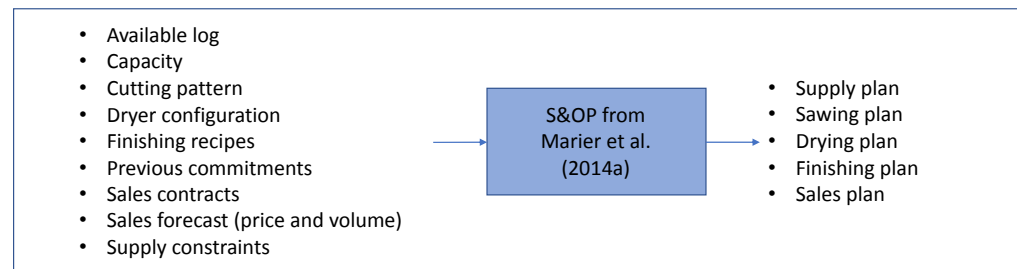


Figure 2: Inputs and outputs used in the model from Marier et al. (2014a)

At the operational level, three independent planning models for the sawing, drying and finishing operations are also exploited. For sawing, a model from Marier et al. (2014b) based on the work of Gaudreault et al. (2010) is used. This model maximizes produced value while generating a sawing plan which takes into consideration the raw material (the available logs), the sawing capacity, and the different cutting patterns. In particular, the output plan states which process is used, when, for how long as well as how many sawn products are produced. We suppose that the raw material is not limiting the production and that production is available 14 hours per day, 7 days a week. All cutting patterns have the same

operational cost, but each product has a different expected market value. The planning horizon is 4 weeks and replanning occurs once a week. Figure 3 shows the inputs and outputs used by this model.

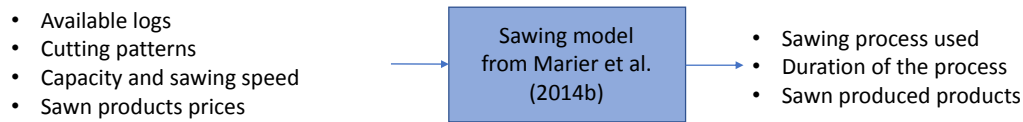


Figure 3: Inputs and outputs used by the model from Marier et al. (2014b)

For drying, the MIP model developed by Marier et al. (2016) is used. A kiln dryer can be represented as a huge container (defined by its length, height and width) where bundles to be dried are assembled on a wagon and then pushed inside the kiln. The planning horizon is 4 weeks with replanning occurring once a week. The model can be used to minimize order lateness or to maximize production value. The output drying plan states which wood bundle to dry, when, in which dryer, as well as how to load the kiln (loading pattern)

Figure 4 shows the inputs and outputs used in this model. For more information about the MIP model, see Marier et al. (2016).

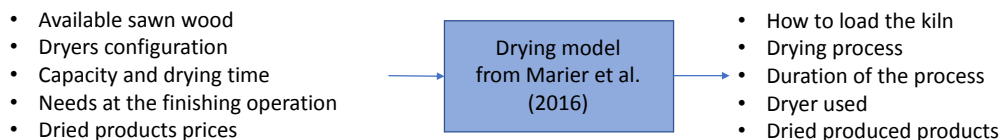


Figure 4: Inputs and outputs used in the model from Marier et al. (2016)

For the finishing operation, a model from Marier et al. (2014b), based on the work of Gaudreault et al. (2010) is used. mixed-integer programming model used tries to minimize order lateness. The model states the quantities of each product that should be planed for each production shift, as well as the finishing recipes to use. Figure 5 shows the inputs and outputs used in this model. For more information about the MIP model, see Marier et al. (2014b).

- Available dry wood
- Demand
- Sales contracts
- Finishing recipes
- Capacity and finishing speed
- Finished products prices

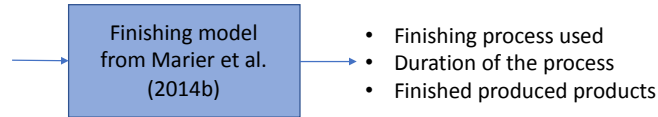


Figure 5: Inputs and outputs used in the model from Marier et al. (2014b)

3.2 Operational level coordination

As the operational models work in a decentralized manner, a mechanism is therefore required to ensure coordination. This coordination mechanism makes sure that the need or the demand for each subsequent operation will be taken into account. It is based on a hybrid push / pull approach which considers the decoupling point in the production system. The decoupling point is located between the drying unit and the finishing unit (Figure 6), as finishing is the bottleneck of the system. A decoupling point is defined by APICS (2008) as “the locations in the product structure or distribution network where inventory is placed to create independence between processes or entities”.

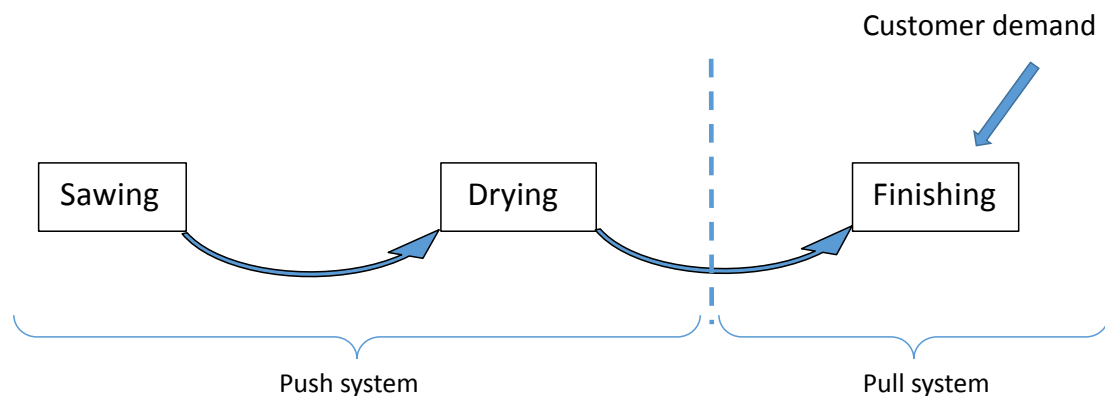


Figure 6: Decoupling point before the finishing stage (From Dumetz et al. (2018))

Before the decoupling point, operational planning does not take into account firm orders. It considers only targets or other information provided by the tactical model. The sawing model first computes a plan that maximizes its production value (taking into account constraints from the tactical model). The drying model then does the same, taking into account sawing production. The finishing model is the one dealing with firm’s orders while taking into account drying production and targets from the tactical models, but most of all deals with firm orders. For additional information, see Dumetz et al. (2018).

3.3 Tactical-operational coordination

The tactical and operational levels have different planning horizons and review frequencies. In the proposed simulation, the tactical model is configured for a planning horizon of 12 periods of 1 month. It is rerun each month according to the rolling horizon principle. The operational models work on a basis of 14 periods of 12 hours worked each week. The plan covers the upcoming 56 periods (1 month), with weekly replanning.

Information input at the tactical level (e.g. orders) is aggregated by month. Instructions transmitted from the tactical to the operational level, such as inventory targets at the end of the month, are assigned to the last period of the corresponding model for the month in question. For a monthly production target (at the tactical level), the target is subdivided for each sub-period present at the operational level. (See Figure 7)

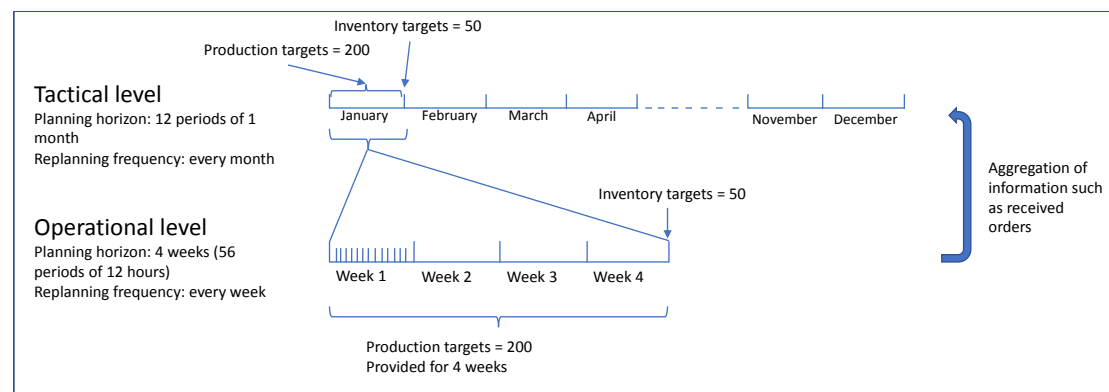


Figure 7: Tactical-operational coordination

Products are not aggregated into families since previous work from Gaudreault et al. (2010) and Marier et al. (2014a) showed that this does not help tactical models, which are linear models whose resolution time is little affected by the number of products.

3.4 Validation of the framework

In simulation studies, validation ensures the veracity of the result and analysis (Sargent, 2004). As the

1 system we modeled does not really exist, the simulation could not be validated by comparing historical
2 production data with our simulation model outputs. However, the mathematical models exploited have
3 been validated in the past and are already being used by a Canadian forest products company. In addition,
4 the simulation framework used is the same as the one developed and tested by Dumetz et al., 2016 to
5 evaluate the impact of different order acceptance policies (ATP, CTP, Stock). In the present study, the
6 framework was modified, and some features integrated so as to take into account the tactical level. The
7 model was validated by using the same set of data and parameters as in Dumetz et al. (2016).
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15 **4. Experiments**

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17 To compare and evaluate the impact of different coordination approaches between the tactical level and
18 the operational level on business economic performance, different planning approaches were devised.
19 Each approach is defined by (1) an order acceptance policy (ATP or CTP), as well as by (2) the type of
20 information transmitted from the tactical level to the operational level. In Dumetz et al. (2016) and
21 Dumetz et al. (2018), order acceptance policies have been studied for industries facing divergent
22 processes with coproduction. ATP and CTP were the order acceptance policies that showed the best
23 performances in terms of accepted orders and lower average inventory. Those policies are furthermore
24 enough flexible to be adapted to the forest products industry context. These two order acceptance policies
25 were therefore chosen for the present experimentations. The type of information transmitted from the
26 tactical to the operational level (2) could simply be a forecast of the product market price for the next
27 month or more specific production and inventory targets. As the experiments took 350 hours of
28 calculation, we had to target the key aspects to evaluate so as to limit the number of experiments to
29 conduct. The information we selected is typically the one used in the North American sawing industry
30 while being available from the tactical plan.
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Table 1: Description of the planning approaches evaluated

Tactical instructions Order acceptance policy	Monthly price forecast for each product -The tactical level informs the operational level of monthly selling prices -The operational level seeks to maximize the produced value	Production targets / inventory targets - Production targets (what to produce at sawing, drying and finishing) and inventory targets extracted from the tactical plan -Information transmitted to the operational level which seeks to maximize the produced value under these constraints
ATP	(Blue dashed line) -Order acceptance is made under the ATP policy. -Order acceptance does not create a future shortage.	(Red dashed line) -Order acceptance is made under the ATP policy, with additional constraints (inventory targets must be met). -Order acceptance does not create a future shortage.
CTP	(Full blue line) -Order is established if it can be accepted under the ATP policy. -If this is not the case, the production plan is modified to include this new order only if it does not compromise previous commitments	(Full red line) -Order is established if it can be accepted under the ATP policy, subject to the additional constraints (inventory targets must be met). -If this is not the case, the production plan is modified to include this new order only if it does not compromise previous commitments under constraints that the new production plan meets the production and inventory targets.

Working with industrial partners, parameters of the tactical model and the operational models were defined to be representative of a typical Canadian sawmill, although only the 10 most representative products were kept. For example, cutting patterns, drying processes and finishing recipes were set according to real patterns, adapted to fit these 10 products. To determine this, we used a real production plan of a partner company. This production plan listed all the products produced over a year. We used the Pareto law and found that 80% of the production volume concerned only 10 products. Those products were therefore the ones used in the experimentation as taking into account the remaining 20% would only have weighed down the model. The sale prices associated with these products were real prices provided by the sawmill (we were provided with historic data). In our study, the operational costs are those linked to each processing stage (sawing, drying, and finishing). We assume that they are the same for each cutting pattern, each finishing recipe, and each drying process. The simulation covers a two-year production horizon. The raw material supply (logs) has infinite capacity. The demand for each product is randomly generated using a Poisson distribution as in Ben Ali et al. (2014). The delivery time required by the customer is randomly generated using a triangular distribution. Each order consists of a single product with a fixed order quantity of 50 MPMP. The PMP board foot is a measurement used for lumber in North America and a MPMP corresponds to one thousand feet of board. In addition, two other parameters define the market context: (1) the magnitude of the seasonality of product prices and (2) the annual demand intensity in relation to production capacity. With respect to price seasonality (1), the industrial data used for this case study reflected the seasonality of prices on the market. In addition to the original demand scenario (average seasonality), two other seasonality scenarios were defined for analysis purposes: one where there was no seasonality (a product has the same average value each month) and one where the seasonality was amplified (strong seasonality). To amplify the seasonality of a product's sales price, the 6 highest selling prices of the year were increased by \$ 50 (or 10% on average), whereas the other 6 sales prices (lowest prices) were decreased by \$ 50. Figure 8 illustrates the seasonality amplification process for a product.

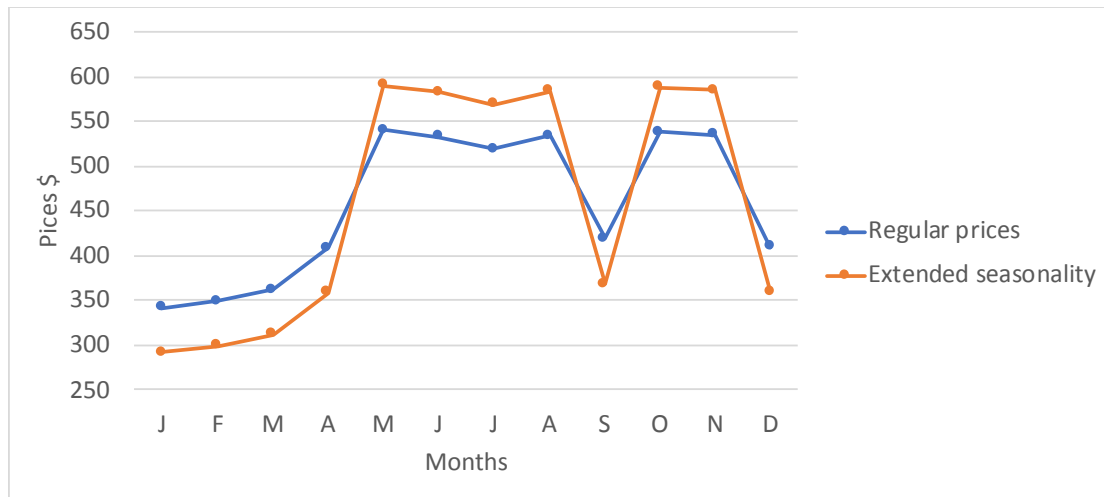


Figure 8: Seasonal amplification process

As for demand intensity (2), it quantifies demand as a percentage of the company's maximum production capacity. By first planning production supposing infinite demand, it becomes possible to compute the ideal demand maximizing the company's productivity. This demand corresponds to the 100 % demand intensity. The demand intensity parameter is used by the simulation model to generate orders.

It represents the number of orders received by the company in 1 year. For example, a company that receives a significant demand for 1 year will sell almost everything it produces. Conversely, if demand is low, a company will have to choose carefully what will be produced (finished products) in order to sell it to the right customer. In this case, it is important to produce the right product at the right time. In these experimentations the demand intensity represents the entire range between these two extremes. To quantify it, the intensity of demand is expressed as a percentage of the company's maximum production capacity. At a 100% intensity, the demand that the company will receive over one year will be equal to its entire annual production capacity. Other percentages are also tested since it has been shown (see Dumetz et al., 2016) that due to the coproduction phenomenon, the demand must be much greater than the production capacity to be able to sell all the products. For this reason, this intensity was varied between 200% and 3000%. This quantity is distributed among the different products manufactured and represents the typical demand profile of a North American sawmill, although the number of products taken into account has been aggregated. The following table shows the quantity of demand that a company may receive every year for an intensity of 100% and 300%. Quantity is expressed in thousand board feet (MFBM)..

Table 2: Quantity of demand received in one year in MFBM (intensity of 100% and 300%)

Product \ Demand intensity	100% of the maximal production capacity (MBFM)	300% of the maximal production capacity (MBFM)
P1	3 145	9 435
P2	10 464	31 392
P3	14 517	43 551
P4	22 064	66 192
P5	50 362	151 086
P6	265	795
P7	1 258	3 774
P8	3 586	10 758
P9	18	54
P10	13	39

For an intensity of 300%, the company will receive a quantity of demand equivalent to 3 times its maximal production capacity over the year. The demand is distributed throughout the year randomly. As 1 order represents 50 MPMP, it is possible to receive several orders for the same product in the same week depending on the intensity.

A total of 15 replications per scenario were conducted in order to obtain significant confidence intervals (95% confidence level). The total simulation time was 350 hours.

In these experimentations, stochastic events affecting the production process were not taken into account. Hence, all the production planned at the operational level was produced. With this assumption, results between scenarios could be compared to determine the impact of the choice of the information inherited from the tactical level on the generated revenue.

4.1 Results

4.1.1 Market without seasonality

Figure 9 shows the income according to the demand intensity in a market without seasonality.

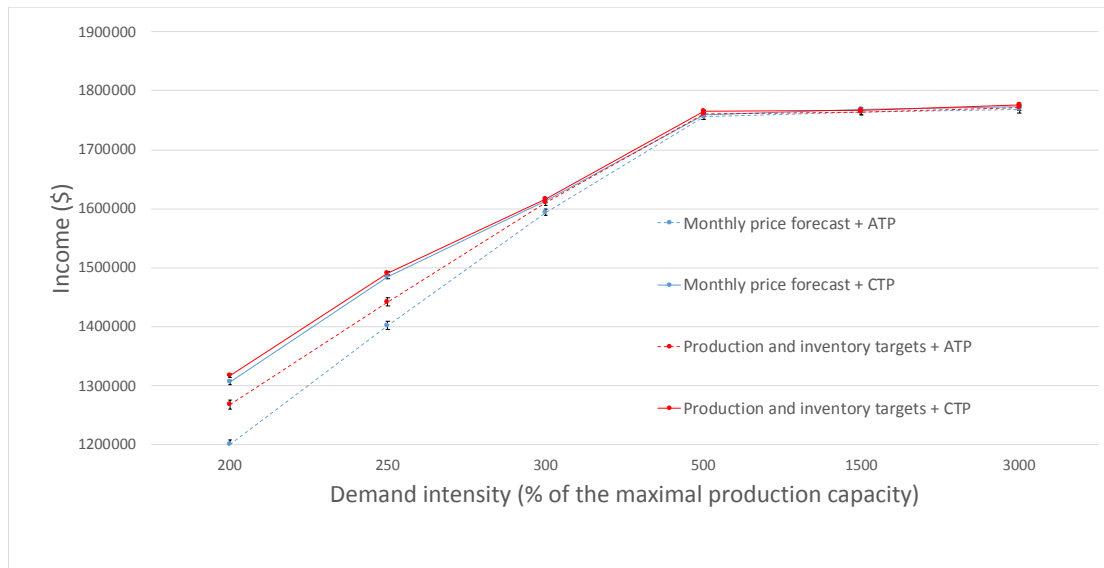


Figure 9: Income according to demand intensity, type of targets transmitted from the tactical level to the operational level and order acceptance policy used (no seasonality).

Considering results concerning the ATP policy (dashed lines), providing production targets (red dashed line) at the operational level gives a better income than only providing operational price information (blue dashed line). The phenomenon is especially noticeable at low intensity. This is because if the operational level works only on the basis of the selling price (blue dashed line), it will produce a basket of products with a maximal value, without taking into account the possible volume to be ordered in the future. The demand for some products will then be too low and it will not be possible to sell all of the created stock. Many orders that are not in line with the products stocked will be rejected, and a high level of stock will be observed. On the other hand, when the tactical level transmits production targets and inventory targets (red dashed curve) established by the tactical level, the planning takes into account demand profiles, therefore, the performance is better. Logically, as the demand intensifies, the difference between these two lines decreases.

When strictly comparing the two approaches using the CTP order acceptance policy (full lines), the performance is very similar whether the tactical level provides inventory and production targets (full red line) or simple forecasts of sales price (full blue line). Nevertheless, at low intensity of demand, there is a slight statistically significant added value with the approach that meets the production targets of the tactical level (full red line). Indeed, although the inventory targets are zero because there is no seasonality (so no interest in building a stock in order to sell it when the price is high), this approach is slightly better

because it allows taking into account the demand profile.

In general, it can be noted that for low demand intensity (less than 300%), the two approaches using a CTP policy (full lines) perform better than approaches using the ATP policy (dashed curves). In fact, any order accepted in ATP is also accepted in CTP (see the algorithm associated with the CTP policy, section 3.1) and changing the production plan makes it possible to accept more orders (CTP policy). At high intensity (more than 500%), all the curves generate an almost equal income. On the one hand, the demand is large enough that order acceptance using the ATP policy has used up all of the production capacity. On the other hand, the production plans are almost the same, regardless of the tactical targets used. Indeed, the production forecasts from the tactical level are large enough to manufacture only the most profitable products, so production plan will match the one based on sales prices.

4.1.2 Low seasonality market (base case)

Figure 10 shows the income according to the demand intensity for a market with low seasonality.

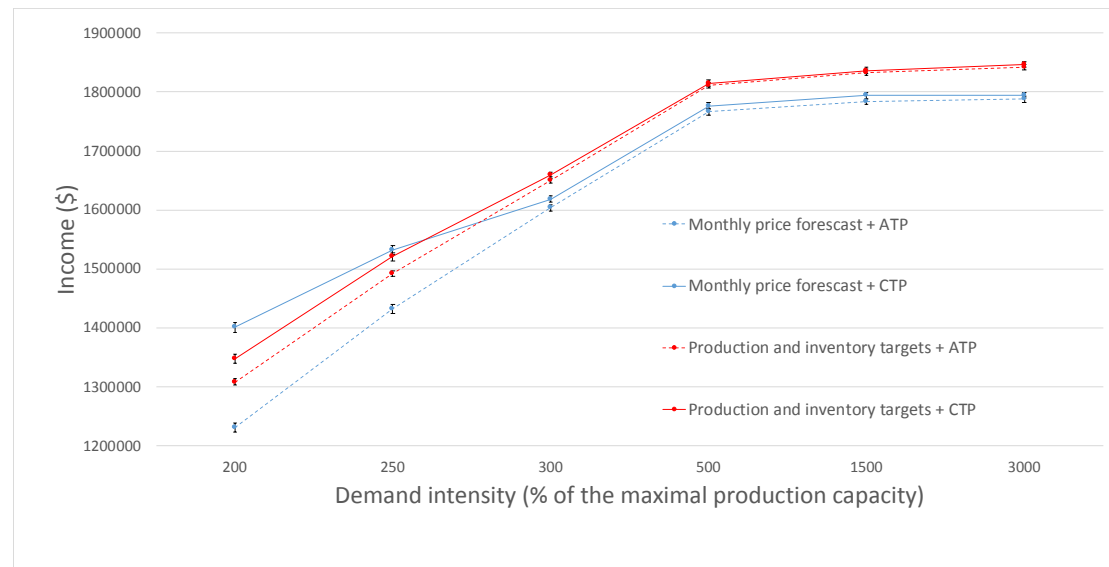


Figure 10: Income according to demand intensity, type of targets transmitted from tactical level to operational level and order acceptance policy (low seasonality)

Results show that using an ATP policy, following production targets and inventory targets from the tactical level, increases the income (red dashed line) compared to maximizing the generated value by taking into account the information on the monthly sales prices of products (blue dashed line). Unlike

the case without seasonality (previous section), this superiority is valid even at high demand intensity. Indeed, this comes from the fact that by respecting inventory targets, it is possible to sell a product at a higher price in a future period.

Concerning the approaches using the CTP policy (full red and full blue lines), at low demand intensity (here below 260%), the CTP policy where the tactical level provided simple price forecasts (full blue line) presents a better income. This indicates that when the demand is low with a seasonal market, it is better for operational planning to be based on sales price forecasts rather than following production and inventory targets dictated by the tactical plan. This seems counter-intuitive but is mainly due to the following. Producing a new plan that satisfies the new order, past commitments and inventory targets all together seems very difficult. Many orders are thus refused because the new plan cannot meet all of these constraints. On the other hand, removing the constraint of following the inventory levels allows the CTP policy to be more agile in a situation where demand is low. At high intensity (above 260%), the full red and blue lines are reversed. This indicates that operational planning is better based on production and inventory targets than on price forecasts. This is due to the combination of two elements. As a reminder, any order accepted in ATP is also accepted in CTP (see the algorithm associated with the CTP policy, section 3.1). With this in mind, these two elements are: (1) the approach using the CTP policy based only on the information of the selling prices of the products (full blue line) has a performance resembling that of the associated ATP policy (blue dashed line). Indeed, the approach using the ATP policy is more and more efficient because the demand intensity increases. This leaves fewer possibilities to include a new order using the CTP policy. On the other hand, (2) the generated income using an ATP approach that meets production and inventory targets (red dashed line) is much better when demand intensity increases. Although it is still difficult to achieve a plan following all constraints, it is still possible to accept some additional orders using the CTP policy. Therefore, this approach using a CTP policy while respecting inventory and production targets (full red line) benefits from the good performance offered by an ATP policy that follows production and inventory targets, which is better than a policy using ATP and information on the selling prices of products.

Finally, in general, when comparing approaches using the same shared information by the tactical level (blue lines for price forecast and red lines for production and inventory targets), approaches using a CTP

policy give a better income compared to approaches using an ATP policy. This is valid up to a high demand intensity where income becomes almost equal. In fact, the demand is high enough that all the orders which could be accepted according to the production capacity have already been using the ATP policy: then, using the ATP policy or the CTP policy leads to the same results in terms of income.

4.1.3 High seasonality market

Figure 11 represents the income according to the demand intensity in a situation of high seasonality.

In general, with high seasonality market, the behavior of each line corresponds to what was already observed when the seasonality was lower. The results show that income increases for all cases, compared to Figure 9 where seasonality was low (base case). The seasonality being stronger, the income is also higher, and the crossing point of these same lines does not occur at the same demand intensity (shift to the left).

It is therefore important to take into account these market parameters when choosing tactical targets to be transmitted to the operational level.

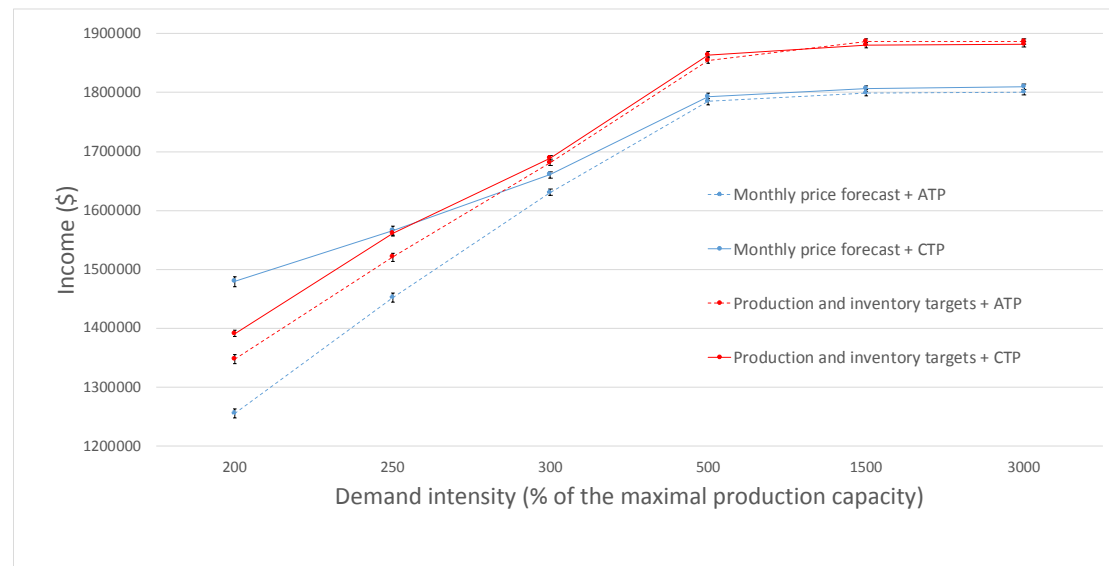


Figure 11: Income according to demand intensity, type of targets transmitted from the tactical level to the operational level and order acceptance policy (high seasonality)

4.2 Discussion

The sawmilling industry is a process industry where most costs are fixed. The main exceptions are the inventory cost and the procurement cost. In our previous paper (Dumetz et al. (2018)), we showed that using planning models to maximize sales decreases average stock levels. As for procurement cost, it is directly proportional to production volume thus looking at production value or volume considers them indirectly. That's why sawmill and studies measure throughput. Furthermore, the sawmilling industry in North America typically plans its activities based on a push mode and measures its financial performance regarding the volume produced. Even though a natural resource playing a key role in the ecosystem is processed, it is rare to see a sawmill using a performance indicator not related to the revenues generated or the volume produced.

These results demonstrate the importance of coordinating production planning at the tactical and operational decision levels in order to achieve a plan that meets the long-term goals as well as the orders that arrive daily. This coordination is especially important because of the particular context studied here (a divergent process with coproduction). The information transmitted from the tactical level to the operational level which was selected for this study (information on sales prices, production target and inventory target) are targets commonly used in the forest products industry. Results showed that the type of information transmitted, and the market context directly impacted the revenues generated. Highly relevant information for the industry, companies in the forestry sector could use these findings as a decision-making tool which recommends the best choice of information to transmit from the tactical level to the operational level according to their business context (production parameters, planning approach and market context). Moreover, as mentioned, transmitted information is already used in this industry. By remaining faithful to what industrials are doing and avoiding the use of information that these companies would not be able to obtain, the gap between reality and research is limited.

Conclusion

This research studied a production planning process that incorporated tactical and operational decision-making levels of North American sawmills. Production plans based on various information transmitted from the tactical level to the operational level were compared and evaluated by simulating the production system, the planning process as well as market behavior. In this context, the information shared from the

tactical level to the operational level became targets or constraints (e.g. quantities to be produced / kept in stock per product and per period, information on the sales prices of the products used at the tactical level). These targets or constraints were used by the operational level to plan production at each stage of the lumber production process and thus meet demand. Results showed that in certain market contexts (defined by a volume of demand and a seasonality in the prices of products), the choice of the targets shared by the tactical plan and seen as constraints for the operational plan could lead to a degradation of the company's performances because of the impossibility of respecting these constraints. Conversely, for other market contexts, these same targets helped to better manage inventories and demand, especially by selling at the right time (when the selling price is higher) thus leading to an increase in income. For example, at a high demand intensity, meeting inventory targets would create a stock to sell later, at a higher price. Conversely, following these same inventory targets at a low demand intensity would lead to poor performance in terms of generated income. This is because the demand is too low or poorly known; stocks cannot be sold. These findings are vital for industries as they demonstrate the importance of coordination between various production planning levels and which information should be transmitted from the tactical plan to the operational plan to maximize income, depending on their business context.

These results were obtained in a particular context, with specific market parameters and business data. These results are therefore not prescriptive but are intended to show the importance and difficulty of choosing the coordination approach for a divergent production system with coproduction, and therefore the need for a systematic analysis of using the methodology proposed in this article. Furthermore, the wood industry is not the only one presenting characteristics such as coproduction and divergent processes. This study could be very interesting for other industries facing divergent processes (several products obtained from the same raw material) with coproduction (the products are obtained at the same). This methodology could very well be adapted for example to the food industry, the oil industry, or the "float glass" industry.

In future work, it would be interesting to vary the calculation of targets in the tactical model based on information other than prices. For example, by setting limits by product type, setting maximum inventory levels instead of minimum levels to keep, or by proposing limits for inventories (e.g. product A must maintain its inventory between the values x and y where $y > x$). This last proposal could possibly offer

good solutions since the inventory targets are currently hard constraints to respect. If these targets were bounds, this would probably offer better opportunities to accept orders and thus increase the generated income. Finally, stochastic events can also be added to the production process. Due to failure, for example, what was previously planned could not be produced and late orders could occur. Firstly, the framework would then be much closer to reality since a company would inevitably face production issues. Secondly, robustness of the framework could also be studied.

Acknowledgements

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Product	Demand intensity	100% of the maximal production capacity (MFBM)	300% of the maximal production capacity (MFBM)
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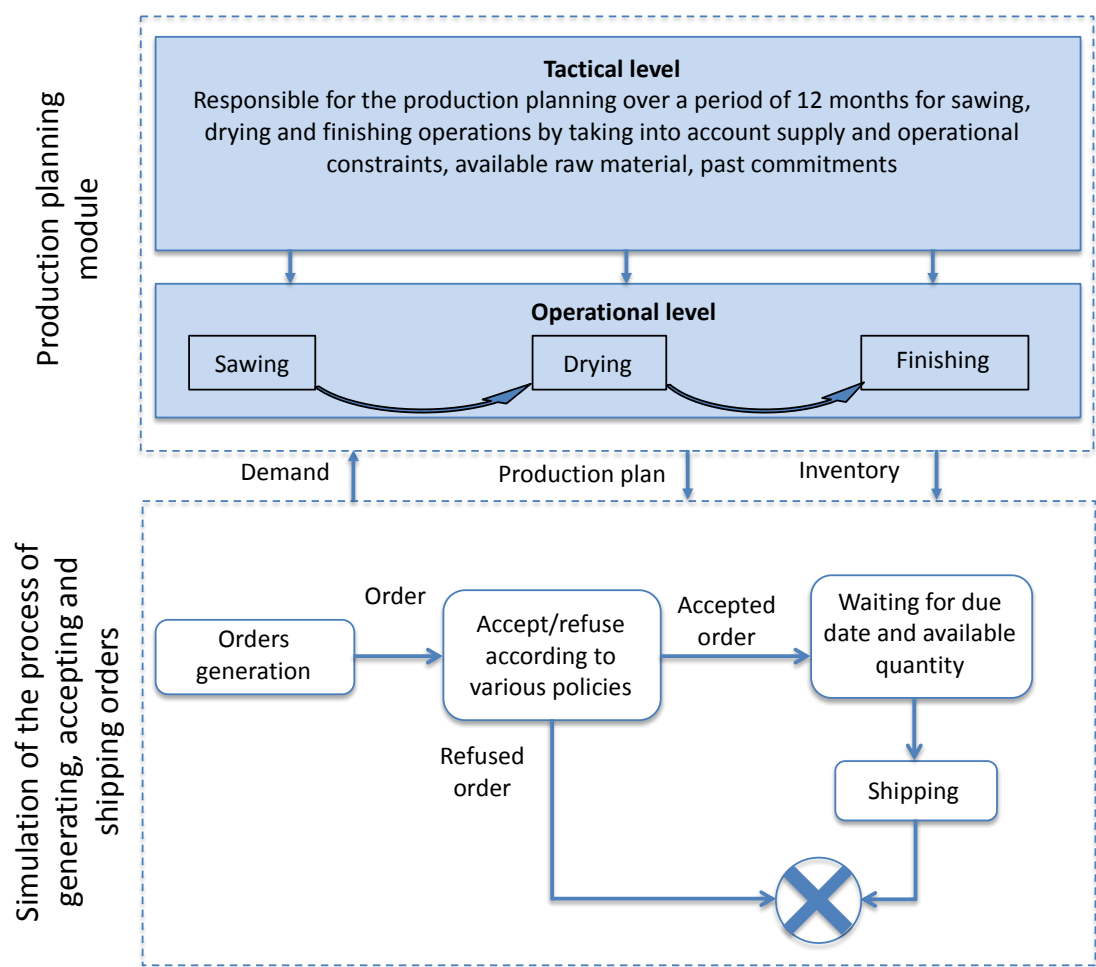


Figure 1: Conceptual representation of the simulation framework (adapted from Dumetz et al., 2016 and 2018)

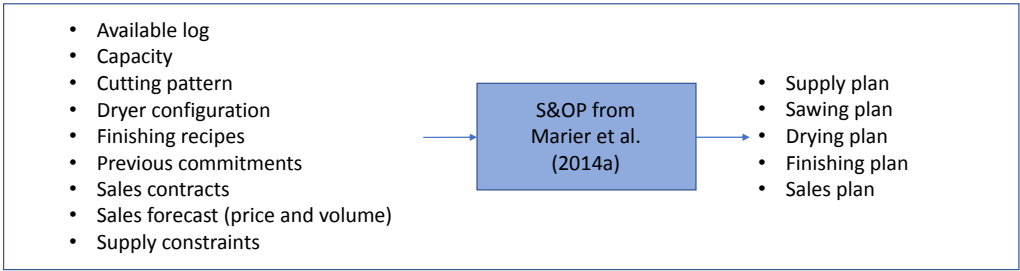


Figure 2: Inputs and outputs used in the model from Marier et al. (2014a)

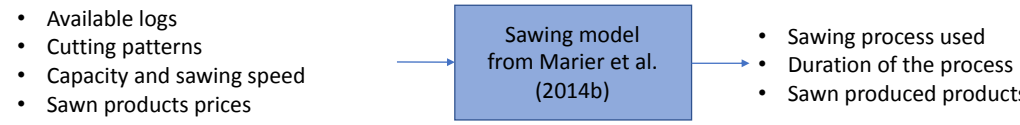


Figure 3: Inputs and outputs used in the model from Marier et al. (2014b)

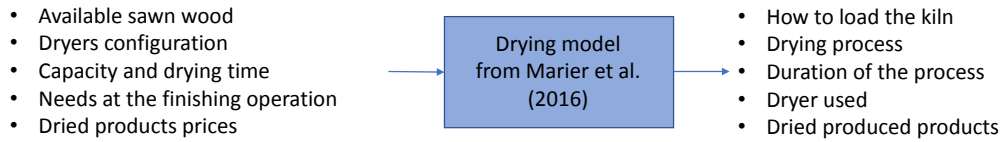


Figure 4: Inputs and outputs used in the model from Marier et al. (2016)

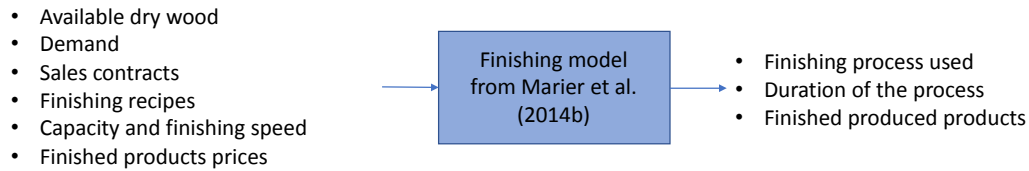


Figure 5: Inputs and outputs used in the model from Marier et al. (2014b)

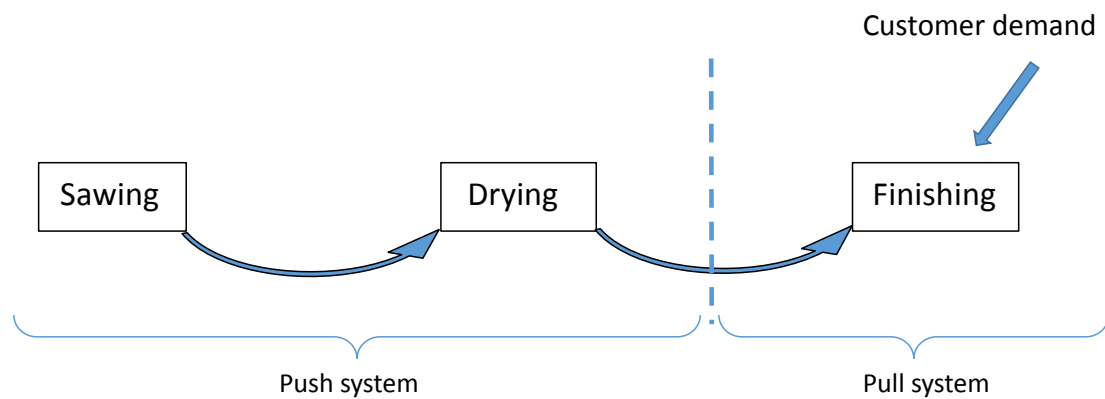


Figure 6: Decoupling point before the finishing stage (From Dumetz et al. (2018))

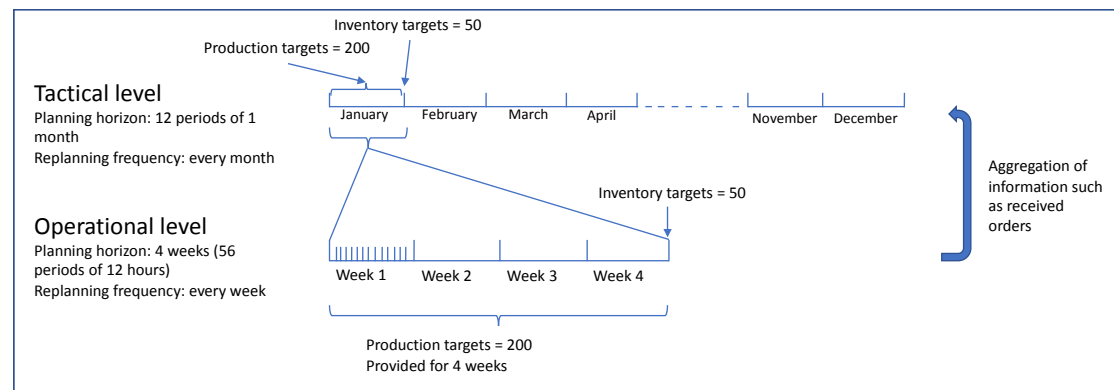


Figure 7: Tactical-operational coordination

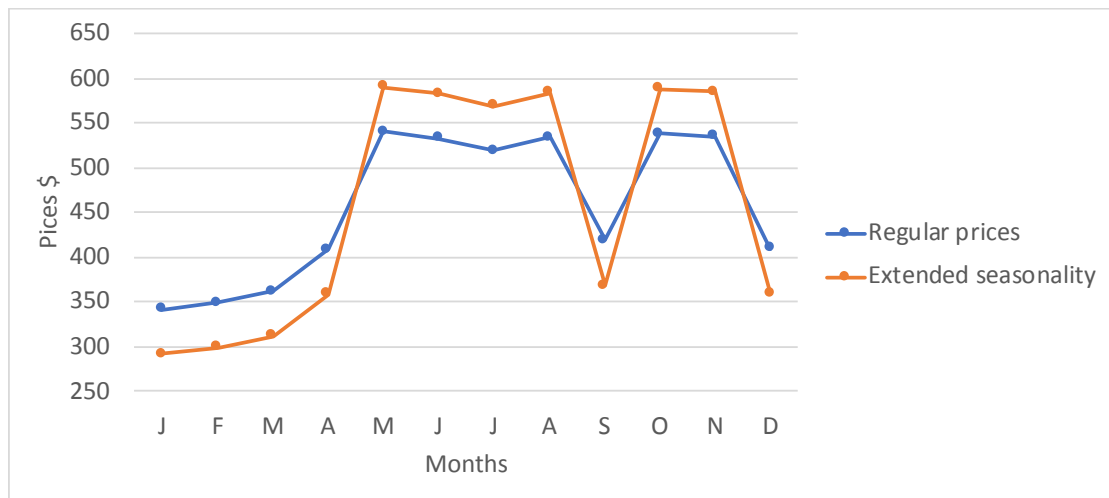


Figure 8: Seasonal amplification process

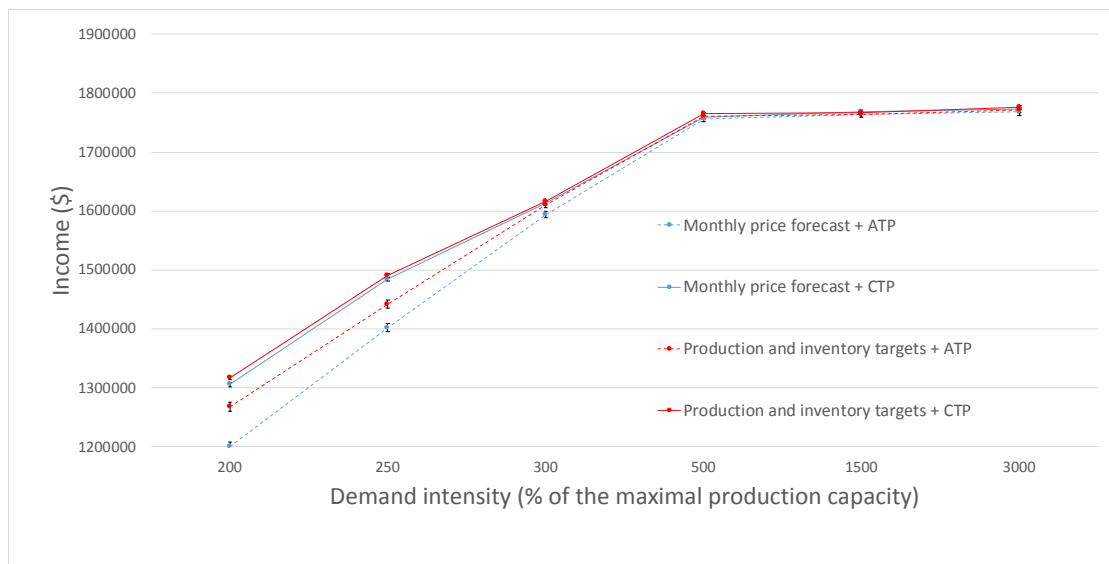


Figure 9: Income according to demand intensity, type of targets transmitted from the tactical level to the operational level and order acceptance policy used (no seasonality).

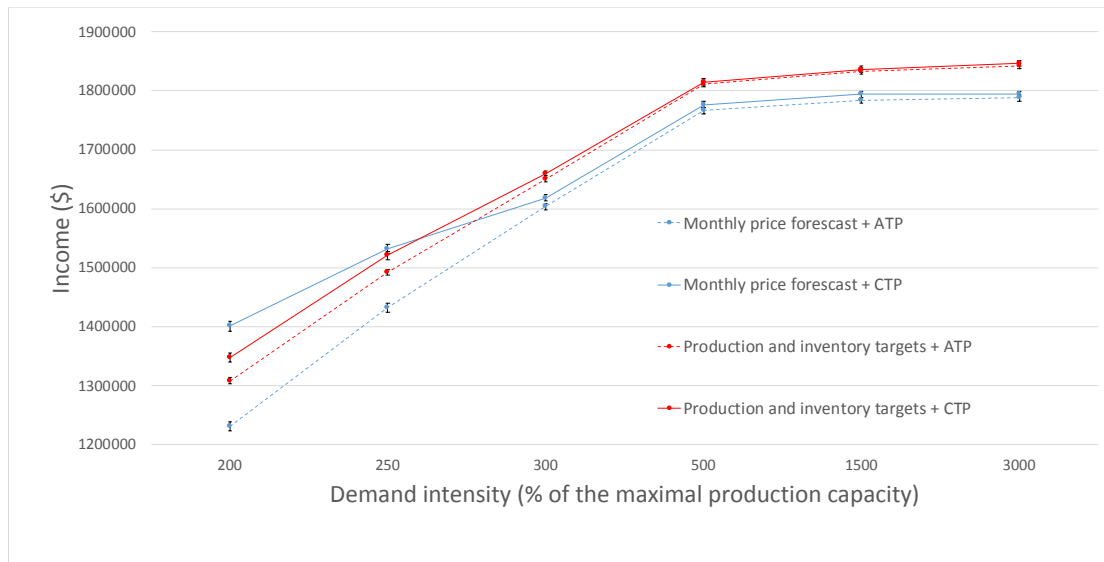


Figure 10: Income according to demand intensity, type of targets transmitted from tactical level to operational level and order acceptance policy (low seasonality)

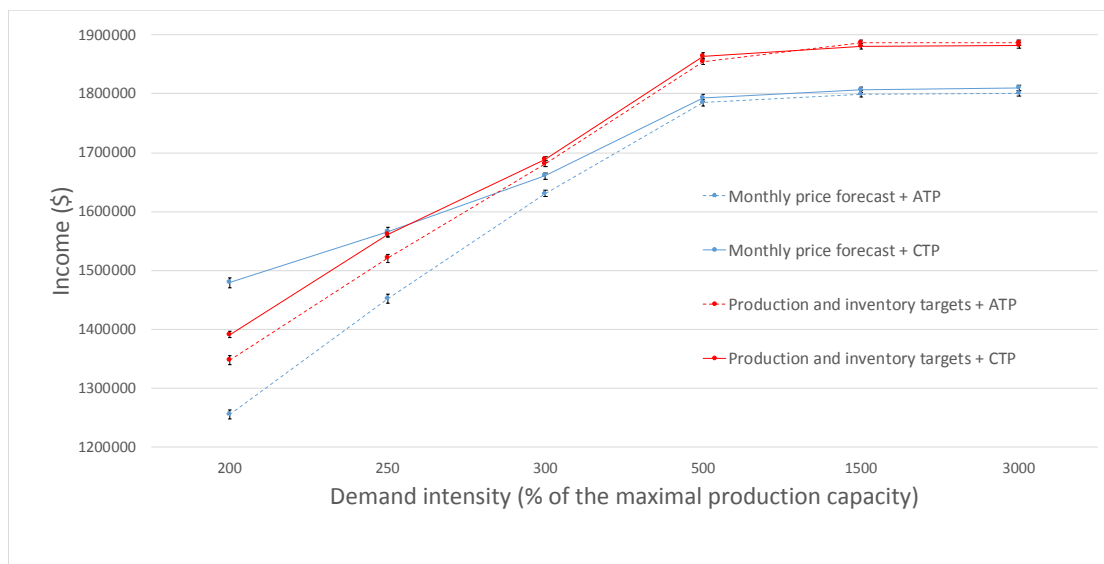


Figure 11: Income according to demand intensity, type of targets transmitted from the tactical level to the operational level and order acceptance policy (high seasonality)