International Journal of Industrial Engineering, 17(3), 168-189, 2010.

DISTRIBUTED OPERATIONS PLANNING IN THE SOFTWOOD LUMBER SUPPLY CHAIN: MODELS AND COORDINATION

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Agent-based technology provides a natural approach to model supply chain networks. Each production unit, represented by an agent, is responsible for planning its operations and communicates with other units for coordination purposes. In this paper, we study a softwood lumber supply chain made up of three production units (the sawing unit, the drying unit and the finishing unit). We define the local problems and propose agent-specific mathematical models to plan and schedule operations. Then, in order to coordinate these plans between the three agents, we propose different coordination mechanisms. Incorporating these developments, we show how an agent-based simulation tool can be used to integrate planning models and evaluate different coordination mechanisms.

Keywords: Distributed operations planning, coordination, optimization, agent, supply chain, lumber.

(Received 22 March 2010; Accepted in revised form 18 May 2010)

1. INTRODUCTION

Canadian lumber companies are confronted with the need to reengineer the way they manage and plan their supply chain operations. Supply chains are global networks of organizations where material and information flow in many directions within and across organizational boundaries through complex business networks of suppliers, manufacturers and distributors, to the external customers. These organizations can be part of the internal supply chain that consists of members of the same company or part of the external supply chain, which includes members of different companies. They must all exchange materials and information in order to maximize customer satisfaction at the lowest possible cost.

As concerns the lumber supply chain, it is similar to that of other industries: lumber material flows from forest contractors, to sawing facilities, to value-added mills (referred to as secondary transformation), and through the many channels of distributors and wholesalers to finally reach the markets. However, lumber operational planning represents a major challenge. Unlike the traditional manufacturing industry which has a convergent product structure (i.e., assembly), the lumber industry needs to master industry-specific operational processes. These are characterized by: (1) a divergent product structure (i.e., trees are broken down into many products), (2) the highly heterogeneous nature of its raw material and (3) radically different planning problems must be solved by each production center.

Distributed planning is an interesting approach for supply chain operational planning since it enables the use of specific optimization strategies and information available only locally. Unlike centralized planning approaches, which generally cannot take into account specific operational details, distributed planning makes it possible to create detailed models of specific planning problems.

The purpose of this paper is to propose planning models for the lumber production units and then to compare different coordination mechanisms. In Section 2, we present a description of the softwood lumber production processes and planning strategy used by practitioners. Next, in Section 3, a literature review is provided on lumber planning, supply chain and coordination. Then, in Section 4, we propose a distributed planning system, including specific planning models for each production unit as well as coordination mechanisms to ensure coherence between agents. Section 5 reports how an industrial supply chain was modeled in order to validate the models and evaluate the coordination mechanisms, using agent-based tools. Finally, Section 6 concludes the paper.

2. SOFTWOOD LUMBER PRODUCTION AND PLANNING

2.1 Production Units

This section introduces the three different production units involved in softwood lumber production:

- the sawing facility, where logs are cut into various sizes of rough pieces of lumber;
- the drying facility, which reduces the lumber moisture content and
- the finishing facility, where lumber is planed (surfaced), trimmed and sorted.

Figure 1 presents the different production units.

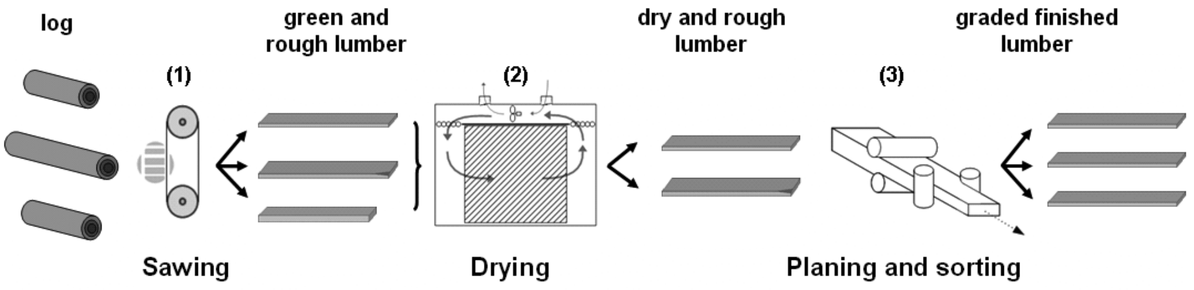

Figure 1. Production units and products in a lumber supply chain

This paper does not address the log supply problem. Forest is harvested by entrepreneurs responsible for felling trees and crosscutting them into logs according to an annual harvest plan. Therefore, logs are supplied to the sawing unit more or less according to this plan.

Sawing Unit

Logs often times remain in a sawmill yard for a lengthy period of time before being processed. They are stored in huge lots according to certain physical characteristics (species, length, average diameter, etc.), each lot representing a specific class of logs.

Logs are then broken down into various sizes of rough pieces of lumber. Different dimensions of lumber will be obtained at the same time from a single log, which is called co-production. Most of the time, sawmills have access to data regarding past production, allowing them to forecast the expected quantities of the different types of lumber to be produced from a specific quantity of logs of a given log class. This information defines a production matrix (Figure 2). Arcs show the quantity of each type of lumber expected when sawing a given volume from a specific log class. According to this example, if a batch of 100 logs from Class 2 is about to be processed, it is expected to produce 110 pieces of 2”x3” and 95 pieces of 2”x4”.

In most sawmills, the production line can be set up in different modes, each setup being associated with a specific production matrix which gives the production manager some control over the production output mix. However, certain log classes may be incompatible with certain setups; for example, in most sawmills, fir and spruce cannot be processed in the same production shift and are thus associated with different setups. Therefore, the decisions the production manager must make are the following:

(1) decide how the plant will be set up for each production shift, and
(2) decide which quantities of each log class to be consumed at each production shift.

Once logs are sawn, green pieces of lumber are assembled into bundles of the same *dimension* (2”x3”, 2”x4”, etc.) and *length* (8-foot, 12-foot, 16-foot, etc.), and generally of the same *species* (spruce, fir, etc.) in order to be dried.

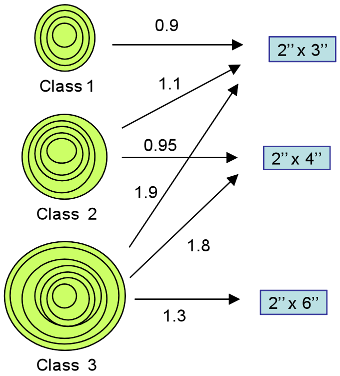

Figure 2. Example of a production matrix

Drying Unit

Lumber drying is a transformation operation which aims at decreasing the lumber moisture content in order to meet customer requirements. These requirements are usually specified by industry standards, although some customers may require specific levels of moisture content. Softwood lumber drying is a rather complex process to carry out. It takes days and is done in batches within large kiln dryers. Bundles of lumbers of different lengths can be dried in the same batch (e.g. 8-foot and 16-foot), but lumbers must be of the same dimension and species (although there are some exceptions). A batch must be assembled as a rectangular prism filling the kiln dryer almost entirely. There are many constraints related to the stability of this stacking. For these reasons, each sawmill defines its own set of *loading patterns* that can be used. Figure 3 shows two examples of loading patterns.

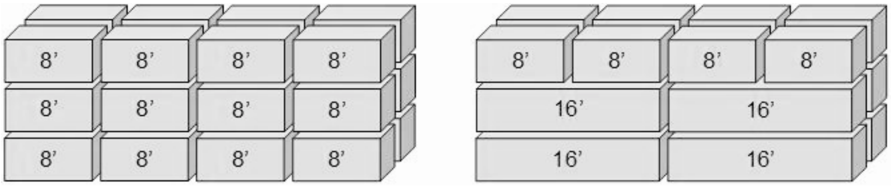

Figure 3. Examples of small loading patterns (actual kilns and patterns contain a few hundred bundles)

Under certain circumstances, special sections of the wood yard may be used to perform air drying. Air drying, which precedes kiln drying, may take several weeks but allows the reduction of the drying time in the kiln. Air drying also plays a role in increasing the overall quality of the finished product (obtained after finishing).

For a given batch of green lumber, there are different possible alternative operations that can be used for air-drying and kiln-drying. Figure 4 presents an example of four possible alternative combinations of operations. For air drying, these are mostly differentiated according to their durations. For kiln operations, they are different with regard to air temperature, humidity parameters, and duration. The planning decisions for this production unit are the following: (1) what drying activities to perform, (2) what loading pattern to use, and (3) when to perform them.

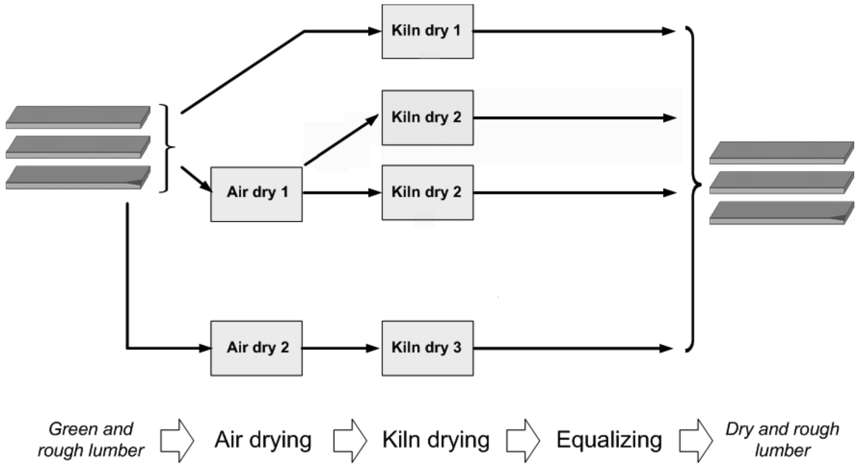

Figure 4. Example of drying processes available for a given batch of lumber

Finishing Operations

At the finishing facility, lumbers are first planed (or surfaced). They are then sorted according to their grade (i.e. quality) with respect to the residual moisture content and physical defects. Lumber may be trimmed in order to produce a shorter lumber of a higher grade and value. This process is usually optimized by hardware to produce products with the highest value, with no consideration for the actual customer demand. This causes the production of multiple product types at the same time (co-production) from a single product type in input (divergence). It is important to note that the co-production cannot be avoided from a planning point of view: it is embedded within the transformation process. It is common to obtain more than 20 different types of products from a single product. The expected products mix to be obtained from a batch depends on the drying process used. Therefore, in the planning models introduced hereafter, we consider the output product associated with each of the drying processes (paths in Figure 4) as a different kind of input for the finishing process.

There is also a setup cost each time the facility processes a different dimension (e.g. from 2"x3" to 2"x6"). Consequently, most sawmills allow such a setup only between production shifts as they prefer campaigns (a batch of products of the same dimension but variable length) with a duration of more than one shift.

To sum up, the decisions that must be taken in order to plan the finishing operations are the following: (1) which campaign to realize (i.e. which lumber dimensions), (2) when and for how long and (3) for each campaign, what quantities of each length to process. Figure 5 shows a simple example of a production plan, including the campaigns (2"x3", 2"x6" and 2"x4") and the time spent on each length.

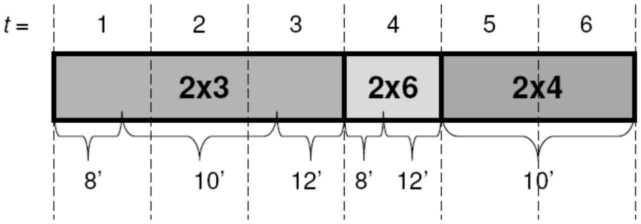

Figure 5. Production plan for a finishing line for six consecutive production shifts

2.2 Lumber Production Planning and Sales

Due to the highly heterogeneous nature of the resource and the inherent complexity of forecasting production throughput, the dominant thinking in the North American lumber industry is to produce the maximum volume with the available resource. This can be identified as a *push* production mode, where demand from specific clients is not taken into account. Production is oriented towards large batches to take advantage of economy of scale, resulting in large inventories, low flexibility and low agility. The production manager has as main objective to feed the production line continuously, in order to maximize the production rate and throughput. He also tries to forecast the quantity of output products as precisely as possible. Once a week, he transmits to the sales department an updated forecast about what product should be available (and when) during the following four to six weeks.

The sales process is triggered by clients calling to ask if a specific product will be available at a specific date. If it is forecasted the product will be available at this date, the sale is concluded. If not, the sale is lost and the client will look for the product elsewhere. It is also common for a client to request the product availability list and then make its selection (if any) from that list. In that case, if no sale is concluded, the company will not be aware of the missed opportunity as the need of the client was never revealed. This is mainly a *spot market* approach.

2.3 Toward a Pull Production System

While the previous planning approach has the advantage of maximizing the throughput value, it does not take client needs into account. On-hand or forecasted inventory can be different from what final clients really want, leading to missed sales opportunities. This is why some Canadian lumber producers are investigating the possibility of evolving from a *push* production mode to a *pull* production mode.

This approach consists in crafting long-term agreements with certain clients, whose favored supplier you wish to become. The client and the supplier agree upon annual volumes and a mechanism for determining prices. The exact moment for deliveries, volumes and the identification of products will vary in time however, as a function of the client's needs. Several times a year, the client transmits a list of product quantities and preferred delivery dates, called *demand plan*. The supplier does his best to fulfill this demand and transmits a *supply plan* to the client, where delivery dates can differ from those requested by the client. Although clients are usually flexible regarding delivery dates, the supplier will be evaluated, in a long-term perspective for its capacity to carry out deliveries as closely as possible to the delivery dates requested. As current planning tools used by the lumber industry (generally in-house spreadsheet applications) were designed for *push* production systems, they cannot be used in a context where production is planned according to demand. Companies must, in fact, limit themselves to selling only a marginal portion of their production in the context of these long-term agreements, and do so even when these sales prove to be more profitable. Therefore, a new planning paradigm should be adopted.

To design such a pull production system, some characteristics of the problem must be taken into account. For example, it takes days to produce a batch of green lumber that is ready to be dried because of co-production at the sawing unit. The relatively large size of kiln dryers and the constraint to dry similar products together imposes some important production lead times. Furthermore, due to co-production at the finishing unit, a single batch of green lumber to be dried and finished contributes to the fulfillment of many customer orders for different product types. Also, because the volume of each customer order for a specific product is usually larger than the amount produced with one single batch, many batches are usually needed to fulfill one particular need. These specific issues have raised the need for a tightly integrated process planning and scheduling (Bartak *et al*, 2002).

3. LITERATURE REVIEW

3.1 Lumber Production Planning

Certain authors have worked on the specific problem of softwood lumber production planning. Among them, Maness *et al* (1993) have proposed a mixed programming model that simultaneously determines the optimal bucking and sawing policies based on demand and final product price (integration of stem bucking and log sawing). This model was later modified to handle several periods (Maness *et al*, 2002). These works focus on the identification of new cutting patterns/policies.

Taking a more global view of the supply chain, Singer *et al* (2007) recently presented a model for optimizing planning decisions in the sawmill industry. They modeled a simplified internal supply chain, including two transformation stages and two inventory stages. The objective was to demonstrate how collaboration can benefit the partners, by transferring timber and using the competitive advantages of each. Other interesting studies have been presented about integrated supply chain planning in the wood furniture industry (Ouhimmou *et al*, 2005) and in the OSB panel industry (Feng *et al*, 2008).

3.2 Supply Chain Planning

Operations planning within supply chains is a complex issue. Companies usually deal with this by implementing and using information and decision support systems that address various planning tasks. Some companies also adopt just-in-time approaches to control the pace of production and replenishment. When organizational units are part of the same company, centralized information and planning systems are sometimes used. Gathering information in a centralized management system and redistributing plans can ensure synchronization and optimization of plans. Decision support systems, such as Advanced Planning and Scheduling (APS) systems are sophisticated sets of decision support applications using operational research (OR) techniques to find solutions to complex planning problems (Frayret, 2002). Many consider APS systems as state-of-the-art manufacturing and supply chain planning and scheduling practices. The reader is referred to Stadtler (2005) and Stadtler *et al* (2005) for a thorough description of APS.

Yet, even in an internal supply chain, the planning problem is complex and difficult to handle. In fact, currently available software solutions generally do not provide the necessary support to network organizations and are clearly insufficient in planning and coordinating activities in heterogeneous environments (Stadtler, 2005). Planning, scheduling and traditional control mechanisms are insufficiently flexible to react to rapid changes in production modes and client needs (Maturana *et al*, 1999). In other words, traditional systems have not been developed to work in decentralized, dynamic and heterogeneous environments, like supply chains. Collaboration and coordination mechanisms are needed to ensure synchronization and consistency throughout the supply chain. This has opened the way to an entirely new research domain, where researchers are interested in coordination and decision-making between supply chain partners to optimize the supply chain performance (Strader *et al*, 1998).

3.3 Coordination in Supply Chains

An important management challenge in supply chains is the need for partners to perform different planning tasks locally while simultaneously managing their interdependencies. Among several authors who have studied coordination in supply chain, Bhatnagar *et al* (1993) differentiate between inter-function coordination, referred to as the general coordination problem, and the multi-plant coordination of the same function. The general coordination problem is usually subdivided into three classes of coordination problems, namely, supply and production planning, production and distribution planning, and inventory and distribution planning. Thomas and Griffin (1996) present a review of the literature concerned with the coordination of these functions, while Bhatnagar *et al* (1993) focus on issues concerning the multi-plant coordination problem.

This work focuses on the multi-plant coordination problem and proposes three operations planning models linked by their material flow variables (i.e., delivery and order variables), and coordination mechanisms to make sure the resulting operations plans are coherent with each other.

4. DISTRIBUTED PLANNING FOR THE LUMBER SUPPLY CHAIN

In this section, we present a distributed-APS system for the lumber supply chain. The local problems associated with each production unit (sawing, drying and finishing) are modeled and solved separately. This specific structure is neither unique nor optimal, as it would be possible to design a more centralized structure with a single agent responsible for the planning of all production operations. Unfortunately, due to the complexity and the specificities of those problems, it appears difficult to take advantage of such a centralized planning algorithm because it is more than likely that only aggregated information could be handled with such a single agent. On the other hand, distributed planning enables the use of specific optimization strategies and information available only locally. Finally, by replicating natural interactions existing between the units, it permits faster reactivity to local perturbations.

In the remaining portion of this section, different Mixed Integer Programming (MIP) models for the operations planning and scheduling of the three production centers are proposed. These models can be used individually or collectively. Afterwards, we propose different coordination mechanisms to ensure the coherence and feasibility of the production plans.

4.1 Planning and Scheduling Models

In order to plan individually or collectively the operations of the different production centers, planning and scheduling models have been developed. The following subsections present the optimization models developed specifically for the sawing unit, the drying unit and the finishing unit.

Sawing Model

The following defines the proposed planning and scheduling model for the sawing unit. Each processing activity is modeled as an association between a quantity of logs to consume, expected production, and machine usage. More than one processing activity can be used during the same production shift, but with certain limitations imposed by setup constraints (see Section 2.1).

Sets

T	the number of periods in the planning horizon. The index t refers to the periods $t = 1,\ldots,\mathrm{T}$;
$\mathbf{P}$	set of products p;
$\mathbf{P}^{consumed}$	products p that can be consumed (raw products). $\mathbf{P}^{consumed} \subseteq \mathbf{P}$;
$\mathbf{P}^{produced}$	products p that can be produced. $\mathbf{P}^{produced} \subseteq \mathbf{P}$. Please note that $\mathbf{P}^{consumed}$ and $\mathbf{P}^{consumed}$ are non intersecting subsets.
$\mathbf{M}$	set of machines m;
$\mathbf{A}$	set of processing activities $a \in \mathbf{A}$ available to the unit;
$\mathbf{F}$	each $f \in \mathbf{F}$ defines a mode in which the plant can be set up to operate;
$\mathbf{F}^a$	specifies the modes $f \in \mathbf{F}^a \subseteq \mathbf{F}$ such that the plant can execute the processing activity a. An activity may be compatible with many modes and many activities can be compatible with the same mode.

Parameters

$i_{p,0}$	inventory of product $p \in \mathbf{P}$ in stock at the beginning of the planning horizon;
i_p	holding cost (per period) for product p;
$s_{p,t}$	supply for product $p \in \mathbf{P}^{consumed}$ provided at the beginning of period t;
$d_{p,t}$	demand for product $p \in \mathbf{P}^{produced}$ the plant is expected to deliver by the end of period t;
w_p	backorder cost that occurs when one unit of product $p \in \mathbf{P}^{produced}$ is late for one period;
v_a	variable cost associated to performing a, including cost of raw material, if it applies;
$\phi_{a,p}$	volume of raw material $p \in \mathbf{P}^{consumed}$ consumed each time a is executed. A single processing activity a can consume different product types at the same time;
$\rho_{a,p}$	quantity of product $p \in \mathbf{P}^{produced}$ produced each time a is executed. A single processing activity can produce many product types at the same time.
$\delta_{a,m}$	capacity of machine $m \in \mathbf{M}$ (number of time units) used each time a is executed;
$c_{m,t}$	available capacity of machine for period t (number of time units).

Variables

$QC_{p,t}$	total volume of product $p \in \mathbf{P}^{consumed}$ consumed during period t;
$QP_{p,t}$	total volume of product $p \in \mathbf{P}^{produced}$ produced during period t;
$I^+_{p,t}$	volume of product $p \in \mathbf{P}$ in stock at the end of period t;
$I^-_{p,t}$	cumulated demand for product $p \in \mathbf{P}$ not satisfied at the end of period t (that is, backorder);
$I_{p,t}$	volume of product $p \in \mathbf{P}$ that would be in stock if the cumulated demand was satisfied. This variable can take negative values. It is introduced in order to simplify flow constraints formulation. See constraint (1.7) for the relation between $I_{p,t}$, $I^+_{p,t}$ and $I^-_{p,t}$;
$Y_{f,t}$	binary variable equals 1 if the plant is set up in mode f at period t; 0 otherwise;
$X_{a,t}$	usage of processing activity a during period t (continuous variable).

Objective function

Within the industrial application considered in this paper it is impractical to consider demand as a hard constraint (late deliveries are inevitable). Consequently, we try to minimize the cost of these backorders. We also take into account inventory cost and variable production cost:

$$\text{Min} \sum_{\forall p \in \mathbf{P}^{produced}} \left(w_p \sum_{t=1}^{\mathrm{T}} I^-_{p,t} \right) + \sum_{\forall p \in \mathbf{P}} \left(i_p \sum_{t=1}^{\mathrm{T}} I^+_{p,t} \right) + \sum_{\forall a \in \mathbf{A}} \left(v_a \sum_{t=1}^{\mathrm{T}} X_{a,t} \right) \tag{1.1}$$

Production constraints

The product consumption and production of the plant are related to the number of times each processing activity is used:

$$QC_{p,t} = \sum_{a\in\mathbf{A} \mid \phi_{a,p}>0} \left(X_{a,t} \times \phi_{a,p} \right) \qquad \forall p \in \mathbf{P}^{consumed},\ t = 1,\ldots,\mathbf{T} \qquad (1.2)$$

$$QP_{p,t} = \sum_{a\in\mathbf{A} \mid \rho_{a,p}>0} \left(X_{a,t} \times \rho_{a,p} \right) \qquad \forall p \in \mathbf{P}^{produced},\ t = 1,\ldots,\mathbf{T} \qquad (1.3)$$

At each period t of the planning horizon, the sawing line can be set up in only one mode and thus can only use the processing activities compatible with that mode:

$$\sum_{f\in\mathbf{F}} Y_{f,t} \le 1 \qquad \forall t = 1,\ldots,\mathbf{T} \qquad (1.4)$$

$$0 \le X_{a,t} \le \left(\infty \times \sum_{f\in\mathbf{F}^a} Y_{f,t} \right) \qquad \forall a \in \mathbf{A},\ t = 1,\ldots,\mathbf{T} \qquad (1.5)$$

where ∞ is a significantly large number

The number of times each processing activity is executed is constrained by the capacity of each machine:

$$\sum_{a\in\mathbf{A}} \left(X_{a,t} \times \delta_{a,m} \right) \le c_{m,t} \qquad \forall m \in \mathbf{M},\ t = 1,\ldots,\mathbf{T} \qquad (1.6)$$

Flow constraints

Constraint (1.7) and (1.8) together with the objective function allow the computation of backorder level. Of course, no backorder is allowed for raw products (1.9).

$$I_{p,t} = I^{+}_{p,t} - I^{-}_{p,t} \qquad \forall p \in \mathbf{P}, t = 1,\ldots,\mathrm{T} \qquad (1.7)$$

$$I^{+}_{p,t} \ge 0; \quad I^{-}_{p,t} \ge 0 \qquad \forall p \in \mathbf{P}, t = 1,\ldots,\mathrm{T} \qquad (1.8)$$

$$I^{-}_{p,t} = 0; \qquad \forall p \in \mathbf{P}^{consumed}, t = 1,\ldots,\mathrm{T} \qquad (1.9)$$

Constraints (1.10) and (1.11) establish the relation between inventory, supply and consumption of logs.

$$I_{p,1} = i_{p,0} + s_{p,1} - QC_{p,1} \qquad \forall p \in \mathbf{P}^{consumed} \qquad (1.10)$$

$$I_{p,t} = I_{p,t-1} + s_{p,t} - QC_{p,t} \qquad \forall p \in \mathbf{P}^{consumed}, t = 2,\ldots,\mathrm{T} \qquad (1.11)$$

Constraints (1.12) and (1.13) establish the relation between inventory, demand and production.

$$I_{p,1} = i_{p,0} - d_{p,1} \qquad \forall p \in \mathbf{P}^{produced} \qquad (1.12)$$

$$I_{p,t} = I_{p,t-1} + QP_{p,t-1} - d_{p,t} \qquad \forall p \in \mathbf{P}^{produced}, t = 2,\ldots,\mathrm{T} \qquad (1.13)$$

Model implementation and resolution

For real industrial problems, this model was easily solved using the MIP solver ILOG CPLEX 9.1. Near optimal solutions can be found in a few minutes.

Drying Model

Drying is a multi-stage process (see Section 2.1). In the proposed model we chose not to model directly the alternative combination of activities (paths in Figure 4). Instead, we modeled the individual activities. The connection between the activities (i.e. a valid precedence relationship between two activities) is enforced by the stocks level constraints for intermediary products (an intermediary product needed by an activity, must first be produced by its predecessor).

Figure 6 presents the main idea involved in this model. We have different activity types $a \in \mathbf{A}$. Each type of activity can be executed on a compatible machine $m \in \mathbf{M}_a \subseteq \mathbf{M}$, and has a specified duration δ_a. The parameters $\phi_{a,p}$ and $\rho_{a,p}$ specify the consumption and production for products $p \in \mathbf{P}$. In this context, building a plan can be seen as deciding which activities to perform, when to do them and which machines to use. A solution can be represented by a Gantt chart of activities (see Figure 6). Each type of activity can be inserted as many times as needed in the plan. Inserted activities have an impact on product inventories $\left(I_{p,t} \right)$ by increasing or decreasing it since they produce and consume different products.

Demand from the finishing unit $\left(d_{p,t}\right)$ also influences product inventories. These kinds of models are referred to as *timetable* models or *time-line* models (Bartak, 1999a; 1999b; 2002).

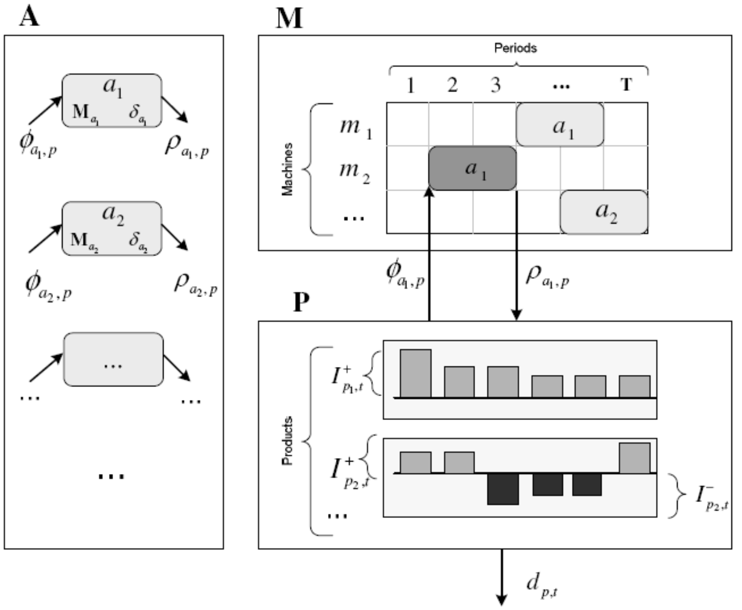

Figure 6. Illustration of the drying model

Sets

This drying model uses notation similar to the sawing model. The following sets have the same meaning in both models: periods (T), products $\left(\mathbf{P},\ \mathbf{P}^{consumed},\ \mathbf{P}^{produced}\right)$ and machines $(\mathbf{M})$. Because drying processes allow intermediary products that can be both produced and consumed, $\mathbf{P}^{consumed}$ and $\mathbf{P}^{produced}$ may now intersect. Consequently, in order to simplify the presentation of flow constraints, we will consider each product $p \in \mathbf{P}$ as a resource that can be consumed, produced, supplied and shipped.

The following defines other sets used by the drying model:

$\mathbf{A}$	set of all types of drying activities a;
$\mathbf{A}_p^{consume}$	subset of activities which consume the product p. $\mathbf{A}_p^{consume} \subseteq \mathbf{A}$;
$\mathbf{A}_p^{produce}$	subset of activities which produce the product p. $\mathbf{A}_p^{produce} \subseteq \mathbf{A}$;
$\mathbf{A}_m$	subset containing all types of activities that can be processed on machine $m \in \mathbf{M}$. $\mathbf{A}_m \subseteq \mathbf{A}$;
$\mathbf{M}_a$	subset of machines that can carry out activity a. $\mathbf{M}_a = \left\{ m \in \mathbf{M} \middle| a \in \mathbf{A}_m \right\}$.

Parameters

The following parameters have the same meaning as in the sawing model although they are now defined for every product $p \in \mathbf{P}$: supply $\left(s_{p,t}\right)$, demand $\left(d_{p,t}\right)$, initial inventory and costs $\left(i_{p,0},\ i_p,\ w_p\right)$, material consumption and production of activities $\left(\phi_{a,p},\ \rho_{a,p}\right)$. However, we will suppose that $d_{p,t}$ is equal to zero for all products that can be consumed. The parameter v_a also has the same meaning as in the sawing model. In addition, we define these parameters:

$c_{m,t}$	1, if machine m is available during period t, 0 otherwise;
δ_a	number of consecutive periods needed to accomplish activity a.

Variables

The following variables have the same meaning as in the sawing model although they are now defined for every product $p \in \mathbf{P}$: $QC_{p,t}$, $QP_{p,t}$, $I^{+}_{p,t}$, $I^{-}_{p,t}$, $I_{p,t}$. In addition, we define this decision variable:

$X_{(a,m),t}$	Binary decision variable taking value 1 if an activity of type *a* starts on machine *m* at period *t*, 0 otherwise. It is defined for each couple $(a,m) \mid a \in \mathbf{A}_m$.

Objective function

The objective function is similar to the one in the sawing model:

$$\text{Min} \sum_{\forall p \in \mathbf{P}} \left(w_p \sum_{t=1}^{\mathrm{T}} I^{-}_{p,t} + i_p \sum_{t=1}^{\mathrm{T}} I^{+}_{p,t} \right) + \sum_{\forall (a,m) \mid a \in \mathbf{A}_m} \left(v_a \sum_{t=1}^{\mathrm{T}} X_{(a,m),t} \right) \tag{2.1}$$

Production constraints

The consumption constraint (2.2) defines $QC_{p,t}$ as being the total consumption of activities starting during period *t* and consuming product *p*. The sum is computed only for the couple of activities *a* and machines *m* for which *m* can carry out *a*, and *a* consumes *p*. Consumption for products that are never consumed is set to zero.

$$QC_{p,t} = \sum_{(a,m) \,\middle|\, \substack{a \in \mathbf{A}_m \\ a \in \mathbf{A}_p^{consume}}} X_{(a,m),t} \times \phi_{a,p} \qquad \forall p \in \mathbf{P},\ t = 1,\dots,\mathrm{T} \tag{2.2}$$

The production constraint (2.3) is the counterpart of the previous constraint. It sets that total production is the sum of what is produced by activities *a* ending during period *t* (i.e. those starting at period $t - \delta_a + 1$) and producing product p.

$$QP_{p,t} = \sum_{(a,m) \,\middle|\, \substack{a \in \mathbf{A}_m \\ a \in \mathbf{A}_p^{produce} \\ t-\delta_a+1 \ge 1}} X_{(a,m),t-\delta_a+1} \times \rho_{a,p} \qquad \forall p \in \mathbf{P},\ t = 1,\dots,\mathrm{T} \tag{2.3}$$

The capacity constraint (2.4) sets that the number of activities running on a machine *m* at period *t* must be smaller than or equal to 1. For each type of activity *a*, there is an instance running at period *t* if one has started in the interval $[t - \delta_a + 1, \dots, t]$.

$$\sum_{a \in \mathbf{A}_m} \sum_{\tau = \max[t-\delta_a+1,\ 1]}^{t} X_{(a,m),\tau} \le c_{m,t} \qquad \forall m \in \mathbf{M},\ t = 1,\dots,\mathrm{T} \tag{2.4}$$

Flow constraints

Flow constraints are similar to those of the sawing model, with the exception that some products can both be consumed and produced:

$$I_{p,t} = I^{+}_{p,t} - I^{-}_{p,t} \qquad \forall p \in \mathbf{P},\ t = 1,\dots,\mathrm{T} \tag{2.5}$$

$$I^{+}_{p,t} \ge 0; \quad I^{-}_{p,t} \ge 0 \qquad \forall p \in \mathbf{P},\ t = 1,\dots,\mathrm{T} \tag{2.6}$$

$$I^{-}_{p,t} = 0; \qquad \forall p \in \mathbf{P}^{consumed},\ t = 1,\dots,\mathrm{T} \tag{2.7}$$

$$I_{p,1} = i_{p,0} + s_{p,1} - QC_{p,1} - d_{p,1} \qquad \forall p \in \mathbf{P} \tag{2.8}$$

$$I_{p,t} = I_{p,t-1} + s_{p,t} + QP_{p,t-1} - QC_{p,t} - d_{p,t} \qquad \forall p \in \mathbf{P},\ t = 2,\dots,\mathrm{T} \tag{2.9}$$

Model implementation and resolution

For real industrial-size problems we were not able to obtain good feasible solutions in reasonable time. Consequently, we propose a simple greedy heuristic to solve this problem. First, a list of the available drying processes must be established *a priori* (i.e. each path in Figure 4). Then, the plan is produced incrementally (starting with an empty plan) by performing the following steps:

Compute the value of the objective function for the current plan.

Insert into the plan the process that will most reduce the value of the objective function. Each process is evaluated by performing these steps:

a. Compute the earliest date for which one of the products produced by the process is backordered.
b. By considering this as being the due date, backward schedule the activities of the process using just-in-time planning.
c. Compute the improvement of the objective function.

Go back to step 1 (the algorithm stops when it becomes impossible to insert a process reducing the value of the objective function in step 2).

Finishing Model

In practice, the three steps of the finishing process (i.e., planing, sorting and trimming) are performed on a single production line. For planning purposes, this line can be considered as a single machine, whose production rate is equal to that of the machine that is the bottleneck on the line.

As stated in Section 2.1, a finishing production plan is a sequence of campaigns (see Figure 5). Each one has a product family associated to it (e.g. 2"x4"), which is related to a specific setup for the plant. During the campaign, different types of products corresponding to the family can be processed (e.g. 2"x4"-8', 2"x4"-10'). However, they must be processed in a specific order.

It the following model, binary decision variables specify how the plant is set up at each period. A setup cost (ζ) must be accounted each time there are two consecutive periods with a different setup (that is, each time a new campaign begins). Other decision variables in the model represent the quantities of each length (e.g. 8', 10') to process at each period (rather than the quantity to process at each campaign as imposed by the problem). To compensate for this "relaxation", a constraint states that the entire consumption of the campaign takes place at its beginning, and its production at the end. On the other hand, we have to maintain two different inventories: one in the yard (similar to the sawing and drying problems) and one in the plant.

Sets

This finishing model uses notation similar to previous models. The following sets have the same meaning: T, $\mathbf{P}$, $\mathbf{P}^{consumed}$, and $\mathbf{P}^{produced}$. Similar to the sawing model, each $f \in \mathbf{F}$ defines a mode in which the plant can be set up to operate. Each mode corresponds to a product family (e.g. 2″x4″). In addition, we define the following sets:

$\mathbf{P}_f^{consumed}$	products *p* that can be consumed when the plant is set up in mode *f*. $p \in \mathbf{P}_f^{consumed} \subseteq \mathbf{P}^{consumed}$;
$\mathbf{P}_f^{produced}$	finished products *p* that can be produced when the plant is set up in mode *f*. $p \in \mathbf{P}_f^{produced} \subseteq \mathbf{P}^{produced}$;
$\mathbf{FP}$	set of couples $(f,p) \big| (f \in \mathbf{F}) \wedge \left(p \in \mathbf{P}_f^{consumed}\right)$.

Parameters

The following parameters have the same meaning as in the sawing model: $s_{p,t}$, $d_{p,t}$, $i_{p,0}$, i_p, and w_p. In addition, we define these parameters:

$\rho_{(f,p'),p}$	volume of product $p \in \mathbf{P}^{produced}$ produced when one unit of product $p' \in \mathbf{P}^{consumed}$ is consumed while the plant is set up in mode *f*. Defined for couples $(f,p') \in \mathbf{FP}$;
$\delta_{(f,p)}$	time needed to consume one unit of product $p \in \mathbf{P}^{consumed}$ when the plant is set up in mode *f*. Defined for couples $(f,p) \in \mathbf{FP}$;
$v_{(f,p)}$	cost of processing one unit of product $p \in \mathbf{P}^{consumed}$. Defined for couples $(f,r) \in \mathbf{FP}$;
c_t	capacity of the plant (number of time units) for period *t;*
ζ	cost of performing a setup change.

Variables

The following variables have the same meaning as in the sawing model. Variable $Y_{f,t}$ identifies in which mode the plan is set up. The variables $I_{p,t}^{+}$, $I_{p,t}^{-}$ and $I_{p,t}$ corresponds to the inventory in the yard. Variable $QC_{p,t}$ corresponds to a quantity transferred in the plant at the beginning of a campaign. Variable $QP_{p,t}$ to a quantity transferred from the plant to the yard at the end of the campaign.

In addition, we define these variables:

$BS_{f,t}$	1, if the plant is setup for mode *f* at period *t* and this was not the case at period *t*-1. 0, otherwise. In other words, this variable is equal to 1 if a campaign using mode *f* begins at period *t*;
BS_t	1, if a campaign (of any mode) begins at period *t*. 0, otherwise;
BE_t	1, if a campaign (of any mode) ends at period *t*. 0, otherwise.
$UC_{(f,p),t}$	volume of raw product *p* to process at period *t* while the plant is set up in mode *f*. The product must be already in the plant to be processed. Defined for couples $(f,p)\in\mathbf{FP}$.
$UP_{p,t}$	volume of product *p* produced at period *t*. The product remains in the plant and is not available to satisfy demand until the end of the campaign. It will be released and thus be considered a production of the plant only when the campaign is over. Defined for $p\in\mathbf{P}^{produced}$;
$UI_{p,t}$	volume of product *p* in the plant at the end of period *t*. Defined for $p\in\mathbf{P}$.

Objective function

The objective function is similar to the one in the sawing model although in this problem the setup costs are taken into account. Production costs depend both on how the plant is set up and the raw material consumed.

$$\text{Min} \sum_{\forall p\in\mathbf{P}^{produced}} \left(w_p \sum_{t=1}^{\mathrm{T}} I^-_{p,t} \right) + \sum_{\forall p\in\mathbf{P}} \left(i_p \sum_{t=1}^{\mathrm{T}} I^+_{p,t} \right) + \zeta \sum_{t=1}^{\mathrm{T}} BS_t + \sum_{\forall (f,p')\in\mathbf{FP}} \left(v_{(f,p')} \sum_{t=1}^{\mathrm{T}} UC_{(f,p'),t} \right) \tag{3.1}$$

Production constraints

First, the plant can only be set up in one mode at a time (3.2) and a product can be processed (consumed) only if the plant is configured in a compatible mode (3.3).

$$\sum_{f\in\mathbf{F}} Y_{f,t} \le 1 \qquad \forall t = 1,\ldots,\mathrm{T} \tag{3.2}$$

$$0 \le UC_{(f,p),t} \le \left(\infty\, Y_{f,t}\right) \qquad \forall (f,p)\in\mathbf{FP},\, t = 1,\ldots,\mathrm{T} \tag{3.3}$$

where ∞ is a significantly large number.

Constraints (3.4) to (3.6) state a batch can start or end only if the plant is set up in a compatible mode. Constraint (3.7) ensures that a specific batch will run until it has ended.

$$BS_{f,1} = Y_{f,1} \qquad \forall f\in\mathbf{F} \tag{3.4}$$

$$BS_{f,t} \le Y_{f,t} \qquad \forall f\in\mathbf{F},\, t = 1,\ldots,\mathrm{T} \tag{3.5}$$

$$BE_{f,t} \le Y_{f,t} \qquad \forall f\in\mathbf{F},\, t = 1,\ldots,\mathrm{T} \tag{3.6}$$

$$Y_{f,t} = Y_{f,t-1} - BE_{f,t-1} + BS_{f,t} \qquad \forall f\in\mathbf{F},\, t = 2,\ldots,\mathrm{T} \tag{3.7}$$

Variables BS_t and BE_t respectively take value 1 if and only if a batch is starting (3.8) or ending (3.9) at period *t*.

$$BS_t = \sum_{f\in\mathbf{F}} BS_{f,t} \qquad \forall t = 1,\ldots,\mathrm{T} \tag{3.8}$$

$$BE_t = \sum_{f\in\mathbf{F}} BE_{f,t} \qquad \forall t = 1,\ldots,\mathrm{T} \tag{3.9}$$

Raw products can enter the plant only at the beginning of a compatible campaign (3.10). Finished products are released only at the end of the campaign (3.11). No products can be left inside the plant at the end of the campaign (3.12).

$$QC_{p,t} \le \left(\infty \sum_{f\in\mathbf{F} \,|\, p\in\mathbf{P}_f^{consumed}} BS_{f,t} \right) \qquad \forall p\in\mathbf{P},\, t = 1,\ldots,\mathrm{T} \tag{3.10}$$

$$QP_{p,t} \le \left(\infty \sum_{f \in \mathbf{F} \mid p \in \mathbf{P}_f^{produced}} BE_{f,t} \right) \qquad \forall p \in \mathbf{P}, t = 1,\dots,\mathrm{T} \qquad (3.11)$$

$$UI_{p,t} \le \infty\left(1 - BE_t\right) \qquad \forall p \in \mathbf{P}, t = 1,\dots,\mathrm{T} \qquad (3.12)$$

The following are the flow conservation constraints for the raw products inside the plant:

$$UI_{p,1} = QC_{p,1} - \sum_{f \in F \mid (f,p) \in \mathbf{FP}} \left(UC_{(f,p),1}\right) \qquad \forall p \in \mathbf{P}^{consumed} \qquad (3.13)$$

$$UI_{p,t} = UI_{p,t-1} + QC_{p,t} - \sum_{f \in F \mid (f,p) \in \mathbf{FP}} \left(UC_{(f,p),t}\right) \qquad \forall p \in \mathbf{P}^{consumed}, t = 1,\dots,\mathrm{T} \qquad (3.14)$$

$$UI_{p,t} \ge 0 \qquad \forall p \in \mathbf{P}^{consumed}, t = 1,\dots,\mathrm{T} \qquad (3.15)$$

These are the flow conservation constraints for the finished products inside the plant:

$$UI_{p,1} = UP_{p,1} - QP_{p,1} \qquad \forall p \in \mathbf{P}^{produced} \qquad (3.16)$$

$$UI_{p,t} = UI_{p,t-1} + UP_{p,t} - QP_{p,t} \qquad \forall p \in \mathbf{P}^{produced}, t = 2,\dots,\mathrm{T} \qquad (3.17)$$

$$UI_{p,t} \ge 0 \qquad \forall p \in \mathbf{P}^{consumed}, t = 1,\dots,\mathrm{T} \qquad (3.18)$$

These constraints establish the relation between consumption and production inside the plant:

$$UP_{p,t} = \sum_{(f,p') \in \mathbf{FP}} UC_{(f,p'),t} \times \rho_{(f,p'),p} \qquad \forall p \in \mathbf{P}, t = 1,\dots,\mathrm{T} \qquad (3.19)$$

Finally, the capacity of the finishing line must be respected:

$$\sum_{(f,p) \in \mathbf{FP}} \left(UC_{(f,p),t} \times \delta_{(f,p)}\right) \le c_t \qquad \forall t = 1,\dots,\mathrm{T} \qquad (3.20)$$

Flow constraints (yard)

The constraints for the product flow in the yard are the same as in the sawing model. Therefore, we reuse constraints (1.7) to (1.13) in order to establish the relations between $i_{p,0}$, $I_{p,t}$, $I^{+}_{p,t}$, $I^{-}_{p,t}$, $s_{p,1}$, $d_{p,t}$, $QC_{p,1}$ and $QP_{p,t}$.

Model implementation and resolution

As for the drying model, we were not able to obtain good feasible solutions in reasonable time for real industrial problems. Again, we proposed a simple greedy heuristic to solve this problem. Each time the finishing line is available, we start a campaign for the product family $f \in \mathbf{F}$ for which it is most urgent to start production (i.e. the family with the smallest "first period with unsatisfied orders minus expected production time"). Because of setup costs, we want this campaign to have the longest possible duration (i.e. satisfying as many future orders as possible). However, the campaign must be over before the next delivery date. We also need to leave room for the production of other families. Here is the detailed pseudo code:

```
1. Let $t$ be the first period for which the finishing line and some raw material are available.
2. For each mode $f \in \mathbf{F}$ :
    a. Let $t_f$ be the first period where an order for a product $p \in \mathbf{P}_f^{produced}$ is not satisfied according to the current production plan.
    b. Let us suppose a campaign ending at $e_t = t_f - 1$ that allows satisfying the demand for all $p \in \mathbf{P}_f^{produced}$ at period $t_f$ (without considering raw material availability). Let $s_f$ be the start time of this campaign according to the needed production duration.
    c. If there is no raw material $p \in \mathbf{P}_f^{consumed}$ available at $s_f$, increase $s_f$ until some is ($e_f$ remains unchanged).
Sort the modes $f$ in increasing order of $s_f$.
```

Considering the modes $f \in \mathbf{F}$ for which we have some raw material $p \in \mathbf{P}_f^{consumed}$ available at period t, select the one with the smallest s_f. Insert a campaign for this mode into the plan:

d. It begins at t.

e. It has the longest possible duration (according to raw material availability) but without trespassing t_f (next delivery date for current family) or the next s_f in the vector of step 3 (starting date of a campaign for the next most urgent family).

f. The consumed products/quantities are established as follows:

   i. Quantifies of $p \in \mathbf{P}_f^{produced}$ needed to satisfy the next unsatisfied order for this family.

   ii. If room is available, the quantities for the next order of this family, etc.

Go back to step 1.

4.2 Coordination Mechanisms

In a distributed planning system, it is necessary to deploy a coordination mechanism between the different production units in order to integrate the different plans so as to make sure they are coherent with each other (in terms of material availability) but also to guarantee a certain level of collective performance. Such a strategy defines which information is transmitted from one agent to the other, when it is transmitted and what the sequence used to propagate the information is.

The most common class of coordination mechanisms (both in the literature and industrial practice) can be described as *hierarchical*. In this approach there is a sequence (naturally defined or specified in a long-term agreement) specifying the order in which the partners must plan their operations. Schneeweiss (2003) describes many problems using real industrial applications to illustrate the challenge of distributed decision-making. In this section, we describe three different coordination mechanisms, which are (1) *upstream planning*, (2) *two-phase planning* and (3) *bottleneck-first planning*. Then, a modification to the last two mechanisms is proposed in order to support hybrid push/pull systems.

Upstream Planning

The most common hierarchical approach is referred to as upstream planning (Bhatnagar *et al*, 1993; Dudek *et al*, 2005). Agents plan their operations one after the other, beginning with the agent that is closest to the customer (right-hand side agent in Figure 7). Knowing demand from the external customer, this agent plans its activities. This allows identifying the supply need of the production unit (in the model, its supply parameter $s_{p,t}$ is transformed into a variable). This supply need is then transferred to its supplier and becomes demand for the latter $\left(d_{p,t}\right)$. All this presupposes that each agent is always able to satisfy any demand. Of course, this assumption cannot be met in all contexts. This is why it cannot be used in our application and is furthermore not implemented.

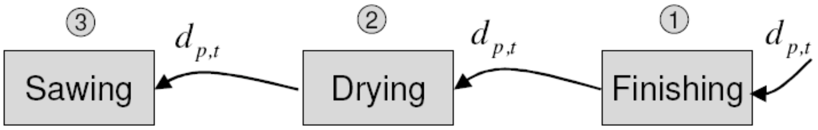

Figure 7. Upstream planning

Two-phase Planning

One variant of this approach, particularly relevant in a process industry with strong supply constraints, is to apply two planning phases: one upstream and the other downstream (see

Figure **8**). This approach involves each agent twice. The agent first makes a temporary plan to compute its supply needs and sends this information to its supplier. In turn, the supplier tries to satisfy this demand and responds with a supply plan that does not necessarily meet all demand (e.g., some deliveries may be planned to be late or some products can be replaced by substitutes). When informed of the supply granted by its supplier, the initial agent has to revise its production plan in order to account for supply constraints. The succession of planning activities forms a loop with two phases: one upstream, where demand is tentatively propagated and the other downstream, where final supply is propagated.

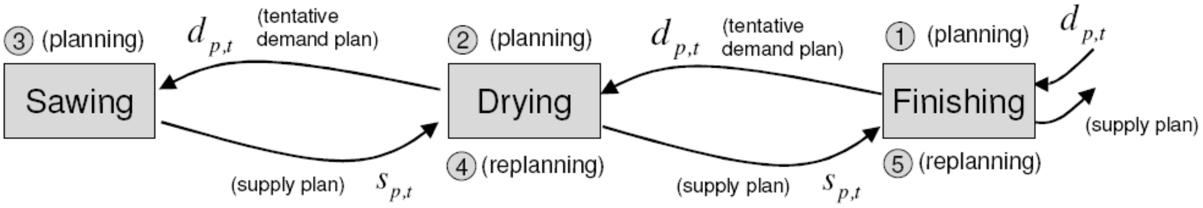

Figure 8. Two-phase planning

Bottleneck-first Planning

A *truncated* version of the two-phase planning approach is illustrated in

Figure **9**. The external customer demand is transmitted directly to the drying agent instead of going through the finishing agent. This modification is inspired by the theory of constraints proposed by Goldratt *et al* (1992) to plan the production bottleneck first. In the lumber supply chain, the drying production center is often the bottleneck because of the investment needed to deploy kiln dryers. Kiln drying duration can span from 12 to 60 hours, immobilizing and having a tremendous impact on the flexibility of the supply chain.

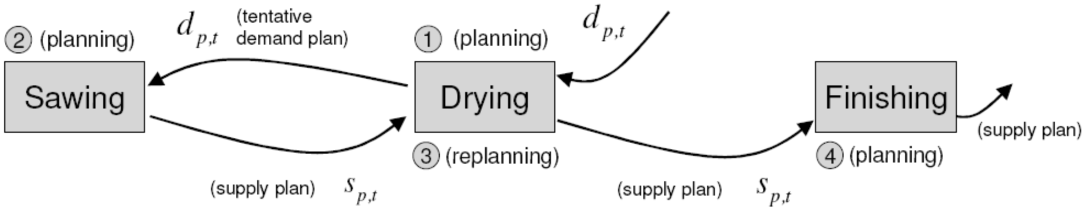

Figure 9. Bottleneck-first planning

Since demand for finished products is transmitted to the drying agent, it must have a definition of the finishing processes, which is done by adding the finishing activities in the graph of activities (see Figure 4), and by doing so, the drying agent has a simplified representation of the finishing unit processes.

Pushing alternative products

In our context, internal demand (demand from one unit to another) cannot be considered as a hard constraint. When a production unit cannot satisfy the entire demand of a partner, it might be useful to propose alternative products to this partner. With this option in mind, a simple modification to the previous mechanisms (two-phase and bottleneck-first) is proposed. In the downstream phase, the unit uses still available production capacity to produce alternative products and "push" them to the next unit (hoping it will be able to use them in order to satisfy demand).

To implement this, we simply run the planning model of the agent another time: we remove the already used capacity and raw material, and provide the model high demand for other products. In the objective function, these products are weighted $\left(w_p\right)$ using their respective expected market value.

Using this strategy also has a consequence: the part of the production capacity that is not needed or cannot be used by the network in order to satisfy the external demand (e.g. associated with long-term agreements) will be used in order to produce products with the greatest expected value (the company will be able to sell them using the more traditional *spot market* approach - see Sections 2.2 and 2.3).

5. INDUSTRIAL APPLICATION

The following section first presents work that was done with an industrial partner in order to validate the models (Section 5.1). We then proceed to demonstrate how an agent-based simulation platform (Section 5.2) can be used to evaluate coordination mechanisms according to the supply chain performance (Section 5.3).

5.1 Process Modeling and Industrial Validation

Intending to validate the proposed planning models, we developed a case study with a lumber company which includes production processes, products, orders, on-hand inventory, selling prices, resource costs, forecasted supply, capacity and work-in-process inventories. Processes were modeled in collaboration with the company's production manager. Customer data and on-hand inventory data were extracted from the partner's ERP system. Finally, the partner's sales team provided the data on product prices and resource costs.

Each planning model was assessed using real industrial data in an off-line planning mode. Over a horizon of several months, the partner's production manager sent us weekly updated production data, which we used to generate a production plan. The production manager gave us feedback concerning the quality and feasibility of the generated plans. This interactive validation phase allowed us to review and adjust the planning parameters as well as the planning models. This validation process took about one year and many adjustments were made to the models.

5.2 Agent-based Planning Platform

With the goal of developing an Advanced Planning and Scheduling (APS) system for the lumber supply chain, the FORAC Research Consortium at Université Laval (Québec, Canada) has proposed an agent-based planning platform. In brief, this platform aims to address: (1) the ability to plan and coordinate operations throughout the supply chain; and (2) the ability to analyze the dynamics of different scenarios through simulation. It allows the user, whether a production manager or a researcher, to evaluate and compare different planning models, coordination mechanisms or supply chain configurations, according to user-specified performance measures. Essentially, each planning model is embedded within a software agent that has the capacity to manipulate data, solve its planning model, and exchange information with other agents according to specific coordination mechanisms. In order to allow the user to designing and implementing various coordination mechanisms, the platform relies on the concept of conversation protocols that are commonly used in multi-agent systems. The interested reader is referred to Frayret *et al* (2007) for a more thorough description of the design specifications and functions of this platform.

5.3 Simulation

We simulated the coordination mechanisms from Section 4.2 that are compatible with a pull production system (i.e. *Two-phase planning* and *Bottleneck-first planning*) using the agent-based planning platform described previously. A virtual supply chain was modeled, based on the industrial case. The planning agents (sawing, drying and finishing) were set up according to these data. The studied case has a total of 448 types of production activities (or processes) and 114 different products, including 45 finished products available to the external customer.

The mechanisms were compared regarding how well they allow suppliers to satisfy external customers under the long-term agreement assumption described in Section 2.3. Recall that in the context of these agreements, the client and the supplier agree in advance on the annual volumes and a mechanism for determining prices. However, delivery dates, volumes, and product types are functions of the client's dynamic needs. At different moments during the year, the client submits a list of products, quantities and preferred delivery dates (*demand plan*). The supplier does his best to fulfill this demand and transmits a *supply plan* to the client (anticipated delivery dates can differ from those of the client). The network is evaluated according to its capacity to carry out deliveries as closely as possible to preferred delivery dates.

The performance indicators used in our experiments are the following: (1) the percentage of orders that cannot be delivered on the preferred date (*deferred deliveries*), and (2) the average *delay* (as all orders cannot be delivered on the preferred date). The evaluation is done for different scenarios. For each scenario, a set of long-term agreements is defined that corresponds to a specific percentage of the theoretical production capacity (in volume). For instance, if zero percent of the production capacity was to be allocated to long-term agreements, the entire production would be sold on the spot-market, no deferred deliveries would occur, and the average delay would be zero. However, as the percentage of the production capacity dedicated to long-term agreements increases, it is expected it will be more difficult to meet the preferred delivery dates expressed by the customers.

Six scenarios were defined for sets of long-term agreements, ranging from ten to sixty percent of the theoretical capacity (in volume)[1]. Demand for each of the six scenarios was generated using a probabilistic demand generator (Lemieux *et al*, 2008), for a sixty day planning horizon. This generator created random daily demand, according to predetermined settings such as distribution functions, minimum/maximum limits and seasonality as well. For each scenario, 10 replications have been generated.

5.4 Results

Figure 10 shows deferred deliveries (in %) according to the capacity allocated to long-term agreements (in %), for both coordination mechanisms and for each replication. For both mechanisms, the percentage of deferred deliveries grows rapidly as long-term agreements are increased (see second-degree polynomial trend lines). However, there is a clear advantage for *Bottleneck-first planning*. Table 1 synthesizes the results; for each scenario it shows average result (μ) for the 10 replications, standard deviation (σ) as well as the worst and best result. The last column of Table 1 shows the relative reduction of deferred deliveries *Bottleneck-first planning* allows in comparison with *Two-phase planning* (between 88.9% and 11.0%). We note that the relative reduction diminishes as the percentage of capacity allocated to long-term agreement grows.

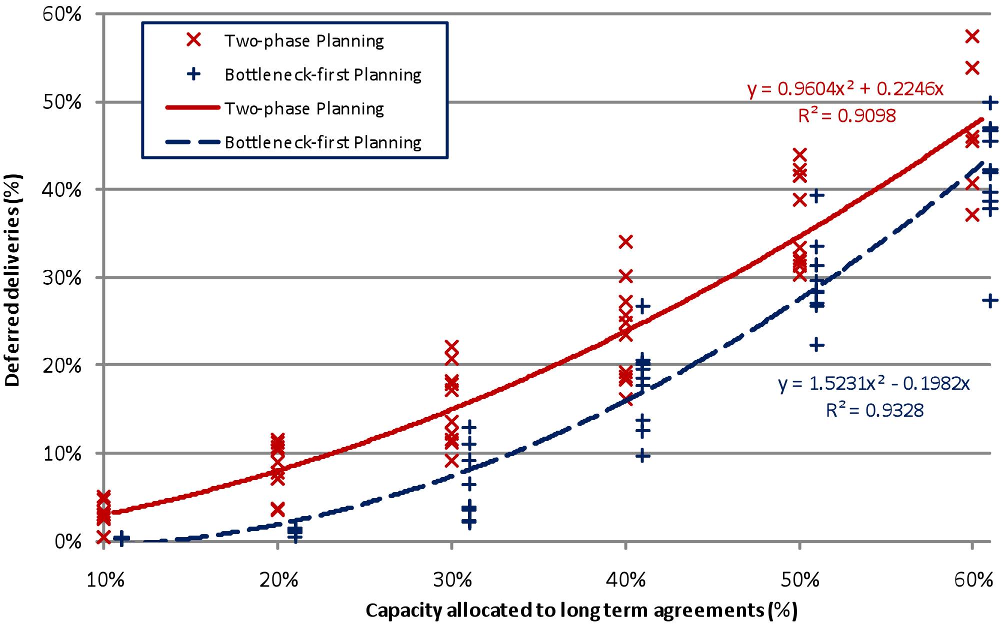

Figure 10. Deferred deliveries (in %) according to the volume capacity dedicated to long-term agreements (in %)

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[1] When X% of the theoretical production capacity (in volume) is allocated to long-term agreements, a lot more than X% of the processors' capacity (in time) is needed in order to fill this demand. As an explanation, we recall from Section 2.1.3 that processing a single product at the finishing unit can simultaneously produce more than 20 products (due to co-production). The same phenomenon occurs at the sawing unit (see Figure 2).

Table 1. Deferred deliveries (in %) according to the volume capacity dedicated to long-term agreements (in %)

Capacity allocated to long-term agreements		Two-phase Planning	Bottleneck-first Planning	Improvement
10%	**µ**	**2.8%**	**0.3%**	**88.9%**
	σ	1.5%	0.1%	96.6%
	min	0.4%	0.2%	42.1%
	max	5.0%	0.4%	92.2%
20%	**µ**	**8.2%**	**1.2%**	**85.8%**
	σ	2.9%	0.3%	90.2%
	min	3.5%	0.5%	84.5%
	max	11.5%	1.5%	87.4%
30%	**µ**	**15.4%**	**5.9%**	**61.4%**
	σ	4.4%	3.8%	12.9%
	min	9.1%	2.1%	76.7%
	max	22.2%	13.0%	41.5%
40%	**µ**	**23.8%**	**17.9%**	**24.5%**
	σ	5.8%	4.9%	15.7%
	min	16.1%	9.7%	39.6%
	max	34.1%	26.7%	21.6%
50%	**µ**	**36.7%**	**29.8%**	**18.8%**
	σ	5.4%	4.5%	15.8%
	min	30.3%	22.3%	26.3%
	max	44.0%	39.3%	10.6%
60%	**µ**	**46.8%**	**41.7%**	**11.0%**
	σ	7.7%	6.4%	16.6%
	min	37.2%	27.4%	26.5%
	max	57.4%	49.9%	13.2%

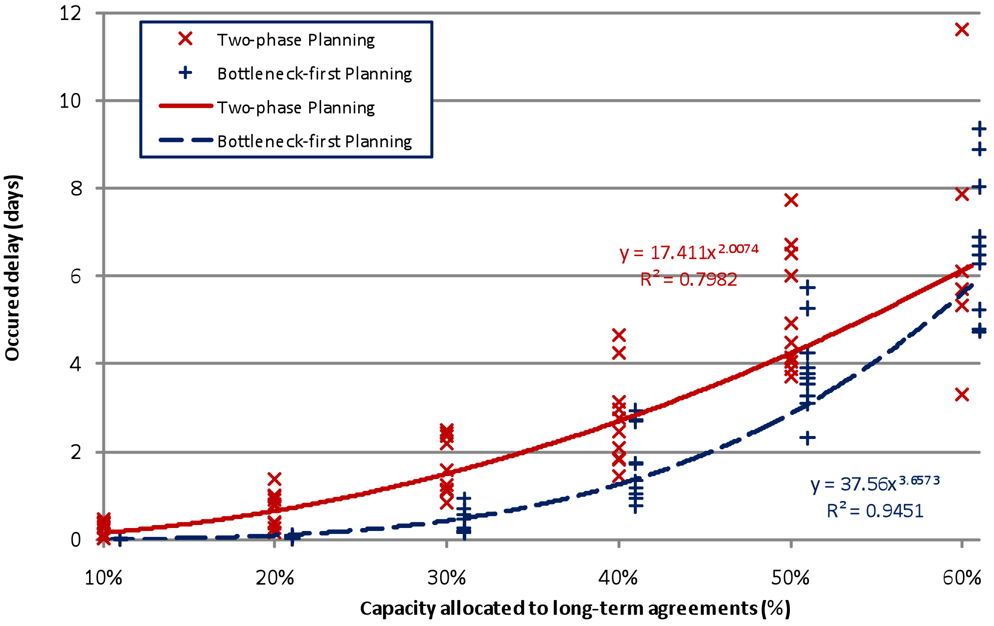

Figure 11. Occurred delay (in days) according to the volume capacity dedicated to long-term agreements (in %)

Table 2. Occurred delay (in days) according to the volume capacity dedicated to long-term agreements (in %)

Capacity allocated to long-term agreements		Two-phase Planning	Bottleneck-first Planning	Improvement
10%	**μ**	**0.271**	**0.013**	**95.1%**
	σ	0.158	0.004	97.6%
	min	0.025	0.008	67.4%
	max	0.452	0.022	95.2%
20%	**μ**	**0.697**	**0.064**	**90.8%**
	σ	0.392	0.023	94.1%
	min	0.147	0.026	82.4%
	max	1.366	0.089	93.5%
30%	**μ**	**1.646**	**0.380**	**76.9%**
	σ	0.650	0.267	58.9%
	min	0.830	0.167	79.9%
	max	2.482	0.926	62.7%
40%	**μ**	**2.749**	**1.706**	**37.9%**
	σ	1.051	0.810	23.0%
	min	1.459	0.763	47.7%
	max	4.650	2.943	36.7%
50%	**μ**	**5.216**	**3.886**	**25.5%**
	σ	1.417	1.005	29.0%
	min	3.698	2.317	37.3%
	max	7.731	5.742	25.7%
60%	**μ**	**6.666**	**6.741**	**-1.1%**
	σ	2.844	1.618	43.1%
	min	3.295	4.737	-43.8%
	max	11.632	9.357	19.6%

Figure 11 and Table 2 show the average delay that occurs. Again, we notice a considerable advantage associated with using *Bottleneck-first planning* when a moderate part of the capacity is allocated to long-term agreements (95.1% of improvement over *Two-phase planning* at ten percent of the production capacity). At 60% of the production capacity, performances of both mechanisms become very similar (in fact, *Two-phase planning* presents an advantage of 1.1%). However, results with *Bottleneck-first planning* still show much less variability (see reported standard deviation, worst and best results).

6. DISCUSSION AND CONCLUSION

This paper describes the production planning problems and models for three production units in the North American softwood lumber industry. The models can be used individually or in a distributed supply chain context. Different coordination mechanisms have been described. We showed how the planning models may be integrated in an agent-based planning platform in order to evaluate how the coordination mechanisms would perform in a pull production setup.

The results should not, however, be used as generic prescriptions for the lumber industry, as they are specific to this case study. The best coordination mechanism to use depends on various factors. Moving the bottleneck or changing the mix of alternative products can have a major impact on the performance of the mechanisms.

In addition, managers within industry could use the proposed methodology to evaluate the right level of production capacity that should be allocated to long-term agreements. However, they should take into account how much their customers will tolerate delays as well as the additional profit margins associated with long-term agreements *vs.* spot-market.

In future research, various improvements can be made to the models and coordination mechanisms. For instance, agents could exploit information about their partners' preferences for alternative products. It would be interesting to evaluate the robustness of the system in an environment filled with unexpected events.

Finally, other coordination mechanisms have been studied in order to offer alternatives to the ones presented in this paper. Forget *et al* (2008, 2009) have proposed and simulated an intelligent planning agent model, called multi-behavior agent, which can adapt its coordination mechanisms according to specific states in its environment. Also, Gaudreault *et al* (2009) have proposed a distributed planning algorithm based on distributed constraint optimization, where agents are requested to submit multiple local plans in order for the collective to find the best arrangements of plans.

7. ACKNOWLEDGMENTS

This work was funded by the FORAC Research Consortium and the Natural Sciences and Engineering Research Council of Canada (NSERC). The authors would also like to acknowledge the impressive work of many FORAC research assistants who have worked on the agent-based platform. Finally, the authors would like to thank the anonymous reviewers of the journal for their relevant comments which contributed to improve this paper.

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