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May 2007 (revised)

Working Paper DT-2005-JMF-1

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Abstract

Because of new economical challenges and recent trends regarding international trade and globalization, many companies from the Canadian forest products industry have reached the point where profit improvement cannot be reaped without the coordinated involvement of their entire organization. Such a new level of efficiency concerns their distributed facilities and offices spread around the world, as well as their customers. One consequence of this new reality is that forest products companies are now facing the need to reengineer their organizational processes and business practices with their partners. To do this they must adopt new technologies to support the coordination of their planning and control efforts in a customer-centered environment. This paper first proposes a generic software architecture for the development of an experimentation environment to design and test distributed advanced planning and scheduling systems. This architecture allows combining agent-based technology and operations research-based tools in order to take advantage, on the one hand, of the ability of agent technology to integrate distributed decision problems, and, one the other hand, the ability of operations research to develop and exploit specific normative decision models. Next, this paper describes how this architecture has been configured into an advanced planning and scheduling tool for the lumber industry. Finally, we present how an application of this advanced planning tool is currently being validated and tested in a real manufacturing setting.

Key words

Distributed planning; forest products industry; multi-agent system; supply chain modeling; supply chain planning;

1 Introduction and research objectives

Because of new economical challenges and recent trends regarding international trade and globalization, many companies from the Canadian forest products industry have reached the point where profit improvement cannot be reaped without the coordinated involvement of their entire organization (e.g., their distributed facilities and offices spread across North America and the world) as well as their business partners (e.g., raw material suppliers, industrial customers and distributors). Companies from other sectors have already faced these challenges a few years ago. In order to adapt to this new reality, they have developed and adopted state-of-the-art business practices and technologies at different levels in their organization. Supply chains are distributed 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 final customers. In that regard, the forest product supply chain is similar to other industries. Forest product materials flow from forest contractors, to lumber or pulp and paper or panel production facilities, to value-added mills (referred to as secondary transformation), and through many channels of distributors and wholesalers to finally reach the markets. However, unlike the traditional manufacturing supply chain, which has a convergent product structure (i.e., assembly), the forest product industry needs to master industry specific production processes. For instance, transformation and production processes along the supply chain have a divergent co-production structure (i.e., trees are broken down into many products at all levels of the production process). Furthermore, wood and wood fiber have a highly heterogeneous nature, which makes planning and control in this context a difficult task with regard to production output control. It is thus important for forest products companies to compensate this lack of control over such stochastic elements. In order to do that, they must be able to (1) exchange promptly information throughout their supply chain about supply availability and quality, production output and demand, and (2) quickly react in a coordinated manner with supply chain members to correct any deviances or disturbances to the plan. Here lies a need for reactive and specific information and decision support systems to address both the need to produce feasible operation plans and to quickly adapt these plans when contingencies occur.

The experimentation planning platform presented in this paper attempts to address these two issues. In particular, we propose an agent-based architecture to develop an experimentation environment to design and test various configurations of distributed advanced planning and scheduling systems. The remainder of this paper is organized as follows. First, a thorough review of the literature dealing with advanced planning and scheduling systems (APS) and with agent-based manufacturing and supply chain management systems is presented. Next the different elements of the proposed generic architecture are introduced. Then, the functional and technological aspects of a specific application in the lumber industry are illustrated. Finally, we present how this application is currently being validated and tested in a real manufacturing setting.

2 Literature review

Operations planning within large organizations is a complex issue. Companies usually face this by implementing and using information and decision support systems, which address various planning tasks such as aggregate planning (also referred to as tactical planning) and detailed scheduling. Some companies adopt just-in-time approaches which are rather meant to address operation and replenishment control issues such as the Kanban approach. This paper focuses on computer supported planning systems in a distributed planning environment.

2.1 Advanced Planning and Scheduling

Advanced planning and scheduling systems are considered by many as the state of the art of manufacturing and supply chain planning and scheduling practices. The reader is referred to Stadtler and Kilger (2000) and Stadtler (2005) for a thorough description of APS. These systems usually exploit operations research, heuristics or constraint programming in order to carry out in an integrated manner true finite capacity planning and scheduling optimization at the long, mid and short term levels of decision making (Fleischmann and Meyr (2003)). These systems are usually designed and implemented as specialized decision support modules integrated together according to the principles of hierarchical production planning (HPP) as presented in Hax and Meal (1975). These principles are mainly concerned with reducing production planning complexity through the decomposition of the various decisions to be made into many levels of decision making where upper level decisions constrain lower level decisions. Such decomposition emerges from the analysis of the hierarchical nature of the production problem, which involves the aggregation/disaggregation of decisions and the coupling of the different levels (Schneeweiss (2003)). In order to relax the strict top-down character of such a decision process, which barely takes into account information about lower levels, an integrative approach to hierarchical production planning is introduced in Schneeweiss (2003). This approach introduces a framework that explains how upper level decisions could be made to can anticipate their impact on lower levels. In other words, this framework explains how to implement top-down coordination approaches, where upper level have a better understanding of the impacts of their decisions on lower levels. More specifically, each decision level possesses a more or less accurate representation of its direct subordinate level decision problem in order to anticipated its potential range of reaction (i.e., decision) when submitted to a particular instruction (i.e., a tentative decision of the upper level). Such representation can be either reactive or non-reactive. A reactive anticipation represents more or less explicitly and accurately the behavior of the base level when submitted to various instructions. On the contrary, a non-reactive anticipation, which is usually easier to implement, represents an approximation of the behavior of the base level that does not take into consideration the various instructions it can be submitted to. Thus, only general characteristics of the lower level are considered.

In these hierarchical decision structures (traditional and integrative), long term decisions for the various supply chain functionalities (i.e., procurement, production, distribution, and sales) involve supply chain design issues including facility location, production capacity setting, technology selection, as well as suppliers' and services providers' selection (Goetschalckx, Vidal, and Dogan (2002)). At the mid term level, aggregate production and distribution decisions are made in order to efficiently plan the use of the production and distribution capacity. Mid-term sales related decisions involve high level demand planning including forecasting, available-to-promise (ATP) planning, as well as the allocation of ATP to the targeted customer segments, referred to as allocated ATP (AATP). Procurement related decisions at the mid-term level involve the definition of inventory and procurement management policies. It may also include the definition of contractual agreements with suppliers. In general, aggregate planning usually defines the rules-of-the-game of the distributed network through different policies or structured business practices. Finally, at the short term level, production operations are synchronized into various plans which take into account real technological and capacity constraints while satisfying detailed ATP requirements and actual orders, as well as maintenance.

For a specific description of some of the many planning problems and optimization applications in the forest product industry, the reader is referred to Rönnqvist (2003), Epstein, Morales, Seron, and Weintraub (1999), Martell, Gunn, and Weintraub (1998) and Frayret, Boston, D'Amours, and Lebel (2005). Finally, Carlsson and Rönnqvist (2005) and Haartveit, Kozak, and Maness (2004) present industrial case studies of various supply chain management issues.

2.2 Agent-based manufacturing and supply chain management systems

In order to address the planning and scheduling of manufacturing and supply chain systems, academics have initiated in the middle of the 1980s a new body of approaches building on distributed computing techniques. By doing so, they created an alternative to traditional OR-based solutions. Some of these approaches are referred to as agent-based manufacturing and supply chain management systems. They intend to tackle the need for reactive, reliable, and (re)configurable operation management systems. They are rooted in the multi-agent technology which is part of distributed artificial intelligence (Weiss (1999)).

An agent-based manufacturing system may be defined as a planning and control system made of inter-dependent software agents designed to (1) individually handle a part of a manufacturing planning and control problem, such as planning a single order or allocating a task to resources, and (2) collectively carry out specific higher functionalities such as planning an entire manufacturing system. Software agents generally exhibit characteristics that allow them to individually behave and interact with each other in such a manner that they collectively fulfill the purpose of the entire system. In their book, Shen, Norrie, and Barthes (2001) identify 12 desirable characteristics of an agent: network-centric, communicative, semi-autonomous, reactive, deliberative, collaborative, pro-active, predictive, adaptive, flexible, persistent, mobile). Among these characteristics, four of them are recognized to be essential (Wooldridge and Jennings (1994)): *autonomy* (i.e., the ability to operate with some kind of control over its actions and internal state); *reactivity* (i.e., the ability to sense an environment and respond in a timely fashion when changes occur); *social* (i.e., the ability to communicate with each other through explicit negotiations or signal exchanges; *pro-activity* (i.e., the ability to exhibit goal-directed behavior by taking initiatives.

Many agent-based approaches for the planning and control of supply chains and manufacturing activities have been proposed in the literature. For recent reviews of these approaches, the reader is referred to Shen, Hao, Yoon, and Norrie (to appear) and Monostori, Vancza, and Kumara (to appear). The reader is also referred to Caridi and Cavalieri (2004) who provide a critical analysis of multi-agent technology applied to manufacturing. Their analysis reveals the lack of real world applications and the low maturity level of agent-based manufacturing technology. This paper intends to partially fill this gap by introducing an experimentation industrial application. Along the same line, the reader is also referred to Tharumarajah (2001) and Frayret, D'Amours, and Montreuil (2004) who analyze important issues related to the design of distributed systems and the coordination of manufacturing activities.

Agent-based manufacturing and supply chain management approaches can be related to one of two generic classes of systems. In the mid 1980s, along with the emergence of heterarchical manufacturing systems (Vámos (1983), Hatvany (1985)), a first class of agent-based systems emerged in the academic community. This class of systems involves agents that exhibit behaviors with limited decisional scope, but when combined altogether permit to address particular manufacturing problems. (Table 1). In this class of systems, referred to as *agent-based manufacturing systems*, the control profile of each agent (e.g., their functions/responsibilities in the overall system, their data access right, their authority and their protocols of interaction with the other components of the systems) is usually predefined. This feature tends to facilitate implementation which thus consists in mapping real elements of manufacturing systems (e.g., orders, resources, products) with predefined building blocks. However, other approaches, such as Barber, Liu, Goel, and Ramaswamy (1999), propose declarative modeling framework that allows system designers to customize the control profile of each agent according to specific requirements.

During the early 1990s, along with the growing interest in supply chain management, agent-based approaches dedicated to supply chain management started to emerge in the academic community. Fox *et al.* (1993) and Beck and Fox (1994) present two early applications of such systems which are referred to as *agent-based supply chain management systems*. In this class of systems, agents address generally larger parts of the overall planning and control problem, such as operations or procurement planning for an entire facility or a production/distribution center. Also, each agent's profile is usually (but not necessarily) customized so as to fit within a particular planning and control context. Some of these systems propose methods that facilitate this customization process through declarative modeling frameworks or customizable agent architectures that are used to specify the desired control characteristics (Fox, Barbuceanu, and Teigen (2000), Cloutier, Frayret, D'Amours, Espinasse, and Montreuil (2001), Nissen (2001), Sadeh, Hildum, and Kjenstad (2003)). In order to carry out their function, agents are also sometime geared up with advanced planning tools, some of which are based on OR technology.

Many agent-based approaches to manage supply chains have been proposed in the literature (see Table 2). The main problems addressed by these approaches are usually related to the synchronization of supply chain activities. However, two main streams of research can be found. In the first stream (e.g., Parunak (1998), Swaminathan, Smith, and Sadeh (1998), Julka, Srinivasan, and Karimi (2002)), the goal is to study supply chain performance in stochastic environments through the design and simulation of supply chain models. These systems can be referred to as *agent-based supply chain simulation systems*.

Table 1 : Agent-based manufacturing systems approaches

Application	References	Contributions
Flow shop manufacturing planning and scheduling	Valckenaers, Van Brussel, Wyns, Peeters, and Bongaerts (1999)	Holonic architecture using the path planning approach of ant colonies to flow shop scheduling
	Caridi and Sianesi (2000)	Mixed-model assembly line sequencing through optimization, heuristics, and agent-based techniques
Job shop manufacturing control	Shaw (1987b) Shaw (1987a)	Distributed scheduling of a cellular manufacturing system using a bidding scheme
	Duffie and Piper (1986)	Bidding-based approach for heterarchical control of a flexible machining cell
	Sycara, Roth, Sadeh, and Fox (1991b) Sycara, Roth, Sadeh, and Fox (1991a)	Distributed scheduling using the concept of texture to guide decision making and focus agents' attention to globally critical aspects of decisions
	Lin and Solberg (1992)	Heterarchical market-like approach to shop floor control using bidding schemes
	Hadavi, Hsu, Chen, and Lee (1992)	Function-oriented architecture (as opposed to task or resource-oriented agent architecture)
	Villa, Brandimarte, and Calderini (1994)	Contract-net allocation of task to resources
	Duffie and Prabhu (1994); Duffie and Prabhu (1996)	Real-time distributed scheduling in heterarchical manufacturing cell using feedback control from a simulated replica of the cell
	Tharumarajah and Wells (1997)	Behavior-based approach to collaboration in a heterarchical shop floor control environment
	Liu and Sycara (1997)	Advanced inter-agent negotiation schemes based on a disparity in the problem structure
	Kutanoglu and Wu (1999)	Lagrangian relaxation of the job shop scheduling problem adapted into a combinatorial auction mechanism
	Sousa and Ramos (1999)	Contract-net application in a holonic architecture context
	Parunak, Baker, and Clark (2001)	Highly distributed approach to production planning based on request-for-quotes and bids
	Shen and Norrie (2001)	Quasi-heterarchical/mediator-oriented architecture using a cascaded bidding-based mechanism
	Wooldridge *et al.* (1996)	Negotiation-based modeling of the product sequencing problem using game and negotiation theories
Tool management	Tsukada and Shin (1998)	Heterarchical architecture using tool manager and task manager agents negotiating with each other
Flexible manufacturing system scheduling	Kouiss, Pierreval, and Mebarki (1997)	Dynamic and local selection of job dispatching rules by agents, guided by global information
Multi-facility production planning and coordination	Parunak (1987)	Application of the contract-net for production control
	Gyires and Muthuswamy (1996)	Application of the global partial planning approach
Warehouse and inventory management	Ito and Mousavi Jahan Abadi (2002)	Hierarchical architecture composed of three sub-systems for agent communication, material handling and inventory management
	Kim, Heragu, Graves, and St. Onge (2003)	Hybrid architecture with order picking optimization, with genetic algorithm-based and mathematical programming optimization
Integrated process and operations planning	Gu, Balasubramanian, and Norrie (1997)	Contract-net application using four type of agents (part, shop manager, machine and tool agents)
	McDonnell, Smith, Joshi, and Kumara (1999)	Adaptation of the contract-net protocol to account for conditional bidding
Capacity allocation planning	Eberts and Nof (1993)	Hierarchical production scheduling using a central planner setting global goals and local controllers to plan cells' activities through negotiation
	Brandolese, Brun, and Portioli-Staudacher (2000)	Contract-net application with a personal digital assistant agent allowing distributed decision making through many firms
Schedule recovery after disruptions	Tsukada and Shin (1996)	Negotiation-based approach to job priority setting and rescheduling in a disrupted environment
Integrated operations planningand scheduling	Miyashita (1998)	Hierarchical architecture to planning and scheduling integration based on manager, planner and scheduler agents
	Gou, Luh, and Kyoya (1998)	Holonic architecture using cascaded Lagrangian relaxation

These approaches focus primarily on the development of modeling and simulation environments. The goal is to support decision makers to design models of their supply chain and decision-making processes in order to simulate their collective and dynamic behavior and analyze their performance. In a context where supply chain members use complex optimization software such as APS systems to plan and synchronize their operations, it is difficult to build accurate models of such complex decision-making behaviors. That is why some authors have undertaken the design of simulation environments that include such optimization tools (Lendermann *et al.* (2001); Lendermann, Julka, Gan, Chen, McGinnis, and McGinnis (2003); Baumgaertel and John (2003)).

The second stream of research (e.g., Fox, Barbuceanu, and Teigen (2000); Shen, Kremer, Ulieru, and Norrie (2003); Sadeh, Hildum, and Kjenstad (2003)) concerns the development of approaches to support the synchronization of supply chain operations. These systems can be referred to as *agent-based supply chain planning systems*. Here, the focus is placed on the development of coordination mechanisms to support supply chain members in coordinating their distributed decision-making processes. In this context, it appears that the approaches proposed within each stream of research clearly benefit from the others: the latter must be tested and evaluated dynamically, while the former should be able to simulate various approaches of coordination.

Among the approaches proposed in the second stream of research, the overall agent-based structures differ from one approach to the other. Some propose to decompose supply chains into function-oriented agents that are integrated within a global planning system.

Other approaches propose to decompose supply chains into organization-based agents, usually responsible for handling the various activities of an organizational unit (e.g., a raw material supplier, a manufacturer, a distributor, a service provider, a retailer) as well as their relationships, usually client-supplier (Montreuil, Frayret, and D' Amours (2000), Qinghe, Kumar, and Shuang (2001), Gerber, Russ, and Klusch (2003), Cavalieri, Cesarotti, and Introna (2003)).

Table 2 : Agent-based supply chain systems and related approaches

References	Contributions
Fox *et al.* (1993); Beck and Fox (1994)	Functional decomposition of the supply chain with inter-agent negotiation to coordinate their planning activities
Barbuceanu and Fox (1997); Fox, Barbuceanu, and Teigen (2000)	Coordination language to design agent conversation plans and rules to coordinate and integrate supply chain activities
Parunak and VanderBok (1998); Parunak (1998)	Multi-agent simulation of the supply chain using a functional decomposition of each firm
Swaminathan, Smith, and Sadeh (1998)	Multi-agent simulation of the supply chain using a library of structural and control elements to build supply chain models
Strader, Lin, and Shaw (1998); Fulkerson and Staffend (1997)	Multi-agent simulation of the supply chain applied to the order fulfillment process
Brugali, Menga, and Galarraga (1998)	Application of the mobile agent technology for supply chain information systems integration
Chen, Peng, Finin, Labrou, Cost, Chu, Sun, and Willhelm (1999)	Supply chain task allocation through performative-oriented negotiation modeled as colored Petri nets
Kutanoglu and Wu (1999)	Distributed resource scheduling based on combinatorial auction and Lagrangian relaxation
Ertogral and Wu (2000)	Supply chain activity coordination using a Lagrangian relaxation procedure and an auction theoretic approach
Montreuil, Frayret, and D' Amours (2000), Frayret, D'Amours, Montreuil, and Cloutier (2001)	Framework for production network modeling and operations coordination through negotiation protocols and optimizations tools
Gjerdrum, Shah, and Papageorgiou (2001)	Supply chain modeling and simulation using actual optimization tools to replicate planning and control functions
Qinghe, Kumar, and Shuang (2001)	Supply chain task allocation based on bidding and a genetic algorithm decision model
Nissen (2001)	Agent-based supply chain process integration using graphcet modeling
Sadeh, Hildum, Kjenstad, and Tseng (2001); Sadeh, Hildum, and Kjenstad (2003)	Wrappers agents are used to coordination supply chain planning and scheduling modules
Jeong and Leon (2002); Jeong and Leon (2003)	Distributed decision making mechanism using functional agents to coordinate interdependent problem solving agent
Julka, Srinivasan, and Karimi (2002); Julka, Karimi, and Srinivasan (2002)	Multi-agent simulation of the supply chain using multi-layered functional agents, application in the petrol industry
Calosso, Cantamessa, Vu, and Villa (2003)	Supply chain planning using request-for-quote coordination scheme and optimization tools for bid evaluation and operations planning
Luh, Ming Ni , Haoxun Chen , and Thakur (2003)	Price-based approach for supply chain activity coordination using a Lagrangian relaxation procedure and the contract-net protocol
Santos, Zhang, and Luh (2003)	Multi-agent model for intra-organizational logistics management based on using Lagrangian relaxation
Gerber, Russ, and Klusch (2003)	Agent based information and trading network to support integrated services in forestry and agriculture using a modified contract-net
Shen, Kremer, Ulieru, and Norrie (2003)	Quasi-heterarchical and functional architecture using specialized agents modeling specific functions
Cavalieri, Cesarotti, and Introna (2003)	Quasi-heterarchical architecture to coordinate distribution networks
Ahn and Lee (2004)	Supply chain task allocation with iterative relaxation contract net and data envelopment analysis for buyer-supplier relationship formation
Poundarikapuram and Veeramani (2004)	Distributed decision making framework based of the L-shaped method to coordinate local distributed problems to near-optimality
Azevedo, Toscano, Sousa, and Soares (2004)	Simulate annealing-based coordination approach of order planning in a multi-echelon context
Lou, Zhou, Chen, and Ai (2004)	Supply chain coordination using contract-net and case-base reasoning
Allwood and Lee (2005)	Multi-agent simulation of the supply chain taking into account the competitive nature of supply chain actors
Jiao, You, and Kumar (2006)	supply chain task allocation using a modified contract-net to manage several interdependent suppliers simultaneously
Lau, Huang, Mak, and Liang (2006)	Supply chain operation scheduling and coordination using a modified contract net to seek and select contractors

Other differences exist between these approaches. For instance, the overall structure of an agent-based system can take other forms. It can be holonic (Gou, Luh, and Kyoya (1998), Gerber, Russ, and Klusch (2003)), heterarchic (Sadeh, Hildum, and Kjenstad (2003), Fox, Barbuceanu, and Teigen (2000), Frayret, D'Amours, Montreuil, and Cloutier (2001), Nissen (2001), Gjerdrum, Shah, and Papageorgiou (2001)), or quasi heterarchical (Qinghe, Kumar, and Shuang (2001), Shen, Kremer, Ulieru, and Norrie (2003), Cavalieri, Cesarotti, and Introna (2003), Lou, Zhou, Chen, and Ai (2004)). The reader is referred to Shen, Norrie, and Barthes (2001) for more details.

Other approaches propose various forms of organization of agents' roles and interactions based on the decomposition of a large planning problem that encompass a network of manufacturers and suppliers. For instance, some approaches build on the Lagrangian relaxation of the coupling constraints of the planning problem that bind manufacturers with their clients and their suppliers (e.g., Kutanoglu and Wu (1999), Ertogral and Wu (2000), Santos, Zhang, and Luh (2003)). similarly, Jeong and Leon (2002) and Jeong and Leon (2003) exploit the same technique to relax the coupling constraints of related sub-problems.

These approaches are methodologically driven. They aim at developing new ways of solving complex problems by defining different agents with complementary capabilities in order to solve part of a large mathematical problem. Another application of such an approach is proposed in Keskinocak, Wu, Goodwin, Murthy, Akkiraju, Kumaran, and Derebail (2002) to solve the planning problem in a paper mill, linking customers needs with production constraints. In their approach, some agents are designed to optimize part of the overall problem, others are designed to consolidate partial solutions to generate feasible global solutions, while other agents evaluate the performance of the global solution in order to make the final decisions. Along the same line, Poundarikapuram and Veeramani (2004) exploit another mathematical method, referred to as the L-shaped method, to design an agent-based distributed decision making framework to coordinate local distributed problems to near-optimality in a supply chain context.

3 Generic architecture

Building on these two streams of research, this paper presents the generic architecture needed to implement distributed advanced planning and scheduling systems with simulation capabilities. Such a system is referred to as a supply chain experimentation platform because it brings together the capabilities of both *agent-based supply chain simulation systems* and *agent-based supply chain planning systems*. This approach is thus part of both streams. In order to address the challenges related to the design of such a platform, agent-based technology, operation research and constraint programming have been applied. Figure 1 presents the main functions of this platform. In brief, this platform is functionally made of an advanced planning and control system (1) exploiting agent-technology. Simulation capabilities are then added to this environment in order to provide various tools (2) to analyze and evaluate various supply chain planning configuration. Finally, users (3), through the use of various dedicated graphical tools and interfaces can develop the various supply chain scenarios (4) to be tested and analyzed. This paper focuses on the development of its generic architecture and on the presentation of practical applicative cases.

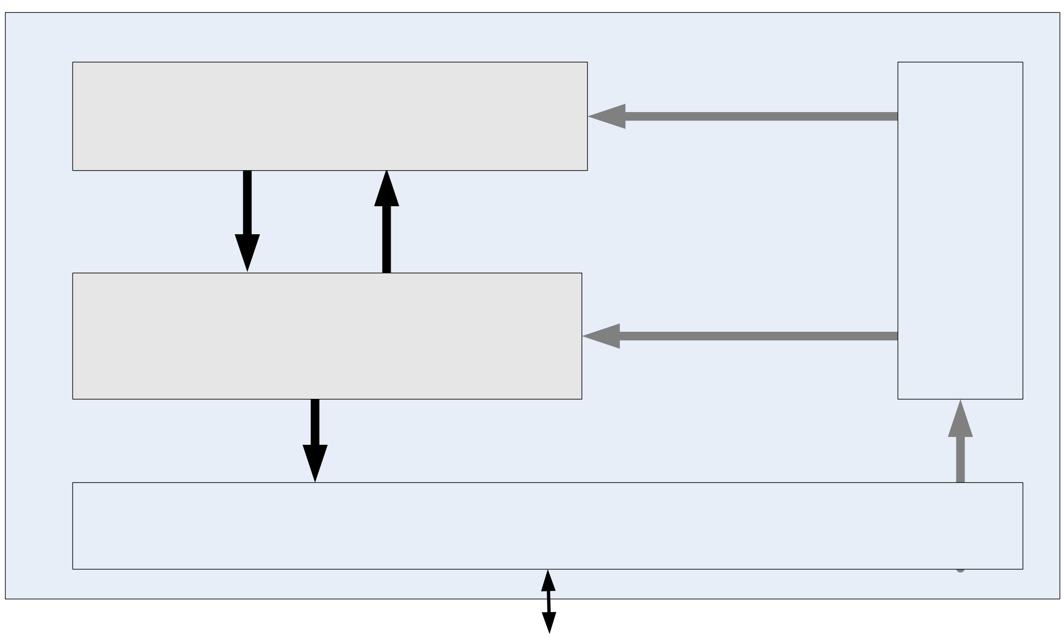

Figure 1 : General overview of the experimentation platform

3.1 Architecture description

The architecture that is introduced hereafter is made of two parts. The first part, the *organizational architecture*, encompasses the method and components used to model the organization and decision structures of the supply chain to be studied or geared up with advanced planning tools. These method and components are based on previous work and the SCOR model of the Supply Chain Council. The second part of this architecture describes the *technological framework* that includes the software components designed to implement all the functions required to support decisions in a distributed environment.

In order to design an agent-based experimentation platform, the methodology proposed here follows the three-level approach presented in this section and shown in Figure 2. The first two levels are built using the organizational architecture that provides the elements required to model a supply chain configuration. These are the business and planning levels. Then, once a supply chain configuration is developed, the technological framework is used to implement all the required software components to materialize it. This is the implementation level. It includes the communication and the message processing functions, the taskflow management capabilities and the planning modules.

In practice, both the *organizational architecture* and the *technological framework* introduce generic components can be used to instantiate any configuration. Even instantiated components of a specific configuration can be reused to build other configurations of a similar supply chain. This feature allows the platform users to simulate and test several configurations of the same supply chain with minimal work.

3.1.1 Business level

The business level of the architecture is based on previous work by Montreuil, Frayret, and D' Amours (2000) et Frayret (2002). It is used to describe the general organization of the supply chain, which is modeled as a network of autonomous and interdependent business units that are responsible to fulfill their mission (defined by their owners) and their business agreements with other business units.

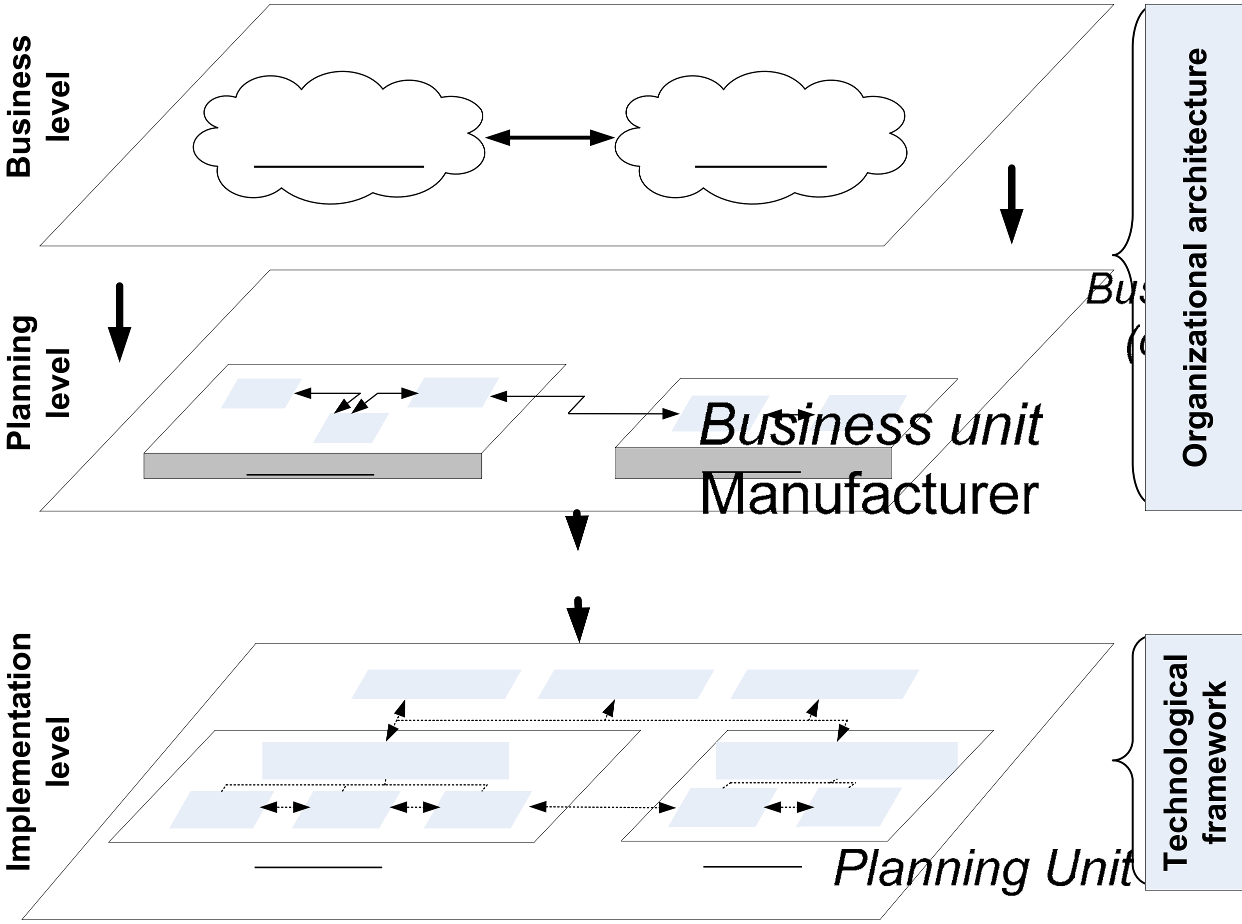

Figure 2 : Three-level general architecture

From a company's point of view, a business unit can be an external entity that represents a business partner (e.g., a customer, a supplier). In the case of a forest company, it can also be an internal division, such as a forest products division or a pulp and paper division. It can even be a single facility to which the corporate management wants to assign a specific business mission. In other words, business units are responsible for achieving the business mission they have been mandated for by their owners. Such a mission can take several orientations (see Montreuil, Thibault, and Paquet (1998) for more details).

The business level also encompasses the description of the agreements and commitments between business units. Such agreements specify business units' rules of interaction as well as their collaborative behavior. For instance, a business unit may agree to provide its customers with any information regarding its inventory and capacity levels, or to contact its customers when particular events occur.

An important consequence of this business design approach is that under the same ownership, business units are coordinated with respect to all business objectives through their hierarchical relationship with their owners. In other words, a business unit owner defines the mission and objectives of all his/her units in an integrated manner. Then, with external business units (i.e., units with a different owner), each unit is responsible to define, in accordance with its owner, its own business agreements which can contribute to help the unit fulfill its mission.

3.1.2 Planning level

The planning level of the architecture consists in all the generic structures and mechanisms required to implement an agent-based supply chain experimentation platform. First, there is a direct correspondence between business units and their planning level counterpart, referred to as a *planning unit* (PU). Similarly, PUs' relationships are specified through a supply chain business configuration. Because of the flexibility of the business level principles, the scope of a PU can take several forms. For example, a PU can be set to support the operations planning of a department, a complete facility, or an entire multi-facility division.

Second, the internal configuration of a PU is composed of specialized planning agents capable of maintaining complex communication and collaborative taskflows with each other, whether they are in the same PU or not. These taskflows are structured conversations based on specifically designed conversation protocols (see part 3.2.3). These internal configurations are built and customized in order to implement the particular planning support models of the PU's decision processes. In other words, the agents' behavior and their ability to communicate with each other are designed in order to handle specific events related to the desired collaborative planning process. This generic structure of a PU is designed to be transparent to offer a single interface to its customers and suppliers.

3.1.3 Implementation level

The configuration of an agent-based supply chain experimentation platform specifies the PU's internal configurations and its relationships with other PUs. Its design and implementation is made through a software component called *supply chain modeler*. Supply chain modeler enables system designers to customize and deploy PUs through a network of computers specifically equipped with a software environment to host their components. In other words, supply chain modeler enables system designers to specify each PU's internal configuration, the agent's specific behavior and conversation protocols, their relationships in terms of product to provide, and each agent's local information concerning products, processes and processors. Once the PUs are deployed, supply chain modeler serves as the corporate "yellow pages" of the system in order to help PUs find where the other PUs are located on the network. It also manages security, permits the definition of appropriate user profiles and serves for the maintenance of the system in order to update or modify supply chain configurations. Supply chain modeler finally contains the standard information about agents interact protocols in order to simplify their configuration.

In order to provide users with global and local views of their supply chain, they can indirectly access each component's information through a software component called *supply chain cockpit* which centralizes information access and manage access right. These views are built using detailed and aggregated information related to performance indicators and planning information. Each software component and agent has been developed as an application that can be accessed through web-service in order to provide structured information to supply chain cockpit. Information is thus presented through a web browser to centrally access local information through consolidated, aggregated or detailed views of planned inventories, flows, production capacity, and production plans. Finally, supply chain cockpit also serves as the supply chain performance monitoring component.

Another software component, called *planning unit analysis*, has been developed to retrieve data from planning agents and organizes this data visually so as to present Gantt charts and inventory graphs to users. This component does not plan directly, or develop machine loading and schedules. It gathers information from the agents that develop these plans and schedules and simply presents them in a user friendly manner. Finally, In order to enable agents to communicate with other agents, a *planning unit manager agent* (i.e., PUM) has been implemented for the purpose of offering a single communication channel to a PU. The PUM agent of each PU is also the component that connects each agent with the Supply Chain Cockpit in order to transmit PU related information.

3.2 Supply chain configuration

The configuration of a supply chain includes the configurations of all planning units, each of which is composed of two fundamental models. The first model refers to the structural description of the software components which compose the PU. It is referred to as the *internal structure model*. The second model deals with the logical description of the distributed planning process which can span within and across each PU's boundary. It is referred to as the *planning process model*. It describes the decision variables of each PU, their objective function, their constraints and the coupling relationships between the different decision-making agents (i.e., agents' authority and autonomy levels regarding the setting of decision parameters and variables). Finally, the design of such an agent-based supply chain experimentation platform is built around a philosophy that emphasizes collaboration among planning agents. This section describes the role and possibilities offered by the use the concept of supply chain configuration.

3.2.1 Internal structure model

The internal structure of a PU is composed of both generic and customized components (see Figure 3). It is first composed of a set of agents sharing the same specific information regarding the PU's products description, through a centralized product data repository. Because agents' planning activities can be computer power consuming, agents can be distributed throughout a network of computers.

Within a PU, planning activities are carried out by various agents responsible for the many planning functions of the planning process model. The proposed functional distribution is inspired by the SCOR model defined by the Supply Chain Council (Stephens (2000)) and the agent-based supply chain management application presented in Fox, Barbuceanu, and Teigen (2000). First, each PU has a *deliver agent* which function is to manage all relationships with the PU's customers. This deliver agent is especially responsible for fulfilling the commitments that the PU may have with its external customers. To do so, the deliver agent may decide how external customer needs should be fulfilled taking into account customer orders' priority. The deliver agent may also apply revenue management policies so as to select customer orders that maximize the PU's revenue. The deliver agent is responsible for sending on demand to its customers, information regarding the fulfillment of their order. Along the same line, the deliver agent is also responsible for monitoring and ensuring the fulfillment of contracts with customers, for instance regarding the management of an inventory consigned by the PU to its customer (i.e., in a vendor managed inventory context). The deliver agent is also responsible for translating customer product codes into the PU's internal product code. Finally, the deliver agent informs sales people of available-to promise in order to support them with their sales activities.

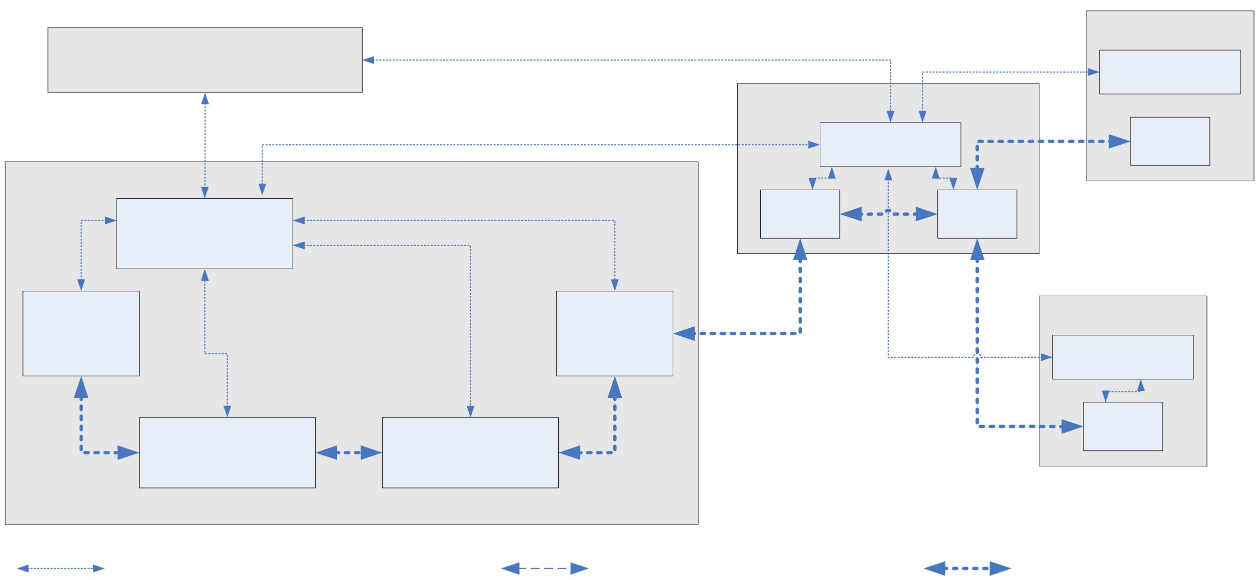

Figure 3 : Components of a specific implementation of a supply chain configuration

On the other side of the functional spectrum, each PU has also a *source agent* whose role is to manage relationships with all the PU's suppliers. The source agent forwards to the right suppliers the needs of the PU that cannot be fulfilled internally or for which it is more economical to outsource. To do so, the source agent is responsible for managing procurement decisions regarding the supply of goods provided externally and for applying procurement policies. For instance, the source agent may have access to raw material inventory data from within the PU and be empowered to send a purchase order to a supplier to

Supply chain cockpit

Manufacturi

Planning unit
manager agent

replenish the inventories. Finally, the source agent is also responsible for translating the PU's internal product code into their suppliers' counterpart.

Next, if the PU is responsible for carrying out production activities, it is geared up with a set of *make agents*. According to the planning process model, production planning functions can be assigned to one or many make agents responsible for a part of the overall planning functions. For instance, the planning functions can be distributed and assigned to make agents responsible for the planning of a set of similar production resources located at the same facility. As presented in the application provided in section 4, a make agent is responsible for the planning of a facility's sawing production lines, while another is responsible for the planning of all wood dryers, and yet another responsible for the finishing facility. Similarly, the planning functions can be distributed and assigned to make agents responsible for the planning of production cells which manufacture a product family. Such decompositions are intimately linked to the internal organization of the PU. Yet they leave the organizational flexibility to exploit the large body of literature dedicated to agent-based manufacturing systems discussed previously. Furthermore, the flexibility of this decomposition approach is necessary for the design of specific decision support tools that are specialized in order to provide operation plans that are both realistic and feasible.

Finally, all agents are responsible for continuously monitoring their own environment and reacting to certain changes that may occur. For instance, the environment of a make agent, which role focuses on defining operation plans, can consist of its planning environment (i.e., plans, parameters, decision variables, constraints and decision criteria). Also, because agents interact with each other, their environment also includes all messages received from other agents specifying a new requirement plan, a new supply plan, a contingency situation, or a high priority requirement. Finally, the environment of an agent, whose role encompasses manufacturing control activities, can include the production execution environment into which it can be "plugged" through a *Manufacturing Execution System* (i.e., MES). Although most agents in the reviewed literature are mainly reactive (i.e., they are designed to carry out specific tasks triggered when specific events occur), the agents envisioned in the proposed approach can also exhibit a proactive behavior by not only reacting to changes in their environment, but also by initiating actions that could improve their performance. This ability requires the definition of goals to guide the agents' proactive behavior. This aspect of the platform is addressed in Forget *et al.* (2006).

3.2.2 Planning process model

The planning process model describes how planning functions are distributed among agents, carried out by these agents, and integrated (see Table 3 and Figure 6). First, the planning process model states, for each agent, its planning profile in terms of decision variables. Second, it states the objective criteria to be optimized by the agent. Then third, it specifies the constraints of the agents' decision problem.

Next, because planning is distributed among agents, it is necessary to describe the coupling planning relationships between agents, such as what products are exchanged between agents (specified as product-client relationships). It also describes the way these relationships are managed in order to provide an integrated planning process. Several coordination mechanisms exist to address the management of these relationships. However, few approaches have been reported to coordinated manufacturing operations in distributed environments. A specific coordination mechanism, introduced in section 4, was implemented in the proposed application. The design of such coordination mechanisms between such planning agents is an issue that if not addressed properly can undermine the performance of the entire system. It is also a challenge for system designers because it appears that coordination mechanisms and agents' internal planning process model are closely related.

3.2.3 Cooperative environment

In order to address both technological and planning process integration challenges, this architecture first exploits the concepts of conversation protocols. These protocols are used to specify how agents should cooperate through structured exchange of messages. Next, agents' cooperative behavior is defined through internal taskflows associated to each potential state of a conversation. At each of these states, each agent participating in the conversation must perform tasks to continue or stop the conversation. The sequence of messages exchanged by the agents represents the conversation. This type of interaction mechanism is more advanced than most integration techniques implemented in advanced planning and scheduling applications, which are usually based on software application programming interfaces (API). Each agent has a single interface to other agents and software components through the ability to receive and send messages. Agents can consequently handle dynamically any conversation protocol as long as they know how to internally perform the tasks that are associated with the receipt of a message. For instance, if the agents are cognitive, they can plan and perform the tasks to cope with the implication of the content of a message. Our implementation of this ability is similar to the one proposed in Fox, Barbuceanu, and Teigen (2000). We exploit the concept of conversation plan to describe how agents should react to specific situations, whether they involve interacting with other agents or not.

Because joint planning of the operations requires the ability to cope with various situations that cannot all be identified in advanced at the configuration stage of the system, it may be necessary to use advanced cognitive agents that can identify themselves what tasks to perform when facing a new situation.

From an implementation perspective, conversation protocols are customized for the need of each agent using a graphical interface and stored in a central database, for which access is granted to all agents. When an agent receives a message associated to a locally unknown protocol, it consults the database and verifies if it has the ability to conduct the different tasks (i.e., taskflow) associated with it. This aspect of the platform is inspired by the FIPA-ACL standards for the interoperation of heterogeneous software agents.

3.3 Simulation capabilities

The design of this platform finally includes simulation capabilities in order to test the performance of various configurations of supply chain planning strategies. Although these developments are currently ongoing, several simulation functions have already been implemented.

The first simulation function implemented involves the development of various types of customer agents. Using data obtained from industrial companies, several types of customers with different demand and behavioral patterns have been developed. In the context of the lumber industry, these customer agents are used to automatically generate a series of orders at variable time intervals, simulating real business lumber buyers. These customers have also been designed to have specific behavior regarding their reaction to offers that differ from their original orders. For instance, if the offer includes alternate products, the customer agents have been designed to refuse, accept or change their order according to preference functions. These customer agents can thus be included in supply chain configurations in order to test the capacity of the configured supply chain planning systems to plan and coordinate operations in time. It is especially design to test the supply chain planning system capacity to adjust to continuously arriving new demand from these customer agents.

Another simulation function that is currently under development concerns the capacity to simulate operation plans. In other words, we intend to not only produce and coordinate industrial size operation plans throughout virtual supply chains, but also to simulate the execution of these plans. The simplest approach (currently under final testing) is to randomly introduce execution discrepancies in the operation plans generated by the planning system. The principle is to use these plans and introduce delays, volume target discrepancies, job cancellation, etc. according to the known variability of the considered industrial processes. This simulation capability also involves the use of a central clock. Indeed, because the execution of the distributed plans requires to be synchronized, all agents must have access to a unique clock. It is also important because the algorithms used to produce the operation plans do not run in simulated time. They produce operation plans as if these plans were not simulated. It is thus necessary to take into account the time require to produce a plan to adjust the simulated execution of the plans. For instance, it is necessary to do so to take the availability of these plans to the shop floor into account during simulation.

4 Application to the lumber supply chain planning problem

The architecture presented in the previous section has been configured to model specific operations planning agents (make, source and deliver agents). The next sections introduce this application.

4.1 Introduction to the lumber supply chain

The Quebec lumber industry that is a part of the Canadian forest product supply chain is described here. In brief, forest is harvested by small size entrepreneurs responsible for felling trees, for crosscutting them into appropriate length logs and handling them by the road. Then, logs remain in the forest until they are transported to mills by transportation entrepreneurs. Once in the mills, logs remain in the log yard until they are broken down into various sizes of rough pieces of lumber. This illustrates the divergence and co-production context of the sawing manufacturing process. A sawing process represents the use of a particular sawing pattern on a particular log class. The concept of sawing process enables the control of co-production through the definition of more or less aggregated lasses of logs. If a log class is indeed not detailed (i.e., this class contains very physically different logs), then it is difficult to know with precision what the output of the use of a particular pattern on that class may produce in terms of product types. On the contrary, the more detailed the definition of this class, the more accurate the knowledge of the output product type mix.

Next, bundles of similar dimension pieces of lumber (e.g., 2x3, 2x4, etc.) are then placed into a kiln dryer (according to the loading pattern corresponding to that dimension) for various duration in order to decrease their moisture content to an appropriate level. Once dried, bundles are disassembled to be planed, cut to length, sorted and graded according to standard rules or customer specifications (altogether, these operations are referred to as finishing in the remainder of this paper). The overall finished products are made of various grades and various sizes of pieces of lumber that are assembled into homogeneous bundles. These bundles are then sent to their final customers, which include wholesalers, retailers, and industrial customers for a second transformation into house components.

In this typical example, a network of facilities is responsible for orchestrating all operations from the forest to the customers, including the operations of many sawmills, while presenting a single face to customers through a corporate office. Concerning harvesting operations, lumber companies are usually responsible for supplying their facilities with logs through the specification of coordinated harvest operations plans (see Beaudoin, LeBel, and Frayret (2007)).

Operations planning in such a context is a complex process for many reasons. First, as presented earlier, the lumber production process is divergent. Furthermore, due to the current push-mode production strategy of the industry and the heterogeneous nature of the resource, production output mix is not accurately known. It is usually known for rather large batches of production. Finally, because the industry is set up to produce commodity products based on standards of sizes and grades, large kiln dryers are usually built to take advantage of scale economies. Consequently, because the size of these facilities force the processing of large batches of lumber, large inventories and low flexibility are common.

4.2 Application

In this context, many decisions must be addressed and coordinated. Here, and for the sake of simplicity, we illustrate only part of the supply chain decision processes. The architecture described earlier and the specific application presented hereafter have been implemented with using C# (Microsoft .NET©) and with ILOG CPLEX and ILOG SOLVER. The following presentation of this application is sub-divided into two sections. The first presents the internal structure of the application, while the second deals with the planning process model.

4.2.1 Internal structure model

In order to keep this illustration simple, only one sawing facility is modeled in the planning unit example presented hereafter. However, as it is usually the case in the industry, such a planning unit would include a much more complex network of production facilities from harvesting to the lumber customer.

As described earlier, in this planning unit, logs are transformed into lumber that is then dried and planed. Then, lumber is transported and delivered to customers directly from an internal warehouse, or through an external warehouse. This is typically the case when a warehouse must be located nearby a train station to consolidate inventories before large batches of lumber can be shipped by train.

The design of the internal structure of this application is guided by the straightforward identification of the heterogeneous planning problems of this supply chain: the planning of sawing, drying, finishing and transportation operations and the management of the external warehouse. This design results with the internal structure presented in Figure 4. In brief, the sawmill planning unit is composed of generic agents: a *planning unit manager agent* (omitted in the figure), a *deliver agent* and a *source agent*. Then, specialized make agents are introduced. A *sawing agent*, a *drying agent* and a *finishing agent* are respectively responsible for supporting the planning of sawing, drying and finishing operations. Another make agent is introduced in order to manage the external warehouse. This agent is named *warehouse agent*. Finally, in order to simulate the use of an agent responsible for managing transportation, a *logistic agent* is created to introduce an offset between required due dates (required by each agent to its supplier) and the due dates that are expected before transportation. This enables to have each agent within a PU in different locations. In a more advanced version of this application, a make agent will be built to carry out this task, and to manage directly the relationship with external logistic providers. Figure 4 presents the different customer-supplier relationships that are configured in this system for each product separately.

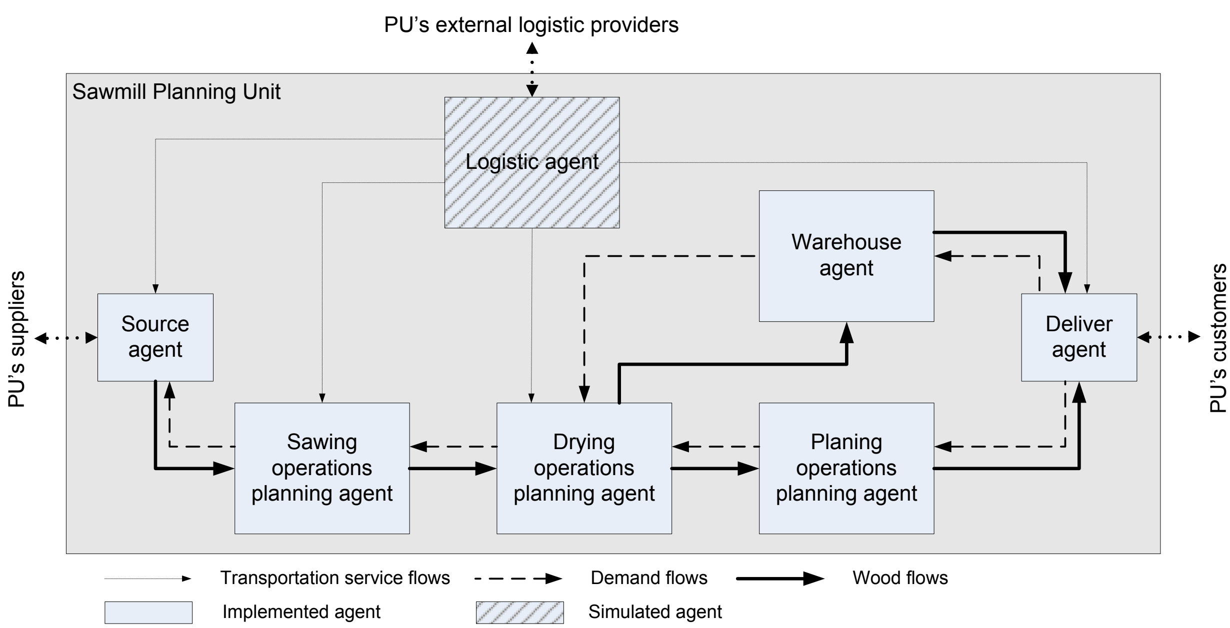

Figure 4 : Sawmill internal configuration

This specific internal structure is neither unique nor optimal. Although it is distributed, a more centralized structure with a single make agent responsible for the planning of all production operations could have been designed. However, due to the complexity of this problem, it seems rather difficult to take advantage of a single generic planning agent that could only be handled aggregated information.

4.2.2 Planning process model

Once the internal structure that identifies homogeneous planning problems defined, the planning process model and all agents' behavior models must be specified. Because this internal structure model is designed to take advantage of the functional specialization of the sawmill internal planning problems, the overall planning process model must be specified in order to (1) build specific planning tools that capture the relatively limited complexity of these homogeneous planning problems, and (2) integrate these specific tools into a planning system that capture their interdependencies and coupling relationships.

The specification of this planning process model includes the modeling of the products, processes and processors information of each planning problem. It also includes the specification of normative planning models for each of these problems. Each make agent is in fact geared up with two normative planning models in order to sequentially plan the production activities pulled by demand (i.e., contract, VMI customers and regular orders), and generate Available-To-Promise based on estimated spot market value. These two planning phases are hereafter referred to as the upstream and the downstream planning phases.

In this process model, each make agent has three main functions: (1) produce an operations plan, (2) allocate demand to suppliers, and (3) allocate production to customers. Table 3 presents the main features of the normative planning models that we have developed for this specific application. In practice, the models of the planning problems have been designed in order to take advantage of some of the specificities of the overall planning context. First, the identified planning problems are radically different with regard to their nature, both in terms of production philosophy and constraints. The sawing operations planning models (i.e., upstream and downstream phases) are designed to identify the right mix of log type (m^3)/sawing pattern in order to control the output of the overall divergent production process. Their objective functions and some constraints are different according to the sequence of planning (i.e., downstream or upstream phases). These planning problems are solved using Cplex.

Table 3 : Planning process models

	Sawing agent	**Drying agent**	**Planing agent**
Objectives	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase) 3. Min. costs	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase)	1. Min. tardiness (upstream and downstream phases) 2. Max. production value (downstream phase) 3. Min. costs 4. Min. resource utilization rate
Process features	Divergent and Co-production Alternative processes	Divergent and Co-production Alternative processes	Divergent and Co-production Alternative processes
Processes model (<supply type, process type → output type>)	<log class, cutting pattern → lumber size distribution> Process compatibility matrix Only compatible processes can be executed within the same production shift	<lumber size, drying sub-process → lumber size, moisture content and quality distribution> Drying activities are assembled together dynamically by agent to create complete processes of drying	< lumber size → lumber size distribution> product families minimum lot size per family Two level setup (product family; product length)
Parameters	Machines capacity calendar Frozen jobs Maximum sales per product Inventory cost Raw product cost	Machines capacity calendar Frozen jobs Operations costs	Machines capacity Frozen jobs Maximum sales per product Expedition windows Inventory, raw material and Setup cost
Method	MIP	Constraint programming	MIP

Next, drying operations planning is batch-oriented and aims at finding simultaneously the type of rough lumber to put in the kiln dryers and the drying processes to implement. For this planning problem, a constraint programming approach was designed as an anytime algorithm (Gaudreault, Frayret, Rousseau and D'Amours (2006)). This approach allows us to find in a rather short time a good feasible solution, all the while allowing finding a better solution if more time is available. A special search procedure was designed in order to increase the speed of the search throughout the solution tree. The problem is solved using Solver. Finally, finishing operations planning aims at finding what dry lumber type and how much of it should be planed, taking into account setup time and sorting booth constraints. A MIP model was designed to address this planning problem.

Intimately related to this aspect of planning process modeling, the coupling relationship between these models must be identified and understood. This must be done to create collaborative planning mechanisms to make sure that planning decisions are not simply made locally and forwarded to other agents, but rather made jointly to take into account all models constraints and take advantage of local opportunities of improvement. The first planning process we have implemented to do this is described hereafter.

The principle of this process is to consider that only part of the production capacity is used to fulfill orders, while the remaining part of the capacity is used to push products to customers. In brief, this process is a two-phased up-stream planning approach where order quantities are derived through operations planning, and expressed upstream the supply chain (see Figure 5).

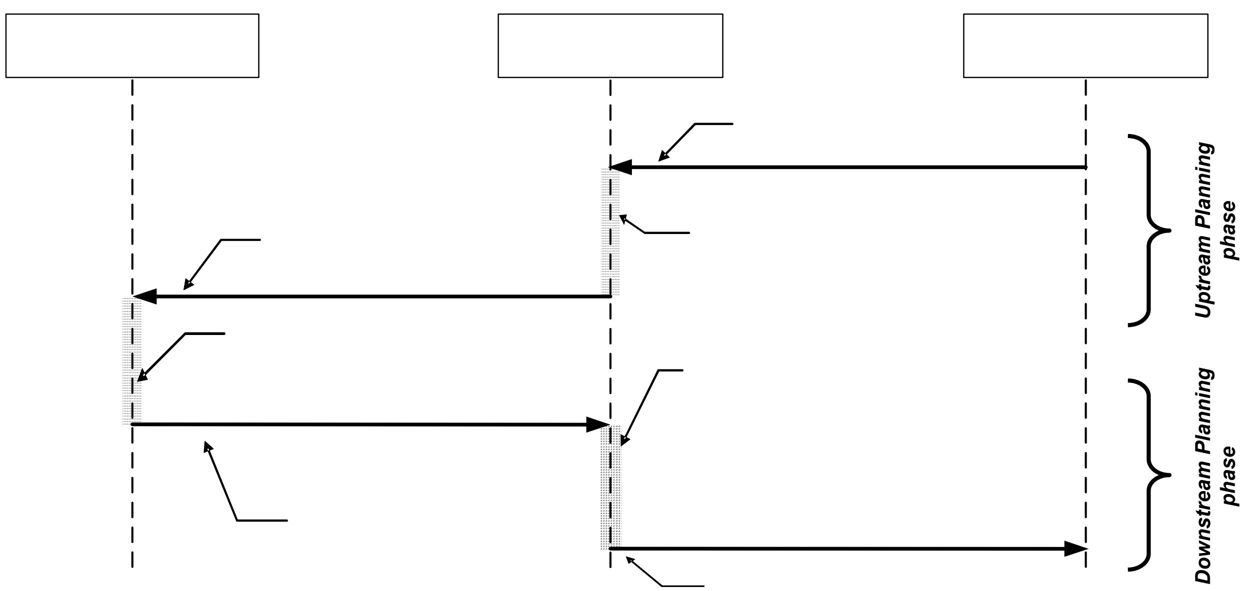

Figure 5 : two-phase planning process

The difference with the single-phased upstream planning is that orders are used by supplier agents in order to plan operations and minimize back-orders. Such an approach is justified in the context of the lumber industry because the heterogeneous character of logs and wood and the divergent nature of sawing, drying and finishing make it difficult to efficiently allocate capacity to each product demand. Consequently, for a given mix of product demand, it is difficult to know whether all products can be produced or not, and in what quantity. That is why we have implemented a back-order minimization approach.

During the upstream planning phase, once demand is expressed to a make agent, this agent first plans his operations in order to minimize tardiness (as shown in Table 3) with no supply constraints. From this plan, he derives and expresses his own dependant demand to his supplier (either a source or another make agent). This phase continues until one of the source agent is contacted. Then, during the downstream planning phase, the first make agent that receives a supply plan from the source agent carries out the following planning sequence: he first plans to minimize tardiness considering the supply constraint he just received and the most updated demand of his own customer. Next, freezing the capacity allocated to satisfy his customer demand, he plans the use of the remaining capacity in order to maximize throughput value, using the current product price list (i.e., estimated product price of the spot market).

In order to adapt this principle to the context of the lumber supply chain, we have adopted the drum-buffer-rope approach of Goldratt's theory of constraints (Goldratt and Cox (2004)). More specifically, this process considers that drying operation represents the constraint of the entire system. Drying is often indeed the bottleneck of sawmills. Consequently, the planning model of the drying agent has been designed to take a central role in the overall planning process. More specifically, it has been designed to plan drying operations with the capacity to anticipate the impacts on finishing operations. In other words, the drying operations planning model considers explicitly primary decision variables that concern drying operations, and secondary decision variables that concern finishing activities. These secondary variables and their associated constraints (including the coupling constraints between the primary and secondary decision variables) represent indeed an anticipation of the planning of finishing operations in order to influence the values of the primary decision variables. However, these primary variables are the only decision variables really controlled by the drying agent. Furthermore, it also means that the drying agent received demand for finished products (and not a demand for rough and dry lumber).

This planning process is depicted in Figure 6. The deliver agent first sends its requirements for dry and planed lumber to the finishing agent (1) who transfers it directly to the drying agent. The drying agent then computes with no supply constraints his own dependant demand for green and rough lumber to be sent to the sawing agent (2). Upon receipt of this new requirement plan, the sawing agent calculates in a finite sourcing capacity mode (i.e., considering the last replenishment plan of its supplier) a new replenishment plan to fulfill the drying agent needs (3). Once this plan is sent to and received by the drying agent, this latter uses it as a supply constraint in order to calculate in a finite sourcing capacity mode a new replenishment plan which it sends to the finishing agent (4). Finally, the finishing agent calculates a new replenishment plan to be sent to the deliver agent or the warehouse agent (5) using the replenishment plan of the drying agent as a supply constraint. In turn, the deliver agent can make decisions regarding the fulfillment of external customers' needs directly from the finishing or the warehouse agent. For transportation, the deliver and the finishing agent send a request for transportation for each transportation need, (6). In turn, the logistic agent plans the fulfillment of these needs using either an internal fleet of trucks or the services of external logistic providers, and sends back transportation availabilities (7).

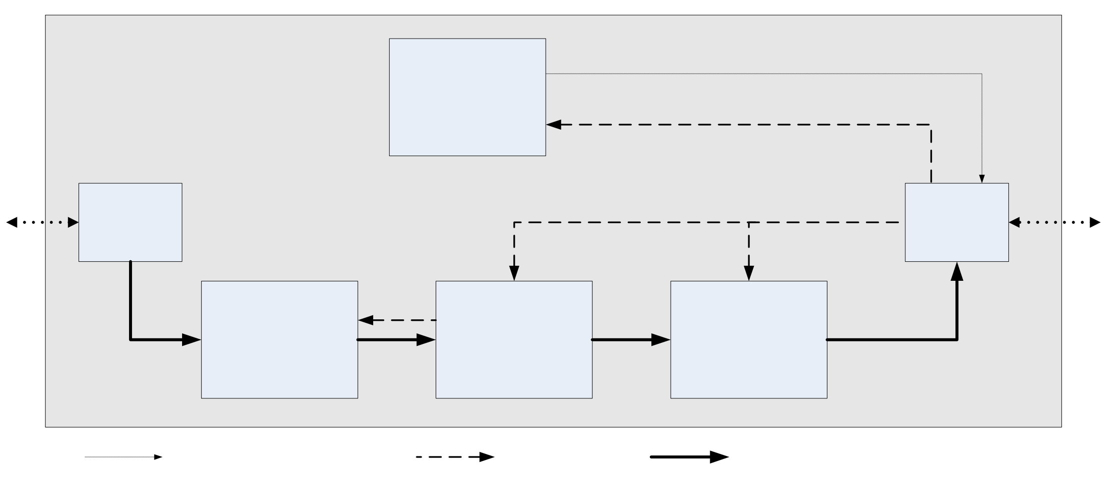

Figure 6 : application planning dynamic

In this setting, the finishing agent does not send any requirement plan for rough and dry lumber to the drying agent. In fact, its only responsibility is to plan finishing operations in order to satisfy requirements from the deliver and warehouse agent and under the supply constraints of the drying agent. The deliver agent can also order from the warehouse agent. In this case, the scenario is the same, the warehouse agent orders directly from the finishing agent. Finally, all materials that are not provided from an internal agent are automatically ordered from the source agent whose responsibility concerns the management of the relationships between the Sawmill Unit and its external suppliers for logs.

In brief, agents can calculate at any given time, a new requirement plan (i.e., a plan of its own needs to be sent to its supplier) that can consider either no constraint of supply, referred to as infinite sourcing capacity mode, or with constraints that represents a model of its suppliers' capacity, referred to as finite sourcing capacity mode. The infinite sourcing capacity mode is meant to identify and communicate to the supplier the requirement plan that best satisfies its local needs. In other words, it is seen as a target for the supplier that, in turn, tries to find a compromise between the full satisfaction of its customer and his own constraint and cost. Penalties for under or over satisfying the demand plan can be used in local planning models to allow such trade-offs. Then, finite sourcing capacity mode can be used either after the receipt of a new replenishment plan from its supplier in order to provide its customer with an accurate plan to fulfill its needs, or using the current replenishment plan in order to provide its customer with a quick answer to a request. In this context, agents' behavior models must be designed in order to explicitly describe the context of using these specific configurations of their local planning models (see Forget, D'Amours, and Frayret (2006)).

Finally, an alternative planning process has been recently implemented and tested to improve the coordination of these agents. The interested reader is referred to Gaudreault, Frayret, and Pesant (2007).

4.3 Industrial test bed

The validation of these developments was carried out with the collaboration of a forest product company. To do so, real data was collected and used to evaluate the feasibility and performance of the agent-based

SC planning function of this experimentation platform. Hence, we developed a specific configuration in order to address the planning of drying and finishing operations for a given plant. This configuration included different types of data, such as production processes, products, orders, on-hand inventory, selling prices, resource costs, forecasted supply, capacity and on-going work. This configuration included over 100 products, two dryers and one finishing line, for a 6 week planning horizon.

The first step of this validation was to model drying and finishing processes with the production manager. Loading patterns for dryers were known and available. However, finishing processes were not documented. The detailed modeling of these processes included 20 finishing processes and 89 drying processes. Customer order and on-hand inventory data were extracted directly from the company ERP system. Their sales team provided the data regarding final product prices and resource costs.

During the test, each week, the partner's production manager sent us his operations plan, including supply from the sawing line, daily capacity of the finishing line and the on-going work. The needed information was then translated in XML format in order to be transferred in the agent-based system, which was then used to generate production and logistics plans. The production manager was able to access these plans through the graphic user interface provided by the *planning unit analysis* module (Figure 7) in order to give his feedback regarding their feasibility. This interactive validation phase allowed us to review and adjust the planning parameters and algorithms. Moreover, by studying the operations plan prepared by the manager, we were able to evaluate the performance of the platform in terms of number of late customer orders, production value, resource utilization, etc. These indicators, easily calculated by the system, were precious to evaluate the performance of both plans and identify possible improvements.

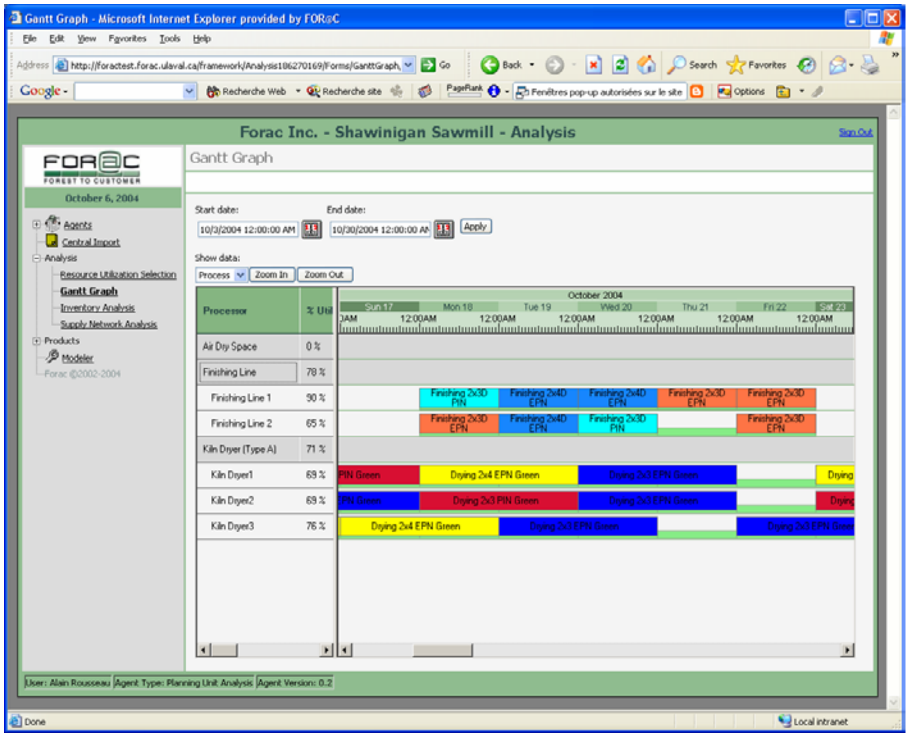

Figure 7 : Screenshot of the drying schedule analysis tool viewed through planning unit analysis

This validation process took about one year and many corrections have been made to improve the system. Now, plans generated by the platform offer considerable improvements over the manual planning process both in terms of .customer satisfaction and planning cycle time.

4.4 Academic simulation use

In a different context, preliminary simulation experiments were also conducted in order to test the simulation capabilities of this experimentation platform. Several alternative configurations of the process model presented above were evaluated and compared in terms of planning performance. In particular, using the basic configuration described previously, other configurations were designed by considering different positions of the decoupling point (i.e., push/pull limit). Indeed, dependent demand can be transmitted up to the sawing agent, or it can be limited to the deliver agent who fulfills customer orders from inventories. These alternative configurations lead respectively to a pull-oriented and a push-oriented supply chain.

In order to compare the performance of such alternatives, each of these configurations was tested with several demand patterns (i.e., various levels of contract to fulfill). The fill rate (Figure 8) and average work-in-process (Figure 9) were then computed using the obtained operations plans and compared. Within the limits of this study, the results show that pull-oriented configuration dominates the others in terms of customer satisfaction and average inventory levels. Although these series of tests were made in a static environment (i.e., the entire demand was know before the beginning of planning), they lead to the conclusion that a better planning and control of production operations holds the potential to improve the forest companies ability to fulfill contracts. This is particularly interesting for these companies because contracts are generally financially very interesting when compared to the unpredictable spot market.

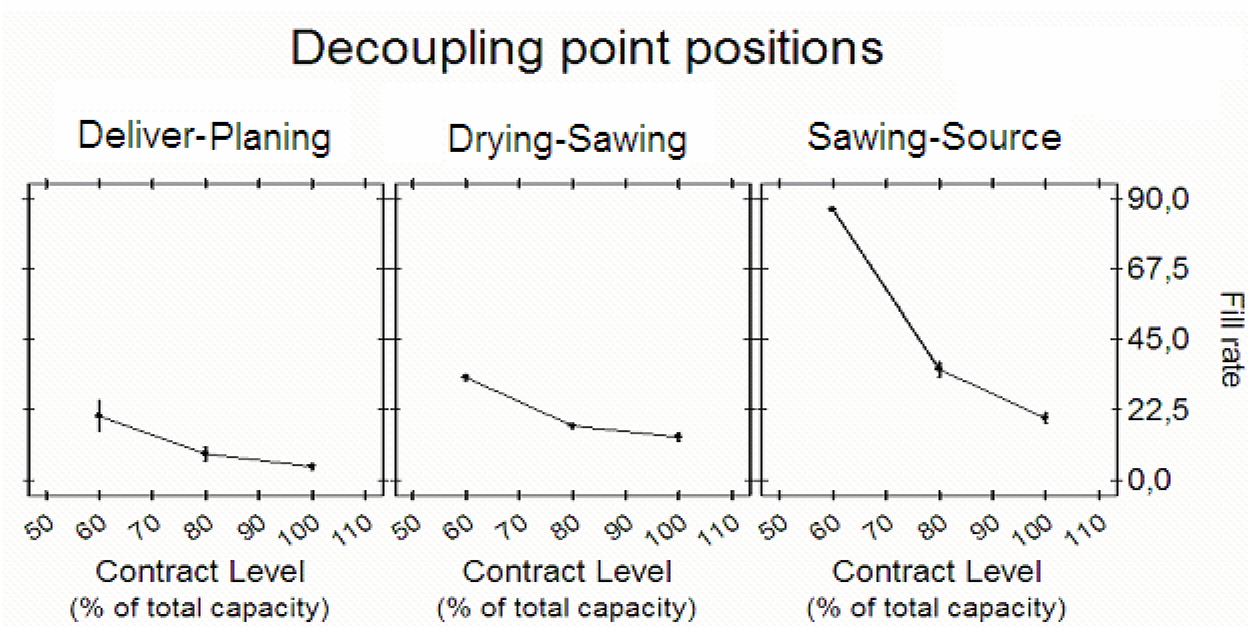

Figure 8 : Fill rate of various supply chain configurations

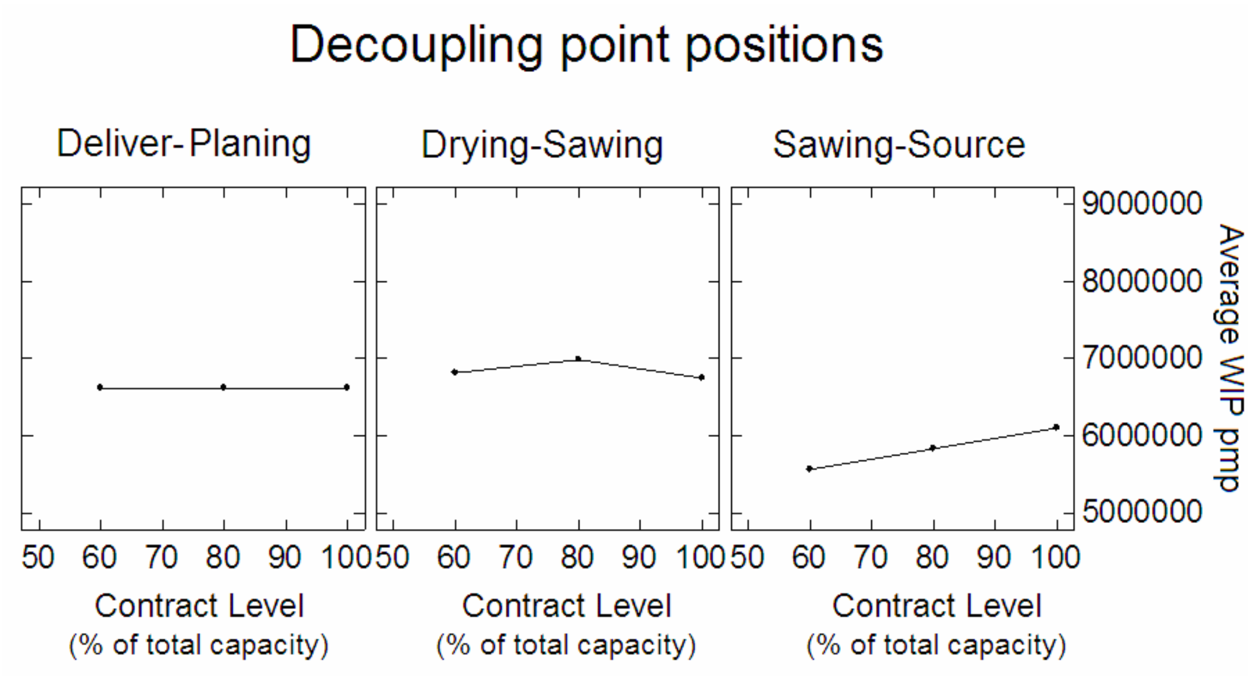

Figure 9 : Average WIP (b) of various supply chain configurations

5 Conclusion and future work

This paper has presented a software architecture which aims at designing distributed advanced planning and scheduling tools for the forest products industry. The presented platform follows the double objective of providing the industry with advanced planning tools, but also with a means of studying the dynamic and performance of such tools working together. The first objective has been already addressed, and quantitative testing of these tools in a real industrial context was undertaken. Concerning the second objective, a research effort focusing on the simulation capacity of the platform has been initiated. This effort aims at designing the mechanisms and software components required to put such distributed advanced planning tools in a simulated environment in order to test them in a live (though simulated) environment.

In terms of research direction, although joint planning relationship can be of the same type whether agents are in the same PU or not, the principles and components to management the financial and contractual relationships when an agent have relationship outside its own PU still have to be developed.

Finally, another research direction that is currently being investigated concerns the agents' architecture. As discussed earlier, agents in such a context seem to require the ability to exploit planning tools in various configurations according to the situation. It thus seems necessary to equip agents with some knowledge about the planning tools they can use, in order to help them exploit the most appropriate setting of these tools.

Acknowledgement

The authors wish to thank the NSERC (National Science and Engineering Research Council of Canada) and the FOR@C Research Consortium (www.forac.ulaval.ca) for their financial support.

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