An optimization and simulation framework for integrated tactical planning of wood harvesting operations and lumber production

Mémoire

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Résumé

La planification tactique des opérations forêt-usines est centrée sur trois éléments principaux : la récolte, le transport et la transformation du bois. La planification de cette chaine d'approvisionnement est très complexe. Il existe déjà des outils pour faciliter la décision de décideur tels que FPInterface et Optitek, tous deux développés par FPInnovations.

Cette mémoire vise à développer un module d'optimisation qui est connecté aux utiles de simulation. LogiOpt est constituée d'un modèle mathématique. Le modèle développé vise l'optimisation de la chaîne d'approvisionnement entre la forêt et l'usine en concentrant les efforts sur les activités que l'entreprise planifie conjointement avec son entrepreneur d'opérations forestières principal. Grâce à ces solutions de logiciels de simulation et de notre modèle mathématique, nous combinons à la fois dans notre cadre récolte, le transport, l'allocation des bois et des opérations de production.

Pour tester notre model mathématique, nous avons utilisé les données d'une année d'exploitation à une entreprise québécoise œuvrant dans le milieu forestier. Nous avons comparé nos résultats avec un plan tactique manuel « simulé ». De ce fait, nous avons constaté que LogiOpt effectue une meilleure allocation de la matière première en allant récolter dans moins de blocs de récolte tout en utilisant des bois ayant un meilleur rendement en usine. Conséquemment, on produit plus de produits finis en usine tout en utilisant la même quantité de bois qu'un plan tactique plus traditionnel.

Abstract

Forest and sawmills tactical planning is based on three main elements: wood harvesting, wood transportation and wood transformation. Planning the whole supply chain, is quite complex. Tools have been built to help manager in his decision process, for example FPInterface and Optitek, which were developed by FPInnovations.

The aim of this thesis is to develop an optimization module, *LogiOpt*, which will be integrated to simulation tools. LogiOpt is made of a mathematical model. The developed model aims at optimizing the supply chain between the forest and the mills. Using simulation software solutions and our mathematical model, we combine at the same time in our framework harvesting, transportation, wood allocation and production operations.

To test our mathematical model, we used data obtained from one business year of a Quebec based wood manufacturer. We compared our results with a manual simulated tactical plan. In this regard, we observed that LogiOpt performs better in wood allocation between sawmills, harvesting in less harvesting while using wood with better output. We then end up producing more finished products at sawmills using the same wood quantity as a traditional tactical plan.

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Chapter 1. Introduction

The job of the timber supply planner is to produce a tactical plan that will allow efficient operations from a regional perspective. The goal is to exploit the logistics network in an optimized way, in order to create the maximum value from the wood resources. The plan must state: (1) the quantities of timber to harvest, (2) the selected harvesting and transportation systems, (3) the destinations where to transform wood fiber, (4) quantifies of logs to be processed at each mill and methods by which logs will be transformed, and finally (5) the expected quantities of finished products. Since a multitude of options are available to the planner, this task requires many calculations.

This problem is particularly complex since the list of finished products to be obtained from the output of a mill varies according to numerous factors. These include: the forest area where raw material comes from, harvesting techniques and the choice of the mill used to transform wood.

In the industry, tactical planning is usually done manually and the decision of the manager is mainly based on his experience and intuition. Problems are characterized by a large number of possible scenarios but the planner usually reduces its analysis to a limited number of possibilities.

Recently, software simulation tools have been developed in Canada to help the forest industry make better decisions based on more detailed information. For example, FPInterface and Optitek simulation software developed by FPInnovations allow forest companies to evaluate different scenarios for harvesting and sawing processes.

These simulators allow evaluating costs and productivity levels. Moreover, they predict the finished products which can be obtained depending on the wood resource, their physical characteristics and technologies used in the mill for wood transformation.

Until now, these tools were only used in order to evaluate the profitability of a plan established manually by the decision maker. What we propose is to have the simulator feed a mathematical model producing an optimized plan. The plan would take into account the network capacity and variations in product resources.

A lot of research has focused on the use of optimization for planning forest operations. The use of mathematical models to plan forest operations began in the 1960s.

Since then, various types of models have been developed to address different aspects of the wood supply chain. Some are designed for specific activities such as skidding and transport, while other research has integrated several activities in a single model to capture the possible synergies between them.

In comparison with existing research, this work brings two original elements. First, the system models the whole supply chain in order to integrate forest and production related decisions.

Additionally, the system connects: (1) a harvesting operations simulator (FPInterface), (2) a sawmill processing simulator (Optitek), and (3) an optimization module establishing the tactical plan.

In Chapter 2, the basic concepts of supply chain management, supply chain planning and different methods of modeling are presented. Moreover, the different components of supply chain in forest product industry and the current planning approach used in the industry as well as available decision making tools which are used in forest products industry are mentioned.

Chapter 3 describes our integrated simulation and optimization solution. A mathematical model is presented in this chapter.

In Chapter 4, different experiments used for model validation and verification are presented. The model was compared with a heuristic emulating manual planning using industrial data.

Chapter 2. Lumber supply chain management: preliminary notions

In this section, preliminary notions regarding lumber supply chain management are presented. In this regard, the basic concepts of supply chain management, supply chain planning and different methods for modeling it are presented. Moreover, the different components of supply chain in the forests product industry and the decision-making tools which are used in the forest products industry are mentioned.

2.1 Forest products industry

The forest products industry is one of the oldest industries in the world. It is also one of the main industrial sectors in different countries such as Canada, Chile and Sweden. In Canada, this industry is one of the largest employers in the country, providing more than 230 000 direct jobs (FPAC, 2012). Among the countries that export primary forest products, Canada is in second rank and is in fourth rank for all forest products in the world (NRCN, 2012).

Canada is also the world's largest exporter of newsprint to more than 100 different countries. The annual harvest amounts are around 1 million hectares (0.4% of the total commercial forest area) (Environment Canada, 2012).

The forest products industry is typically divided into five main sub-sectors (Environment Canada, 2012):

1- Forestry and logging

2- Pulp and paper operations

3- Solid wood products manufacturing (production units of lumber, panels and engineered wood)

4- Energy production

5- New products and materials such as new building materials, biofuel, biochemical and pharmaceutical products and biodegradable plastics.

Several companies with different activities are involved in producing forest products. These companies have to manage the forest, build forest roads, transport logs, and ship the final products to customers. These activities will be planned in order to maximize profit and efficient use of resources within several constraints.

2.2 Supply chain management

A *supply chain* is a network of logistic and manufacturing organizations. In this network, the nodes represent raw materials sources, transformation and distribution centers. These nodes are connected together by links that represent transportation connections. The structure of these networks is important because it influences the performance of a supply chain (Vila et al., 2005).

Several companies can be linked together in a supply chain. These companies may have different objectives. Also, the behavior of each network members has an impact on all other members. Therefore, planning in this context is very complex (Lemieux, 2010).

In addition, in industries such as the lumber industry, the raw material (logs) is cut in various ways to generate several finished products at the same time. This is called a *divergent flow* (in most other industries components are assembled into finished products which is called *convergent flow* (Lemieux, 2010)). Divergent product flows involve many possibilities for production planning and lead to higher complexity.

S*upply chain management* involves the planning and management of all logistics and manufacturing activities. It also includes organization and collaboration with suppliers, producers, service providers, and customers. In other words, supply chain management integrates organizational units and coordinates materials, information and financial flows of the supply chain (Stadtler and Kilger, 2005). Reduced inventories, lower operating costs, product availability and customer satisfaction are all benefits which grow out of effective supply chain management (D'Amours et al., 2008).

Rönnqvist (2003) and Weintraub and Romero (2006) describe different supply chain planning problems in forestry. These include forest management, harvesting planning, transportation planning, production planning and distribution planning for sawmills and pulp-mills.

2.2.1 The lumber supply chain

Singer and Donoso (2007) described well the complexity of integrating several components of the lumber supply chain. In this section these components are described.

2.2.1.1 Harvesting area

A *harvesting area* is a forest area containing a certain volume of wood to harvest. It is characterized by different distributions in terms of species, stem diameters, etc. The harvest areas are generally modeled using a sampling process.

During harvesting, trees are cut and branches are removed. Then the logs are generated in different dimensions and qualities. Many types of log are obtained simultaneously from a specific harvesting area which can be transported to different mills (Lebel et al., 2009), (Lacroix, 2005).

Harvesting can be done using different *harvesting systems* (or harvesting modes). Harvesting systems are all the methods used to produce different types of logs in a harvesting area. For a given area, the volume of each obtained type of log depends on forest characteristics as well as selected harvesting system. Figure 1 shows a harvesting area that has been harvested using a certain harvesting system, the different resulting logs as well as the four species ratio harvested in this area. Using simulation, it is possible to anticipate the quantity of each type of log which would be obtained using each different harvesting system.

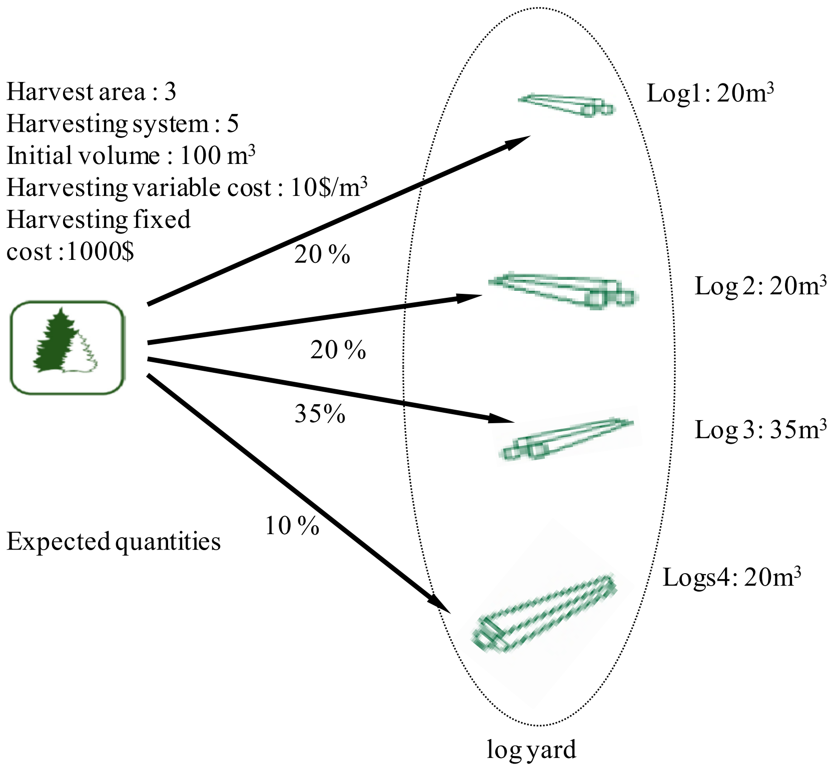

Figure 1: Harvesting an area using a given harvesting system (harvesting mode)

Associated to each harvesting mode there is a *bucking strategy*. Bucking means cutting trees into shorter logs. The value of a log is in relation to the products that can be made from it. Logs are classified typically depending on their length, diameter and quality. Bucking optimization can help obtain the highest value of finished products (Figure 2).

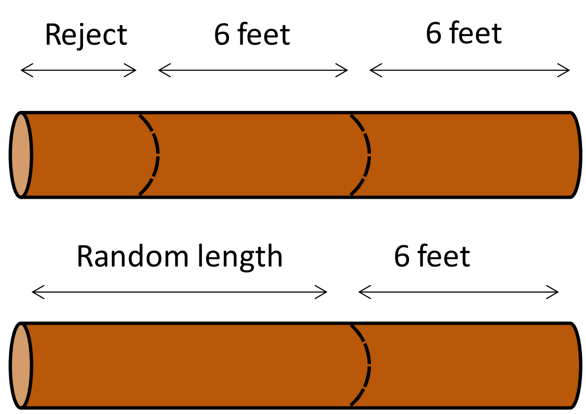

Figure 2 : Two bucking patterns of a specific log

Bucking can be performed in different locations depending on characteristics of harvesting equipment and harvesting areas (Beaudoin, 2008). Bucking patterns can be changed depending on the variations of price and demand (Uusitalo, 2007).

Logging is dragging logs to the roadside. Then, the logs of the same types are stacked. The logs are then transported to mills or to terminals for intermediate storage.

2.2.1.2 Transportation

Transportation is an important activity of the forest products supply chain. Logs are first stacked along the forest roads and then transported to the mill. In the forest products industry, three main *transportation modes* are generally used: truck, rail and ship. Each of these modes has its own type of constraints. Transportation can be done with a single transportation mode or its combination (figure 3).

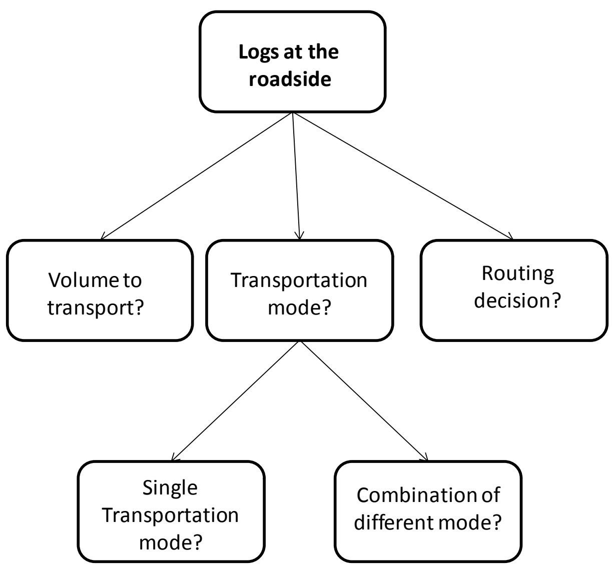

Figure 3 : Decisions related to log transportation from the forest to mills

Since trucking the transportation mode more often used, this type of transportation is explained here in more detail. There are several types of trucks that can be used. Some are multi-purpose trucks which transport logs and lumber or chips. In terms of volume and weight of products, each truck has a specific capacity. Optimizing capacity is one of the important problems in planning. Fuel consumption is another important part of transportation planning. Fuel consumption varies with truck type, road condition and load (Lebel et al., 2009).

Many models have been developed in order to integrate decisions of production and transportation decisions in order to reduce global costs, increase customer service level and flexibility. As an example, a model was proposed by Pirkul and Jayaraman (1996) in order to minimize transportation and distribution.

Chandra and Fisher (1994) proposed a model that minimizes production and transportation costs. Cohen and Lee (1998) developed a model integrating production and distribution in a supply chain network. Martin et al. (1993) developed a linear programming model integrating production, inventory and distribution.

2.2.1.3 Sawmilling

The sawmilling unit transforms logs into finished products called *lumber*. From a given log, several types of lumbers are produced at the same time. As shown in Figure 4, for each log there are several available cutting patterns. Which pattern is available depends on how the mill is configured (or setup). We call these configurations *sawmilling modes*.

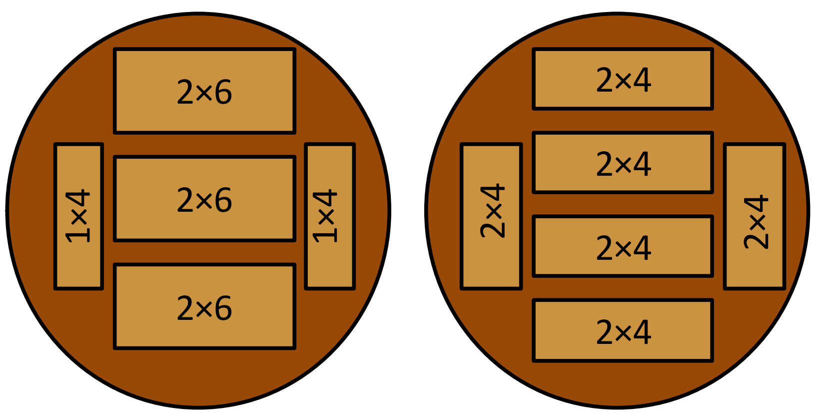

Figure 4: Two sawing patterns for a given log

In most mills, production lines can be configured using different sawmilling modes. For each mode, there is a different associated production matrix. This gives some control over the finished products obtained (Gaudreault et al., 2010). The quantities associated to each product will be variable according to the harvesting area, type of log, harvesting system used, sawmilling mode and specific equipments of the mill. Figure 5 shows an example of a mill production matrix (the ratio of each expected finished product from a type of log is given).

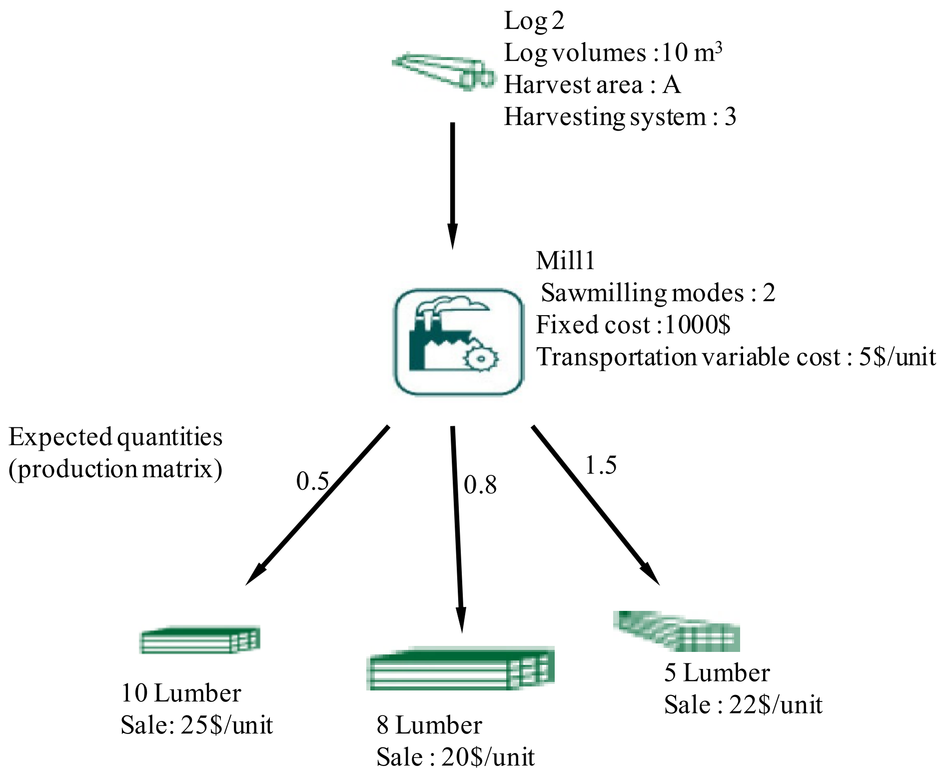

Figure 5 : An example of a mill finished products

In general, a sawmill is composed of three separate units which are called the sawing unit, the drying unit and the planing unit, as shown in Figure 6.

Lumber drying is an operation designed to reduce lumber moisture. Lumber drying is often a time-consuming process and needs much space. This activity can be done with air drying (natural drying) or kiln drying. Air drying is drying a stack of lumber by exposing it to the air. But in kiln drying the lumber is stacked in specific chambers (wood drying kilns), which are equipped with a temperature controller. Then by using heat (natural gas or electricity) this process is done (Desch and Dinwoodie, 1996).

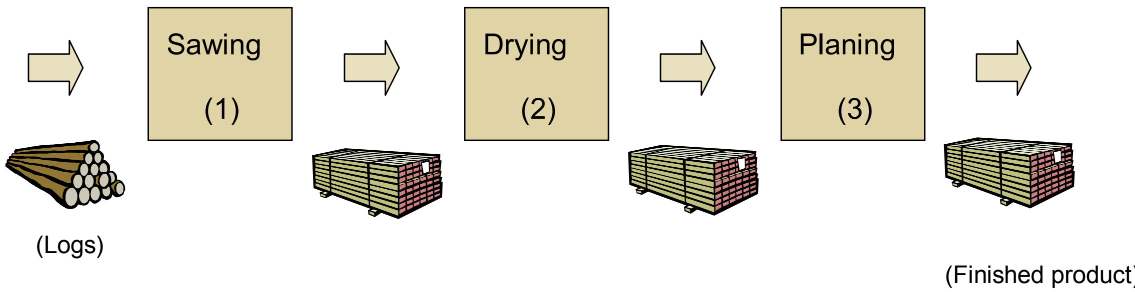

Figure 6 : Sawmilling complex

Planing operation is adjusting the thickness, width and length of lumbers. Moreover, at this stage the final grading decisions are made. The cycle time of this operation may be determined by the speed of the planer, which also has an impact on the quality of the planed lumber.

It should be noted that each unit of the sawmilling complex has its own theoretical maximum capacity. The total capacity of the mill depends on the unit with the lowest capacity, i.e. the bottleneck (Gaudreault et al., 2009), (Lemieux et al., 2009). The capacity can be expressed in terms of transformation capacity (logs total volume), production capacity (lumber total volume), or machine availability (time unit). Machine availability allows taking into account the fact that we do not obtain the same level of productivity depending on the type of log that is processed. This information can be obtained by simulation.

Several models have been developed to plan the sawmilling operations. Singer and Donoso (2007) presented a model for supply chain planning composed of many sawmills and drying facilities. Gaudreault et al. (2010) presented the mathematical models to plan a lumber supply chain composed of three production units (sawing, drying and finishing). In addition, Marier et al. (2009) developed optimization models to evaluate decisions in the design of lumber mills.

2.2.2 Planning in forestry

In the previous sections, supply chain management in the forest products industry and its components have been explained. In the following section, lumber supply chain planning will be explained in more detail. In order to simplify complex planning problems, Hax and Meal (1975) introduced the idea of *hierarchical planning* through dividing the decision process into different problem levels. This approach is done by breaking the planning problem into several planning layers. It allows using different modeling techniques at each layer.

Planning decisions are generally classified into three levels: strategic, tactical and operational. The first layer (*strategic planning*) defines which resources will be available to the next layers. The goal of *tactical planning* is to produce aggregated plans and/or identify targets. Finally, operational planning deals with the detailed planning and scheduling (Davis et al., 2001).

In hierarchical planning, there is a different time horizon for each planning layer. For example, operational plans are highly detailed, but cover short time horizons; however strategic plans cover long time frames in less detail (Figure 7).

The advantages of hierarchical planning are the following: reducing complexity of a problem by breaking it into sub-problems, decreasing uncertainty through differing decisions and increasing planning accuracy through specifying a good organizational fit for all of these planning layers (Martell et al., 1998).

In the following section, the three levels of supply chain planning will be explained in more detail.

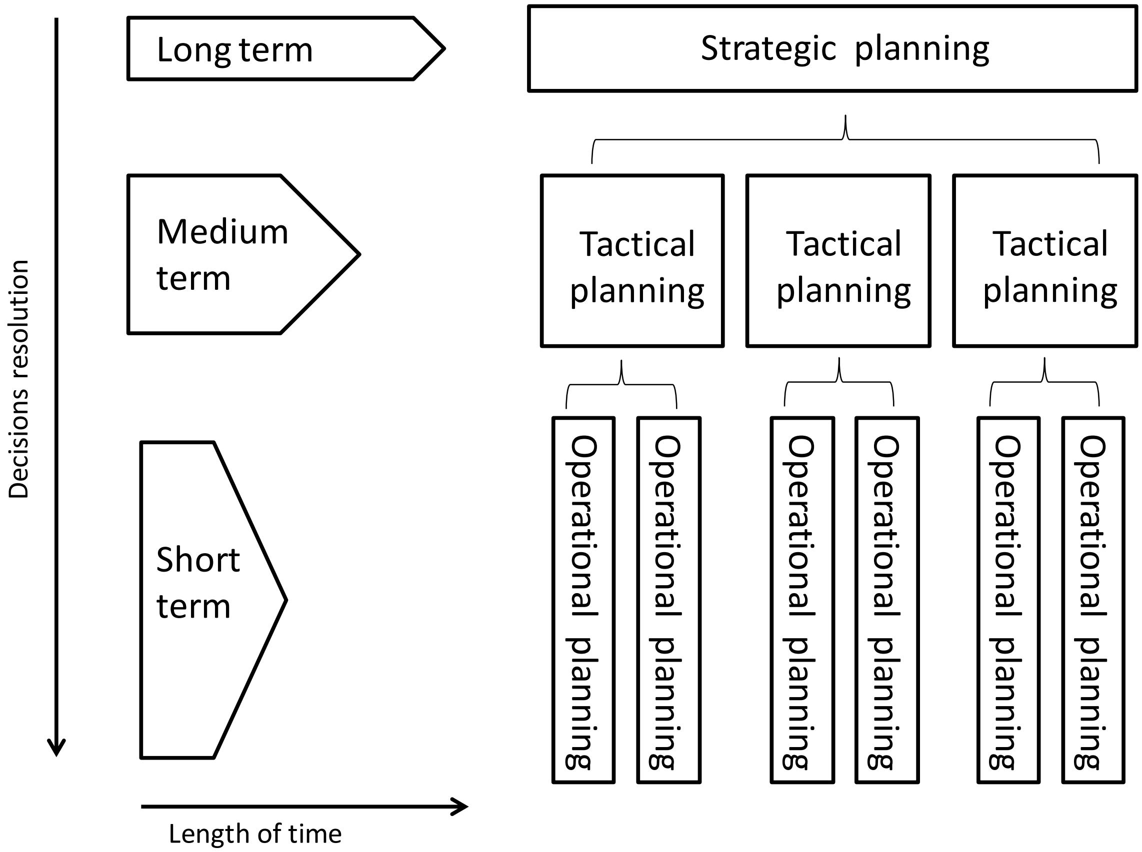

Figure 7 : Supply chain planning hierarchy

2.2.2.1 Strategic planning

Strategic plans are concerned with long-term decisions. Depending on the type of industry, the length of the planning horizon will vary. This planning level is related to fundamental decisions which define the long-term direction of a company. For industries that require several years to provide and install facilities, the horizon can be more than 10 years (Lacroix, 2005).

The forest cycle lasts more than 50 years and a new mill is usually intended to last more than 30 years (D'Amours et al., 2008). Therefore strategic planning uses a very long time horizon in the forest products industry. Several options considered at the strategic level are forest management strategies, silvicultural treatments, identification of conservation areas, road construction, the opening/closing of mills, the location/acquisition of new mills, and product and market development.

The factors which should be evaluated for the supply chain at the strategic level are the following (D'Amours et al., 2008):

1. Available markets.
2. Distribution system.
3. Distribution cost.
4. Supplying system.

The type of forest land (public lands, private lands or both) and government rules may affect the way strategic planning is done (D'Amours et al., 2008).

Many researches deal with strategic planning in the forest industry, such as Navon (1971) and Kent et al. (1991) that use simulation techniques in order to evaluate problem solutions. Different strategic tools using simulation were developed over the years: *Sylva II*, *HSG Wood Supply* and *GIS-Complan*. In some strategic planning tools, an optimization module is used. This type of tool allows the user to identify an optimal management strategy for its decisions. *Patchwork* and *WoodStock* are examples of these tools. *WoodStock* uses linear programming to identify optimal solution, and *Patchworks* uses heuristics methods to identify a sub-optimal solution.

2.2.2.2 Tactical planning

The second step in the hierarchical planning is tactical planning. Tactical plans are shorter than strategic plans and in the forest products industry it is typically over a one to five-year planning period. This layer focuses on the decisions related to activities to perform and materials to consume over a coming year.

Tactical planning is generally considered as a connection between strategic planning and operational planning and has a direct impact on all of operations in the supply chain. Some targets established in the strategic plan can often be used as an input to tactical plans (Martell et al., 1998), and decisions at the tactical level will affect the operational levels: inventory policies, lot sizing and production/distribution lead time.

In the forest products industry, tactical planning usually is used for different activities such as harvesting, road construction and landscape-level silviculture, transportation, as well as sawmills production.

Tactical forest plans may be affected by different factors. For example, in some countries, harvesting operations are seasonal according to their weather conditions which sometimes can make it impossible to transport logs.

There are a lot of researches which have developed different models for tactical planning in forest supply chain, such as Covington et al. (1988), Sessions and Sessions (1992), Church et al. (2000a), Church et al. (2000b) and Jerbi et al. (2012).

2.2.2.3 Operational planning

Operational planning is the lowest layer of hierarchical planning. This level deals with short-term decisions which are frequently made on a weekly or daily basis. The operational problem is to determine the best plan for the near future. In operational planning, the level of detail must be very high which allows creating a plan that can respond to all planning requirements of the processes in supplying, transportation, distribution or production. For operational planning, it is important to consider determined targets in upper levels of planning (Ballou, 2004).

In the forest products industry, the more obvious operational planning problem is harvesting. Another problem is transportation which involves routing and dispatching. For example, to ship finished products from mills to distribution centers, the route of each truck has to be defined.

Burger and Jamnick (1995) developed an optimization model using linear programming for harvest operation at this level of planning. Epstein et al. (1999) developed an optimization model using heuristic.

To summarize this section, examples of strategic, tactical and operational decision-making problems are presented in Table 1.

Table 1 : Examples of strategic, tactical and operational decisions (Adapted from Ballou, 2004)

Decision area	Level of decision		
	Strategic	**Tactical**	**Operational**
Facility location	Number, size and location of mills, warehouses, distribution centers, etc.		
Inventories	Stocking locations, control policies	Safety stock levels, seasonal inventory target	Replenishment quantities and timing
Transportation	Mode selection, investment strategies (e.g. roads construction, trucks, wagons, ships, planning system, etc.)	Seasonal equipment leasing, route definition, transshipment yard location and planning	Routing, dispatching, vehicle loading, daily carrier selection
Order processing	Order entry, transmittal and processing system design, order penetration point strategy		Processing orders, filling back orders
Customer service	Setting standards, customer segmentation, pricing and service strategy, investment in information technology and planning systems	Priority rules for customer orders, customer contracts, allocation of products and customers to mills	Expediting deliveries
Warehousing	Handling equipment selection, layout design, allocation of markets/customers to warehouses, investment in information technology and planning systems	Seasonal space choices, warehouse management policies	Order picking and restocking
Procurement	Wood procurement, forest land acquisitions and harvesting contracts, silvicultural regime and regeneration strategies, development of partnerships	Sourcing plan (log classes), allocation of harvesting to cutting blocks, allocation of products/blocks to mills, log yard management policies, contracting, vendor selection	Order releasing, expediting supplies, detailed log supply planning

2.2.3 Optimization and Simulation in forestry

Several techniques can be used to model the supply chain and solve the planning problems. Figure 8 presents the main modeling and solving techniques: simulation models, optimization models and artificial intelligence (Santa-Eulalia, 2009). In what follows, the first two techniques are explained in more detail.

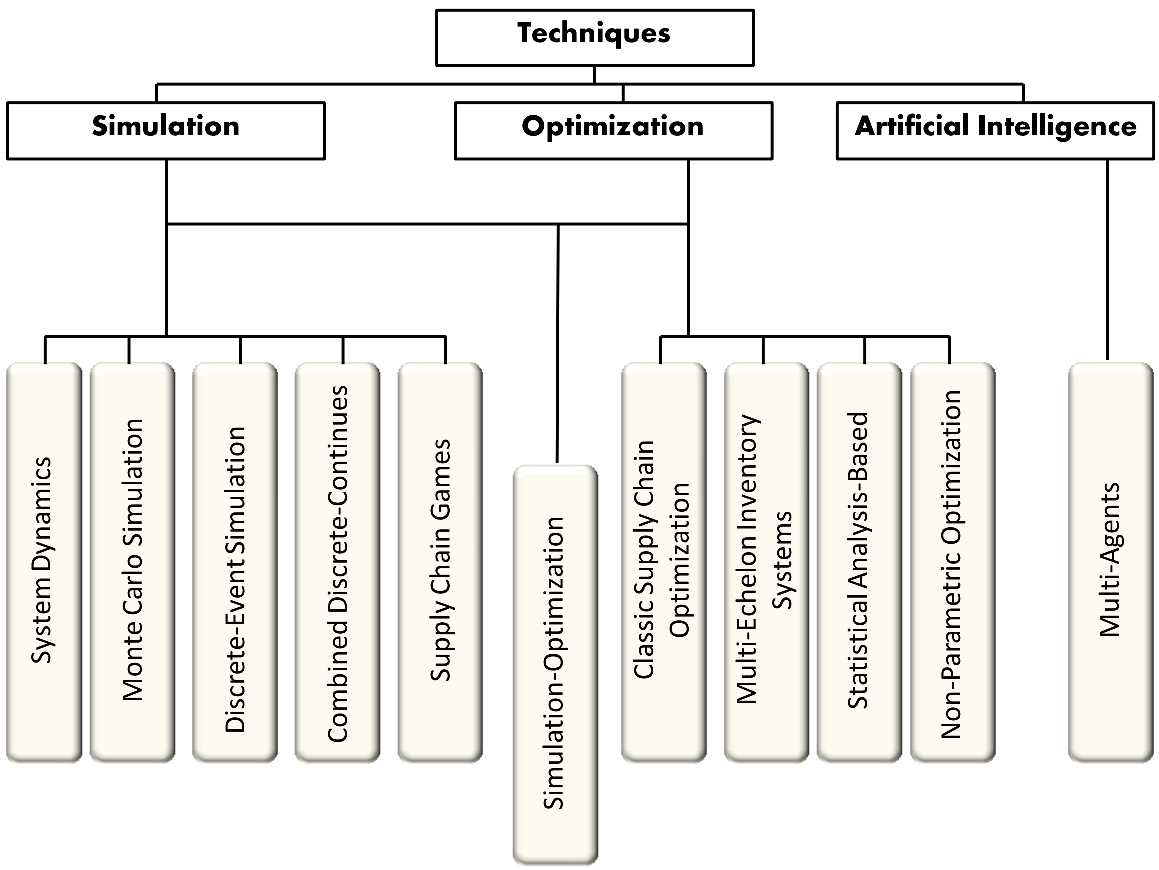

Figure 8 : The main techniques for modeling and solving supply chain planning problems (Santa-Eulalia, 2009)

2.2.3.1 Optimization

Optimization is defined as the selection of the best solution from some available alternatives according to constraints. The main goal of optimization is to provide an optimal solution: a solution for which it is possible to prove mathematically that the resulting solution is the best one (Ballou, 2004).

Mathematical optimization is one of the techniques which can be used for modeling and decision-making problems. To evaluate all possible alternatives and to find optimal solutions, mathematical formulations and algorithms are used.

The main components of a mathematical optimization model are: *objective function*, *decision variables* and the *constraints*. An objective function is the function that needs to be optimized. Decision variables defines the solutions to the optimization problem. In other words, the optimal solution is the set of values for the decision variables such as the objective function reaches its optimal value. The constraints are the restrictions of the values that are acceptable for the decision variables.

Mathematical optimization models can be classified in terms of the nature of the objective function and the nature of the constraint. Special forms of the objective functions and the constraints give rise to specialized algorithms that are more efficient. From this point of view, there are four types of optimization problem (Hillier and Lieberman, 2005):

1. Linear programming model. When an objective function is linear in the variables and all constraints are also linear.
2. Nonlinear programming model. When an objective function is an arbitrary nonlinear function of the decision variables, and the constraints can be linear or nonlinear.
3. Quadratic programming model. When an objective function is quadratic in the variables and all constraints are linear.
4. Unconstrained optimization. When an objective function can be of any kind (linear or nonlinear) and there are no constraints.

In addition, in the linear programming model, the problem is called mixed integer programming (MIP) if some of the variables must take on integer values.

Linear programming is the most popular and commonly applied optimization algorithm. For this type of model, there are many readily available computer programs which can be used to find their solutions (OPL Studio, Gams and GLPK). These programs are very powerful, and unlike many other optimization methods, they can be applied successfully to very large optimization problems.

Several works have been done in order to apply optimization techniques for forest operation planning (Epstein et al., 2007). For instance, Karlsson et al. (2004) proposed a model based on mixed-integer linear programs. Also, Maness and Adams (1993) proposed a model integrating the bucking and sawing processes using a mixed integer program. Eriksson et al. (1989) designed a supply chain mathematically with a linear programming model. Cea and Jofre (2000), Olsson (2004), Henningsson et al. (2007) are some examples of forestry planning and modeling by using mathematical optimization.

2.2.3.2 Simulation

Simulation is a set of techniques used to generate (and experiment with) numerical models using a computer. Simulation imitates operations or processes of a system or real-world facilities in order to analyze them. Thus, these techniques provide a way to describe complex relations among components of a system (Law, 2007).

Simulation software is the obvious tool in numerous industries. Since forest supply chain planning is a complex process, simulation software has proven to be a helpful tool dealing with this complexity.

Simulators can be classified in two main categories, namely deterministic or stochastic. Deterministic simulations do not have a degree of randomness and mostly contain equations with no random variables. On the other hand, in stochastic simulation, probability distributions are used to estimate the uncertainty of events which include random variables (Ballou, 2004). For a problem which includes stochastic elements such as demand and price, stochastic simulation should be chosen rather than a deterministic simulation.

In addition, Kleijnen tried to classify supply chain simulation into four main categories as written bellow (Kleijnen, 2005):

1- Spreadsheet simulation
2- Systems dynamics
3- Discrete-event dynamic system (DEDS) simulation
4- Business games, such as wood supply game (Van Horne and Marier, 2005).

In the forest products industry, a great amount of research has been done on modeling supply chain using simulation (Reeb and Leavengood, 2003). For instance, Reeb and Massey (1996) developed a deterministic simulation model for examining the financial feasibility of producing different proprietary grades. And Gatchell et al. (1999) developed a deterministic simulator for examining processing scenarios in rough mills. Moreover, Howard (1988) used a deterministic simulation model to estimate costs and profits for sawmill production.

Moreover, some simulation tools have been developed while integrated with some optimization tools (Lendermann et al., 2001), (Baumgaertel and John 2003).

Over the years, many software planning tools have been created in Canada, such as SYLVA II (Quebec Ministry of Natural Resources and Wildlife), HSG Wood Supply (Moore et Lockwood 1990), FOREXPERT (Laliberté et Lussier 1997), Woodstock-Stanley (Remsoft Inc., 1996), GISFORMAN (Baskent et Jordan 1991), GIS-Complan (Olympic Resource Management Ltd), Strategic Forest Management Model (SFMM) (Davis, 1999), Patchworks (Spatial Planning Systems) et WPPT (Valéria et al., 2003).

FPInnovations Research Center developed two softwares which allow modeling and simulating the activities related to the consumption of wood namely *FPInterface* and *Optitek*.

2.2.4 FPInnovations tools

FPInnovations is one of the world's largest private, not-for-profit forest research institute, which carries out scientific research and technology transfer for the Canadian forest industry. FPInnovations' research programs focus on harvesting, transportation and roads, wood products, pulp and paper production, silvicultural operations and wild land fire operations in order to develop the knowledge and technology to conduct quality operations (FPInnovations, 2012).

To help the Canadian forest industry in different aspects of their operations, FPInnovations developed several tools and software such as *FPInterface* and *Optitek* which will be explained in more detail in following sections.

2.2.4.1 FPInterface

FPInterface is a platform performing simulations of forest operations. It models the forest supply chain, harvest areas and wood inventories, as well as harvesting and transportation systems. This software also predicts the productivity, costs and value of delivered products to customers directly on the forest map (FPInnovations, 2008).

This tool provides a variety of controls which enable the user to determine the resolution and details of the simulation. FPInterface calculates costs and net value for each harvest area, based on forest inventory data, the desired production systems and harvesting methods. Several scenarios can be created by modifying simulation parameters.

FPInterface includes several components that users can activate to evaluate a given scenario. These components are Harvest Planning, BiOS, Value Chain, MaxTour and Reforestation (FPSUITE, 2012).

The *Harvest planning* module is designed for determining the sequence of harvesting operations and visualizing periodic wood flow in harvesting areas. Also, it can assign harvesting teams to harvesting areas.

The *BiOS* module is developed to approximate the cost of forest biomass. It can be used to evaluate the feasibility of recovering forest biomass for a specific harvesting area.

The *Value Chain* module is another component of FPInterfac which simulates the supply chain in order to determine the costs and income that will be generated by a harvesting area. It can plan several forest operations according to market demand and also calculate the value for a specific scenario.

MaxTour is a module that allows user to manage and control transport activities more efficiently.

The *Reforestation* module can model each of the reforestation activities and estimate the costs of the silvicultural operations. It can be used for different types of silvicultural operations such as regeneration, young stand maintenance and management preparation areas to predict the operation's costs.

FPInterface provides comprehensive simulation reports which may include the characteristics of logs, costs, net value, product flows, transportation, carbon budgets and thematic maps showing the quantities of obtained products. Therefore FPInterface computes costs associated to supplying a mill from a given harvesting area and identifies which type of log would be obtained using different harvesting systems. Users can visualize data through a map, which makes interpreting results easier (Figure 9).

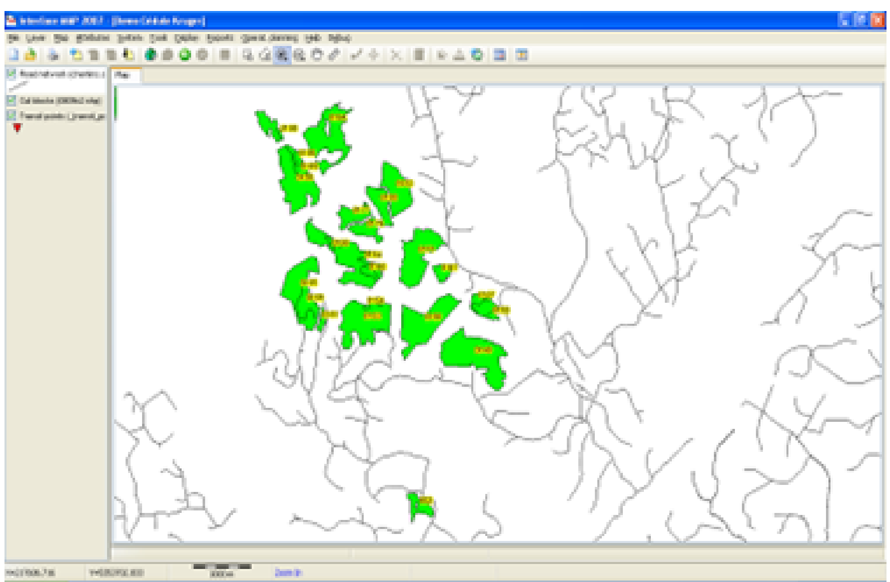

Figure 9 : FPInterface software (FPInnovations, 2012)

Figure 10 shows a simple example of planning in FPInterface by decision maker. In this case, the decision maker proposes three scenarios by selecting specific parameters. These parameters may include: harvest area, harvest mode, types of log, mills locations. Then, the simulation results associated to these scenarios will be analyzed by the user.

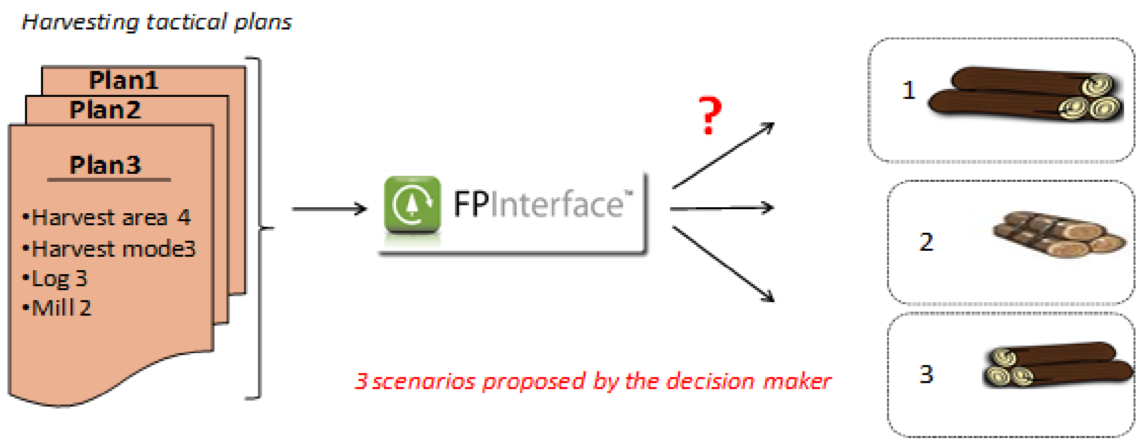

Figure 10 : Simulation decision-making process

Figure 10 : Simulation decision-making process

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2.2.4.2 Optitek

Optitek (Figure 11) is a simulator for sawmill operations. Since 1994, this simulator has been used across Canada. Optitek is able to simulate all operations in softwood conversion mill, including bucking and trimming (Goulet, 2007). Using this simulator, each machine in the production line and each line can be modeled through different modules (Goulet, 2006). Optitek can also increase the economic profitability of the sawing process.

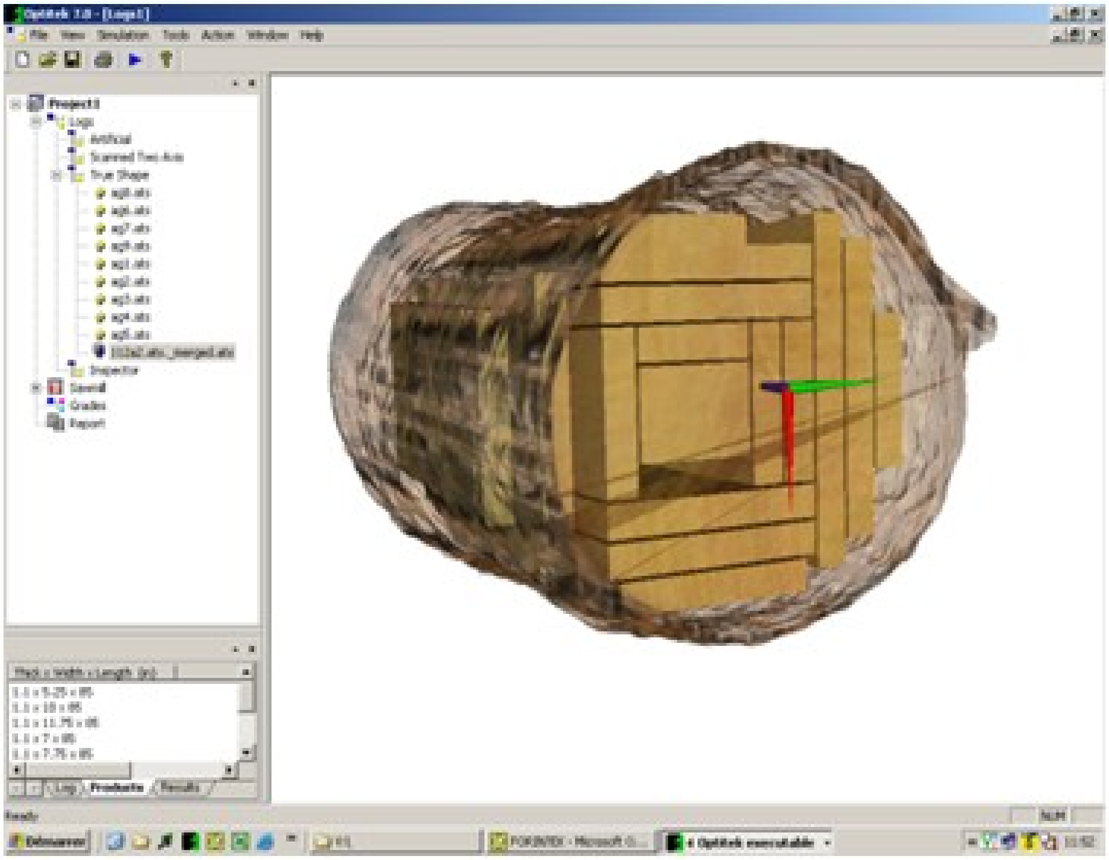

Figure 11 : Optitek simulator (FPInnovations)

When a log description and a model of the mill are provided, Optitek can forecast the lumber production which would be obtained from the mill (Hebert et al., 2000). In other words, this tool can compute the performance of any given configuration of sawmill (Zhang et al., 2005). Therefore, Optitek allows the user to analyze accurately the effect of sawing process changes on the volume and value of finished products.

Figure 12 : Mobile scanner

To simulate a lumber sawing process using Optitek, the characteristics of forest products (the diameter and shape of logs) should be known. There are two ways to obtain these features (Forintek, 1994):

1- Scanning the shape of logs using a mobile scanner (Figure 12). The scanner records the profiles of logs in a 3D format (Figure 13).
2- Manual measurement of diameters along the logs using a caliper.

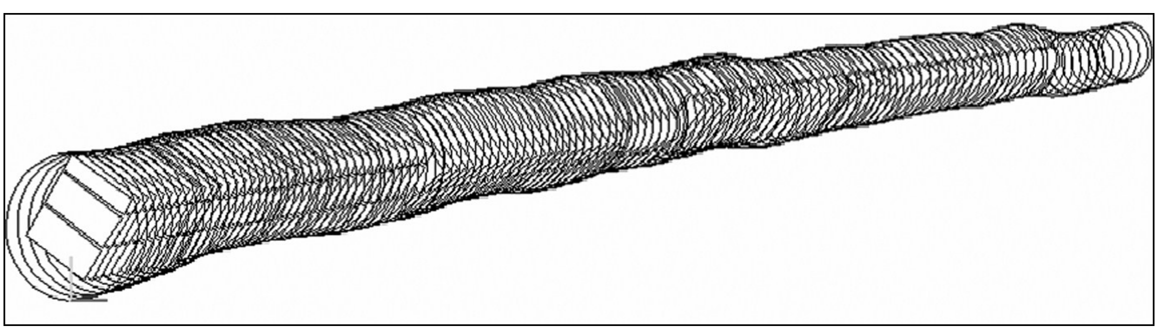

Figure 13 : A real-shape stem used in the real stud sawmill for lumber volume recovery (Liu et al., 2007)

Furthermore, Optitek can be used as a tool to provide performance indicators to help forest managers in their decision-making. Thus, Optitek assigns for each sawmill and product a monetary value which reflects the market. Depending on the objectives of the study, one can use specific selling prices for each mill or the average prices of last year (Forintek, 1994).

FPInnovations has a database of over 5000 logs covering the main commercial species of softwood and hardwood in eastern Canada (Quebec, Ontario and New Brunswick). For each harvesting area, it is possible to associate the features of the logs to FPInnovations database by knowing their distribution function of diameters and heights.

2.2.4.3 FPInterface-Optitek Integration

The simulation of a whole lumber supply chain may be achieved by connecting FPInterface and Optitek. FPInterface-Optitek system simulates the entire supply chain and evaluates plans (or scenarios). It allows the user to asses the economic value generated by a harvesting area allocated to a mill.

In other words, the combination of both applications allows anticipating the economic value generated by a harvesting area allocated to a mill. It therefore helps the manager to establish a reasonable plan for the whole supply chain. As shown on Figure 14, using forest data, harvesting costs, inventories data, transportation data, mills cost and revenues, FPInterface models the lumber supply chain, then it is possible to create and evaluate various scenarios (but these scenarios need to be established manually).

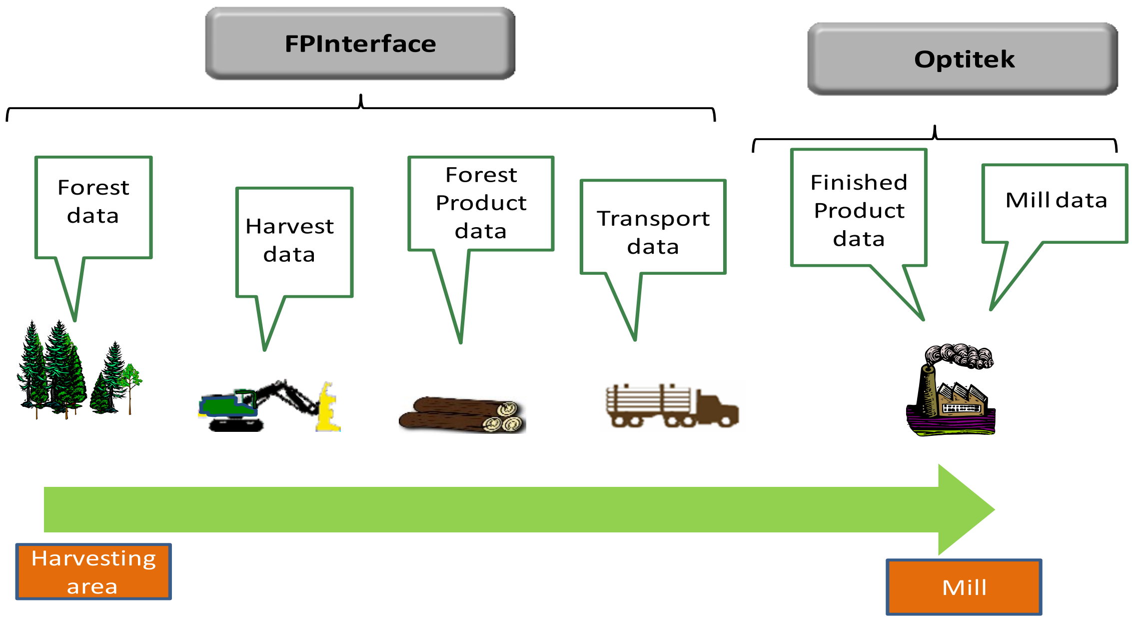

Figure 14 : FPInterfac-Optitek data

A simple example of planning in FPInterface-Optitek system by decision maker is shown in Figure 15. Three different scenarios are proposed by the user by selecting specific parameters. These parameters may include: harvest area, harvest mode, types of log, mills and etc. P1, P2 and P3 are three types of finished product of the mills. Then, the simulation results of all scenarios will be compared in order to select the best result.

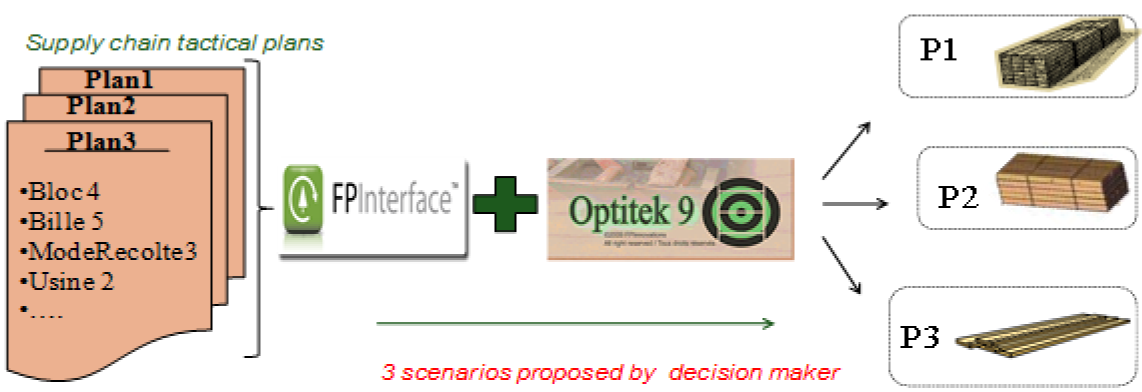

Figure 15 : FPInterfac-Optitek system process

Chapter 3. Integrating optimization and simulation for supply chain tactical planning in the forest products industry

As has been discussed in detail in Section 2.2.4, FPInterface can compute harvesting costs and transportation costs (supply costs) and Optitek can compute processing cost and revenues. Therefore, the combination of FPInterface and Optitek simulates the entire supply chain, evaluates a feasible plan and allows the user to assess the economic value generated by a harvesting area allocated to a mill. However, this system has several limitations which are described in the following:

1- The user must specify a plan manually.

2- It is possible to evaluate only a single plan per simulation.

3- In this system, developing a scenario is based on experience and intuition of decision maker. It should be noted that, numerous alternatives exist to create a scenario in this system.

4- Reconfiguring the system can be quite long and trying all possible solutions is impossible in practice.

5- Decision maker may neglect certain solutions, because they do not seem to have enough potential, while in reality it would have been a good choice.

6- There is no indication of the gap in revenue that separates the plan from what would be the optimal solution.

7- It is also very difficult to assess the impact of a change (real or potential) that may occur in the network (e.g. shut down of a mill).

Having revealed the limitations of the FPInterface-Optitek system, the main objective of this research was finding a way to overcome these limitations and improve the decision making process to achieve an optimal solution, which is explained in next section.

3.1 Proposed optimization-simulation integration

Regarding the limitations of FPInterfac-Optitek system, an optimization module, called *LogiOpt*, is proposed to be added to the integrated FPInterface-Optitek system. *LogiOpt* is made of a mathematical model and a database. The database is used to communicate between the simulators and the optimization module.

Figure 16 shows a schematic of proposed interconnections between the simulation tools and optimization module and data flow between them. All the possible "elementary operations" that can be included into a plan are simulated individually. Forest data and the result of harvesting simulation from FPInterface, and the result of sawing simulation and revenue from Optitek, are fed into the optimization module, which generates an optimal tactical plan. Finally, the plan will be returned to FPInterface to be then displayed to the user. The parameters in Figure 16 are explained in more detail in Section 3.2.

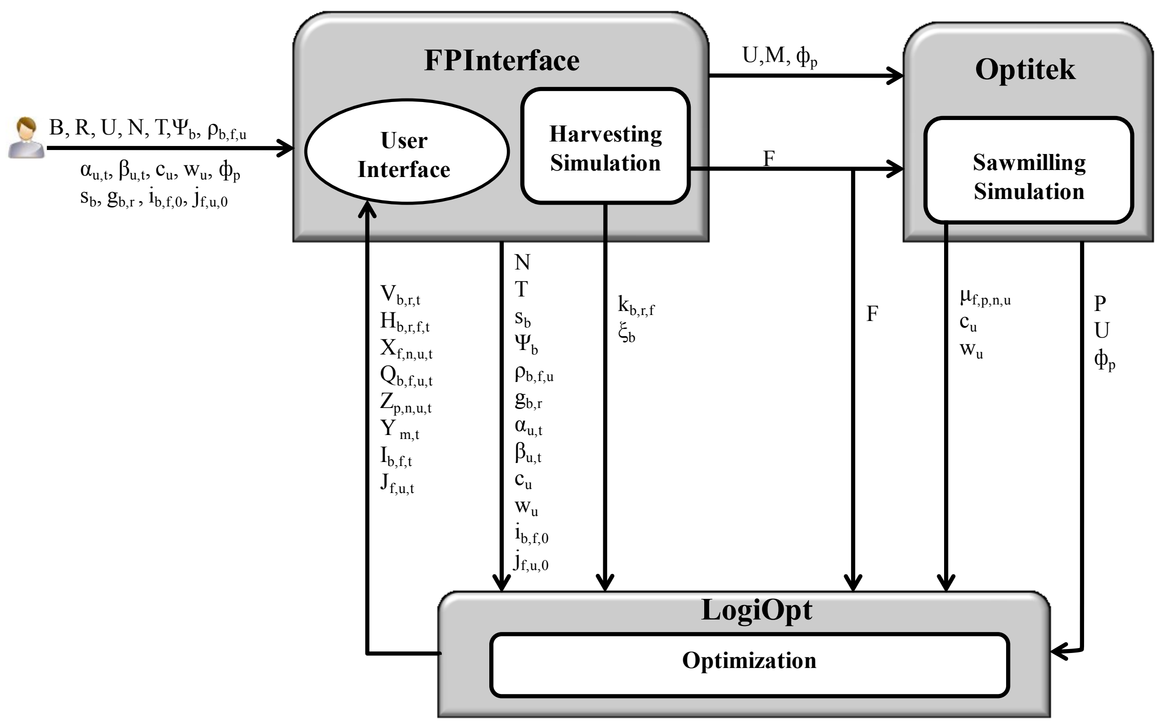

Figure 16 : Integration of simulators and optimization module

Consequently, *LogiOpt* can evaluate all possible and permitted scenarios (valid combinations of the “elementary operations”) and compute the optimal solution. One of the most powerful features of the optimization module is its ability to consider hundreds of thousands of possibilities and determine the optimal decision in a very short period of time.

LogiOpt models and plans the entire lumber production supply chain. It evaluates automatically all possible scenarios in order to determine optimal plan. It is also possible to evaluate the impact of modifying a mill capacity more easily. The tactical plan can be quickly readjusted and the manager can see how the rest of the supply chain should adapt in order to take advantage of these changes. Table 2 shows the advantages of proposed system versus the limitations of the original FPInterface-Optitek system.

Table 2 : Advantages of the proposed system versus limitations of the original system

Limitations	Advantages
In the original system, decision making process is done using a trial and error approach.	In *LogiOpt,* decision making process is based on mathematical optimization.
The user must specify a plan manually and it is only possible to evaluate a single plan per simulation.	*LogiOpt* can evaluate automatically all possible scenarios in order to determine optimal plan.
Reconfiguration of the system can be quite long and trying all possible solutions impossible in practice.	In order to determine optimal plan, this module will evaluate all possible and permitted scenarios.
Decision maker may neglect certain solutions, because they do not seem to have enough potential, while in reality it would have been a good choice.	Optimal plan is chosen according to data obtained from the logistics network (all permitted scenarios are considered)
There is no indication of the gap in revenue that separates the plan from what would be the optimal solution.	The decision maker can evaluate their own tactical plans in comparison with the optimal solution
It is also very difficult to assess the impact of a change (real or potential) that may occur in the network.	The tactical plan can be quickly modified and the manager can see the impact of change in supply chain configuration.

3.2 Mathematical model

A mathematical model describes the behavior of a system in the real world using mathematical equations. Mathematical models are used to solve planning and decision-making problems.

In this section, the mathematical model of LogiOpt is presented. It is a mixed-integer programming (MIP) model. A MIP model is one where some of the decision variables are constrained to have only integer values (i.e. whole numbers such as -1, 0, 1, 2, etc.) at the optimal solution. Also, the model has binary integer variables which are used to model yes/no decisions. Since a mixed-integer program has a linear function subject and linear constraints, MIP is referred as a special type of LP.

In the following sections, data sets are introduced first, followed by parameters and variables used to express the model. Finally the model formulation is described. It should be noted that to develop this model, the specific requirements of FPInnovations tools were taken into account. For example, for each finished product from a specific harvest area, harvesting methods and the transformation mill should be known.

3.3 Sets, parameters and variables

Sets

B Harvest areas (***b*** ϵ **B**)

R Harvesting systems (***r*** ϵ **R**)

F Log types (***f*** ϵ **F**)

P Product (lumber) (***p*** ϵ **P**)

U Mills (***u*** ϵ **U**)

N Sawmilling modes n :{ 1,…, N}

T Periods **t**=1,…,T

Parameters

s_b The total volume (m^3) of wood (*initial volume*) which can be extracted from harvest area *b*. The initial volume indicates the available volume of row material (wood) that can be harvested from a specific harvesting area. This parameter is calculated in terms of cube metres unit.

$k_{b,r,f}$ The generated volume (m^3) of log *f* by using harvesting systems *r* in harvest area *b* is the ratio of harvesting for a specific volume of log, a proportion of initial volume will be transformed into logs.

ξ_b The value of indirect sales (in \$) of harvesting area *b* using harvesting system *r*. *Indirect sales* correspond to products that are sold to third parties which do not need to be transported to a sawmill in our supply chain.

ψ_b *Harvesting Fixed Cost* associated with harvest area *b* in the planning horizon, which is completely independent on the harvested volume. Fixed costs refer to costs that do not change with the activity level of the facility.

$g_{b,r}$ Harvesting variable costs that are generated by a unit of harvested volume (m^3) of log in a harvest area b using harvesting system r, this type of cost directly depends on the harvested volume.

$\rho_{b,f,u}$ Transportation cost of a unit volume (m^3) of a product between harvest area *f* and mill *u*. this cost includes variable costs which are obtained from transportation simulation in FPInterface.

$\mu_{f,p,n,u}$ The products quantity *p* produced by mill *u* which is in sawmilling mode *n* and consumes product *f*. This is the ratio of production where for a specific volume of consumed log, a proportion of volume will be transformed into finished product.

$\alpha_{u,t}$ The maximum volume (M^3) consumed by the mill *u* (representing a production capacity) at period *t*. It is the maximum capacity of log volume (M^3) that can be used by the mill to produce the finished products.

$\beta_{u,t}$ The maximum capacity [in Foot Board Measure (FBM)] consumed by the mill *u* in period *t*. This capacity gives the maximum number of units of (FBM) volume that can be generated by the mill.

c_u Sawmilling *fixed cost* of the mill *u*. Fixed costs are those costs which do not vary with the amount of production. Sawmill fixed costs typically include insurance, licenses, leases, property taxes, etc.

w_u Sawmilling variable costs of operation of the mill *u* (per m^3). It depends mainly on labor and the use of mill machinery and equipment.

Φ_p Incomes for a unit of finished product *p.* This is the price of each unit of finished products.

$i_{b,f,0}$ The quantity of logs *f* which is available along the road of harvest area *b* at the beginning of the planning horizon.

$j_{f,u,0}$ The quantity of harvested logs *f* which is in stock at the mill *u* at the beginning of the planning horizon.

It should be noted that, the board-foot is a specialized unit of measure for the volume of lumber in the United States and Canada. It is the volume of a one-foot length of a board, one foot wide and one inch thick. Board-foot can be abbreviated FBM (for "foot, board measure"), and thousand board-feet can be abbreviated as MFBM.

Also, it worth mentioning that the fixed costs do not depend on the mill production. They are related to costs imposed on the mill even if the mill does not work for some days. And the variable cost depends on the production process.

Decision variables

Each group of variables is actually a matrix of values of adjustable dimensions defined by its indices. For example, for the group ($H_{b,r,f,t}$), the number of variables is defined by the name of harvesting area (b),the number of harvesting mode (r), the type of log (f) and number of periods (t). A total of eight groups of variables were created.

$V_{b,r,t}$ The total volume (m^3) harvested from area *b* using harvesting system *r* in period *t*. This variable represents the harvested volume from initial volume of a harvesting area.

$H_{b,r,f,t}$ The volume of the logs *f* (m^3) obtained from harvest area *b* using system *r* in period *t*. This variable determines the quantity of different types of forest products (log) which will be obtained from each harvesting area.

$X_{f,n,u,t}$ The volume of logs *f* (m^3) consumed by the mill *u* (configured in mode *n*) during period *t*.

$Q_{b,f,u,t}$ The volume of log *f* transported between harvest area *b* and mill *u* in period *t*. This variable defines the amount transported from a harvest area to mill for each type of logs which is presented with specific combinations of harvesting area and harvesting mode.

$Z_{p,n,u,t}$ The quantity of lumber *p* manufactured by mill *u* configured in mode *n* during period *t*. This variable determines the quantity of finished product in (FBM) which will be obtained from each mill.

$I_{b,f,t}$ The quantity of logs *f* harvested in stock at harvesting area *b* at the end of period *t*. The quantity of this variable may be used as a volume of logs transported to the mill.

$J_{f,u,t}$ The quantity of logs *f* harvested using system *r* in stock at mill *u* at the end of period *t*. The quantity of this variable may be used as a volume of logs consumed by the mill.

$Y_{m,t}$ The binary variable takes the value 1 when the mill *u* is configured as sawmilling modes *m* :{ 1… M} at the period *t*, 0 otherwise. This variable can only one the value of 0 or 1. This variable may respects the selection of an sawmilling mode.

3.4 Objective function

The objective function is to maximize profit by taking into account sales, transportation costs, harvest costs and mills costs. The harvesting fixed costs and sawmilling fixed costs have been taken into account only in order to calculate the net value of the supply chain.

$$\text{Maximize}: \quad [\sum_{b\in B} \sum_{r\in R} \sum_{t\in\{1,\dots,T\}} V_{b,r,t} \times \xi_b] - \sum_{b\in B} \psi_b$$

$$+ [\sum_{p\in P} \sum_{n\in N} \sum_{u\in U} \sum_{t\in\{1,\dots,T\}} Z_{p,n,u,t} \times \Phi_p]$$

$$- [\sum_{b\in B} \sum_{r\in R} \sum_{t\in\{1,\dots,T\}} V_{b,r,t} \times g_{b,r}]$$

$$- [\sum_{b\in B} \sum_{f\in F} \sum_{u\in U} \sum_{t\in\{1,\dots,T\}} Q_{b,f,u,t} \times \rho_{b,f,u}]$$

$$- [\sum_{f\in F} \sum_{n\in N} \sum_{u\in U} \sum_{t\in\{1,\dots,T\}} X_{f,n,u,t} \times w_u] - \sum_{u\in U} c_u$$

To explain in more detail, the objective function is presented in two main parts. The first term represents revenues which include harvest revenue and mill revenue.

Harvest revenue:

$$\sum_{b\in B} \sum_{r\in R} \sum_{t\in\{1,\dots,T\}} V_{b,r,t} \times \xi_b$$

In this part of objective function, revenue from all harvesting areas will be calculated, where $V_{b,r,t}$ is total volume harvested and ξ_b is indirect sale of a harvesting area.

Mill revenue:

$$\sum_{p\in P} \sum_{n\in N} \sum_{u\in U} \sum_{t\in\{1,\dots,T\}} Z_{p,n,u,t} \times \Phi_p$$

This equation allows the calculation of mill revenue, where $Z_{p,n,u,t}$ is quantity of obtained lumber (finished products) and Φ_p is sale price for each unit of finished products.

The second part of the objective function represents costs which include harvest cost, transportation costs and sawing costs.

Harvesting costs:

$$\sum_{b\in B}\sum_{r\in R}\sum_{t\in\{1,\ldots,T\}} V_{b,r,t} \times g_{b,r}$$

In this equation using total harvested volume ($V_{b,r,t}$) and harvesting variable costs ($g_{b,r}$) , total harvesting variable cost will be determined. The following equation presents the sum of harvesting fixed cost, where ψ_b is harvesting fixed cost associated with each harvesting area.

$$\sum_{b\in B}\psi_b$$

Transportation costs:

$$\sum_{b\in B}\sum_{f\in F}\sum_{u\in U}\sum_{t\in\{1,\ldots,T\}} Q_{b,f,u,t} \times \rho_{b,f,u}$$

Also, this equation computes sum of transport cost in this supply chain, where $Q_{b,f,u,t}$ is volume of transported logs and $\rho_{b,f,u}$ is transportation cost for each type of log.

Sawing cost:

$$\sum_{f\in F}\sum_{n\in N}\sum_{u\in U}\sum_{t\in\{1,\ldots,T\}} X_{f,n,u,t} \times w_u$$

The total variable cost of sawing operation for network will be calculated in this equation, where $X_{f,n,u,t}$ is volume of logs consumed by the mills and w_u is sawing variable costs for each mill. Also, the following equation can determine sum of sawing fixed cost, where c_u is sawing fixed cost associated with each mill.

$$\sum_{u\in U} c_u$$

3.5 Constraints

The constraints reflect relationships among decision variables and parameters that are imposed by the characteristics of the problem. These relationships can be the limitations that restrict the alternatives available to decision making. This model is composed of several constraints which are classified in different groups.

Maximum allowable harvest:

$$\sum_{r \in R} \sum_{t \in \{1,..,T\}} V_{b,r,t} \leq s_b \qquad \forall b \in B$$

This constraint sets the harvested volume to observe the maximum allowable volume. It is expressed as the available volume of wood in (m^3) for each harvesting area. In this constraint $V_{b,r,t}$ is total harvested volume but s_b is total initial volume for each harvesting area.

Harvested volumes:

$$H_{\mathrm{b,r,f,t}} = k_{\mathrm{b,r,f}} \times \mathrm{V}_{\mathrm{b,r,t}} \qquad \forall b \in B, \quad \forall r \in R$$

$$\forall f \in F, \quad \forall t = 1,\ldots,T$$

This constraint establishes a link between the harvested volumes and the quantity of each log type which will be available for transportation to the mill. In this equation, $\mathrm{H}_{\mathrm{b,r,f,t}}$ is the volume of the logs in (m^3) obtained from harvest area which is calculated from harvesting rate ($k_{b,r,f,t}$) and harvested volume ($V_{b,r,t}$).

Transported volumes:

$$\sum_{u \in U} Q_{b,f,u,t} \leq \sum H_{b,r,f,t} \qquad \forall b \in B, \ \forall f \in F, \ \forall t = 1,...,T$$

This constraint determines maximum volume of transported logs where $Q_{b,f,u,t}$ is volume of log transported in (M^3) and $H_{b,r,f,t}$ is the volume of the logs in (M^3) obtained from harvest area .

Sawmill capacity:

The three following constraints are used in the modeling of sawmill capacity:

$$\sum_{f \in F} \sum_{n \in N} X_{f,n,u,t} \leq \alpha_{u,t} \qquad \forall u \in U, \ \forall t = 1,...,T$$

The first constraint sets the capacity of the mill in terms of consumption where $\alpha_{u,t}$ is maximum production capacity of a mill in (M^3).

$$\sum_{p \in P} \sum_{n \in N} Z_{p,n,u,t} \leq \beta_{u,t} \qquad \forall u \in U, \forall t = 1,...,T$$

The second constraint determines this capacity in terms of production where $\beta_{u,t}$ is mill capacity in (FBM).

$$\sum_{p \in P} \sum_{n \in N} Z_{p,n,u,t} \leq \lambda_{u,t} \qquad \forall u \in U, \forall t = 1,...,T$$

The third constraint gives sawmill capacity in terms of production time where $\lambda_{u,t}$ is maximum number of production time (hours) available in a specific mill.

Two following constraints are used in the modeling of sawing operations.

$$\sum_{f \in F} X_{f,n,u,t} \times \mu_{f,p,n,u} = Z_{p,n,u,t} \qquad \forall n = 1,\ldots,N$$

$$\forall u \in U, \quad \forall p \in P$$

$$\forall t = 1,\ldots,T$$

This constraint sets the relationship between the consumed volume and the produced volume at the mill. This equation determines the quantity of finished product ($Z_{p,n,u,t}$) in (FBM) using sawing production rate ($\mu_{f,n,u,t}$) and consumed volume of logs ($X_{f,n,u,t}$) for each mill.

$$\sum_{n \in N} Y_{n,t} = 1 \qquad \forall n = 1,\ldots,N$$

$$\forall t = 1,\ldots,T$$

$$X_{f,n,u,t} \leq Y_{n,t} \times M \qquad \forall f \in F, \forall u \in U$$

$$\forall n = 1,\ldots,N$$

$$\forall t = 1,\ldots,T$$

Where M is a large positive number

These constraints ensure that a mill can be configured according to only one sawmilling mode. These constraints limit the choice to only one and only one sawing pattern to transform consumed log. The variable $Y_{n,t}$ is a binary variable and *M* is a large positive number.

Equilibrium flow (harvest area):

$$I_{b,f,1} = i_{b,f,0} + \sum_{r \in R} H_{b,r,f,1} - \sum_{u \in U} Q_{b,f,u,1} \qquad \forall b \in B, \quad \forall f \in F$$

$$I_{b,f,t} = I_{b,f,t-1} + \sum_{r \in R} H_{b,r,f,t} - \sum_{u \in U} Q_{b,f,u,t} \qquad \forall b \in B, \ \forall f \in F, \quad \forall t = 2,..,T$$

These two constraints calculate the inventory of harvest products for each harvest area. In the first equation by using the generated volume of logs ($H_{b,f,f,t}$) for each harvesting area, the volume of inventory ($i_{b,f,0}$) at the beginning of the planning horizon and transported volume of logs ($Q_{b,f,u,1}$), the inventory of logs ($I_{b,f,1}$) relating to each harvesting area at the first period of planning is obtained. And in the second equation the inventory of logs for each harvesting area is similarly obtained at the other period of planning.

Equilibrium flow (mill):

$$J_{f,u,1} = j_{f,u,0} + \sum_{b \in B} Q_{b,f,u,1} - \sum_{n \in N} X_{f,n,u,1} \qquad \forall f \in F, \qquad \forall u \in U$$

$$J_{f,u,t} = J_{f,u,t-1} + \sum_{b \in B} Q_{b,f,u,t} - \sum_{n \in N} X_{f,n,u,t} \qquad \forall f \in F, \quad \forall u \in U, \forall t = 2,..,T$$

Also, these constraints determine the inventory of logs at mill. The first one calculates this inventory at the end of the first period of the planning horizon where ($j_{f,u,0}$) is the volume of mill inventory at the beginning of the planning horizon, ($Q_{b,f,u,t}$) is transported volume of logs and ($X_{f,n,u,1}$) is the consumed volume of logs in the first period of planning. And in second equation the inventory of logs ($J_{f,u,t}$) for each mill is similarly obtained at the other period of planning.

Non-negativity constraint

$$V_{b,r,t} \geq 0 \qquad \forall b \in B,\ \ \forall r \in R,\ \ \forall t = 1,..,T$$

$$\mathrm{H}_{\mathrm{b,r,f,t}} \geq 0 \qquad \forall b \in B,\ \ \forall r \in R,\ \ \forall f \in F,\ \ \forall t = 1,..,T$$

$$X_{f,n,u,t} \geq 0 \qquad \forall f \in F,\ \ \forall n \in N,\ \ \forall u \in U,\ \ \forall t = 1,..,T$$

$$Q_{b,f,u,t} \geq 0 \qquad \forall b \in B,\ \ \forall f \in F,\ \ \forall u \in U,\ \ \forall t = 1,..,T$$

$$Z_{p,n,u,t} \geq 0 \qquad \forall p \in P,\ \ \forall n \in N,\ \ \forall u \in U,\ \ \forall t = 1,..,T$$

The five previously mentioned constraints limit value of their variables into non negative value.

Chapter 4. Experiments

In this chapter, the process we used for *model verification* and *model validation* is presented. The model was implemented in ILOG OPL Studio version 6.3. It was solved with CPLEX 12.1 using 2.5 GHz processor with 2 GB RAM.

4.1 Validation of the optimization model with a simplified case

The first step for verification was model reviewing by the different stakeholders during formal meetings. The goal was to evaluate whether or not the model describes the system accurately. Validation involves several tests. We used the common approach of checking whether the results fit with the expected results or not for a small model.

We first developed a small case study (see Figure 17). This case study allowed us to assess the validity of the concepts, parameters and elements of model with our research partners.

The simplified case study's network consists of two harvest areas (b_1, b_2) and two mills (u_1, u_2). The initial volumes of harvest areas are s_1 and s_2 respectively. The harvest areas have a single harvesting mode (r_1 and r_2, respectively). No log of type f_2 comes from b_2. The mill u_2 does not produce lumber of type p_2 and does not accept log (f_2). The optimization results were compared with expected results.

Afterwards, the model was expanded progressively (increasing number of harvesting areas, log types and finished products) ensuring the accuracy of the results at each step. Table 3 shows some scenarios tested to evaluate and anticipate our model for real world case.

Finally, as the last step to evaluate the model more precisely, the model was executed with the data which are more similar to industrial data with test case consisting of 264 harvest areas, 9 type of logs, 1 mill and 18 finished products. It was a simplified industrial case from FPInnovations.

It is noteworthy that to better evaluate and compare the optimization's results, the decisions variables were presented graphically in reports. A results example is presented in Figure 18. It shows the volumes of wood that are transported to a given mill, for each log type.

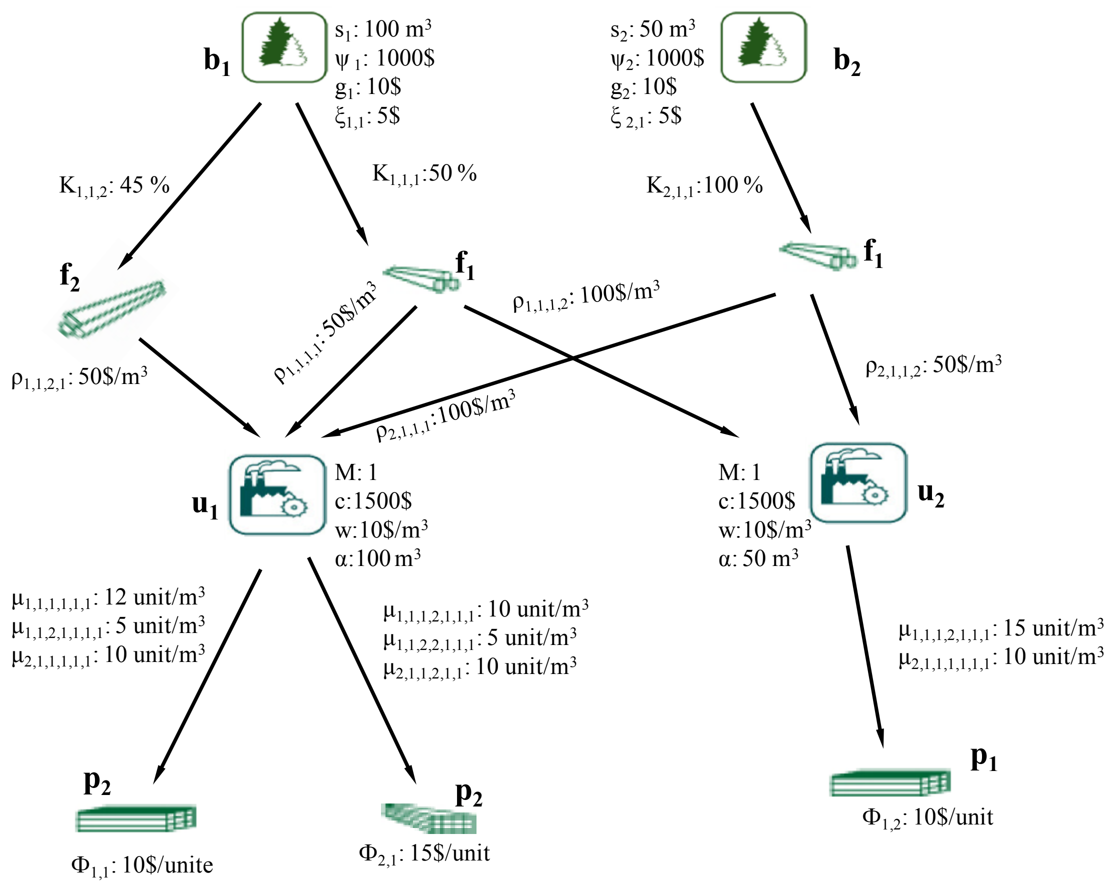

Figure 17: Simplified example of the forest product network

Table 3 : Some scenarios used for validation of the model

Scenarios	Number of harvesting areas	Type of logs	Number of mills	Finished product
Scenario 2	2	6	2	2
Scenario 3	8	6	2	6
Scenario 4	12	12	2	10
Scenario 5	18	12	2	10
Scenarios 6	24	12	2	20
Scenarios 7	264	9	1	18

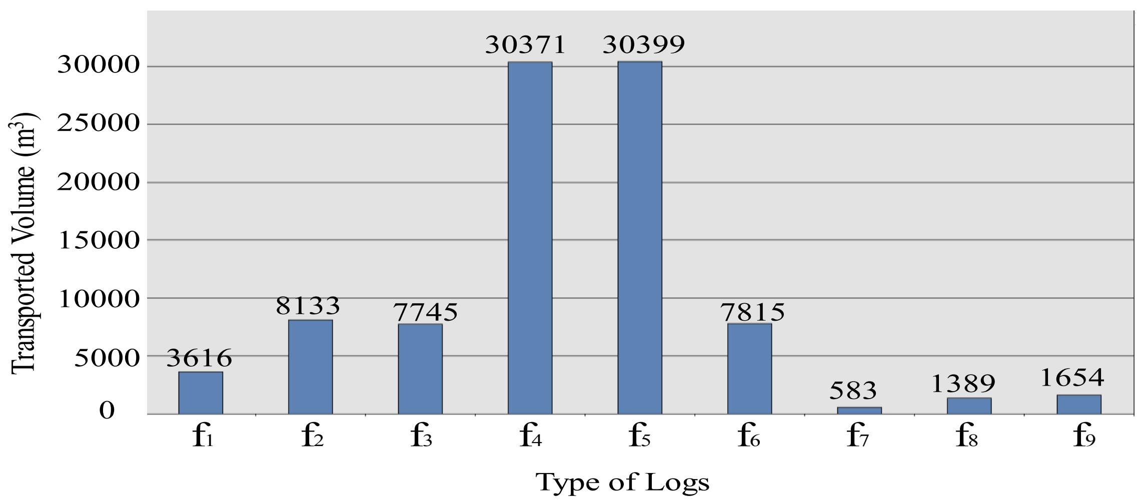

Figure 18 : The transported volume of logs for one mill

4.2 **Optimization / simulation system application: An industrial case**

In this section, an industrial case based on data from a large Canadian forest products company is presented. This case involves hundreds of harvest areas, three mills, dozens of log types and lumber products. First, the description of the case is provided (Section 4.2.1). Then, we show how we presented aggregated results to the user for the purpose of analysis (Section 4.2.2). Finally, we present a quantitative comparison of the plan produced by the model and the plans obtained using a heuristic similar to what human planners use in industry (Section 4.2.3).

4.2.1 Description of the industrial case

We developed a case study with industrial data provided by FPInnovations. This case allowed us to investigate the performance of our model in an industrial context. This industrial case involves 431 harvesting areas with total initial volume 1 394 771 (m^3), 2 harvesting modes, 209 log types, 3 mills and 160 finished products. We had access to data for one business year.

Some parameters and characteristics of this problem are presented in Table 4. For each harvesting area, depending on harvesting mode, a harvesting variable cost ($) and an inventory volume (m^3) has been provided. In addition, for each of 160 finished products, there is a specific market price ($). It should be noted that due to the confidentially reasons, the full data cannot be presented here.

Table 4 : Some characteristics of model

	Number	Volume (m^3)	Capacity (m^3)
Harvesting areas	341	1 504 870	-
Harvesting modes	2	-	-
Log types	209	-	-
Mills	3	-	1 075 000
Finished products	160	-	-

This problem was solved in less than two minutes with the same personal computer mentioned previously.

4.2.2 Providing the user with the optimal plan

In this section, we present some examples of charts we used to display solutions to the user for analysis purpose.

Figure 19 shows some harvesting areas along with the harvested volume. These are aggregated data related to variable $V_{b,r,t}$ (total volume harvested from area *b* using harvesting system *r* in period *t*).

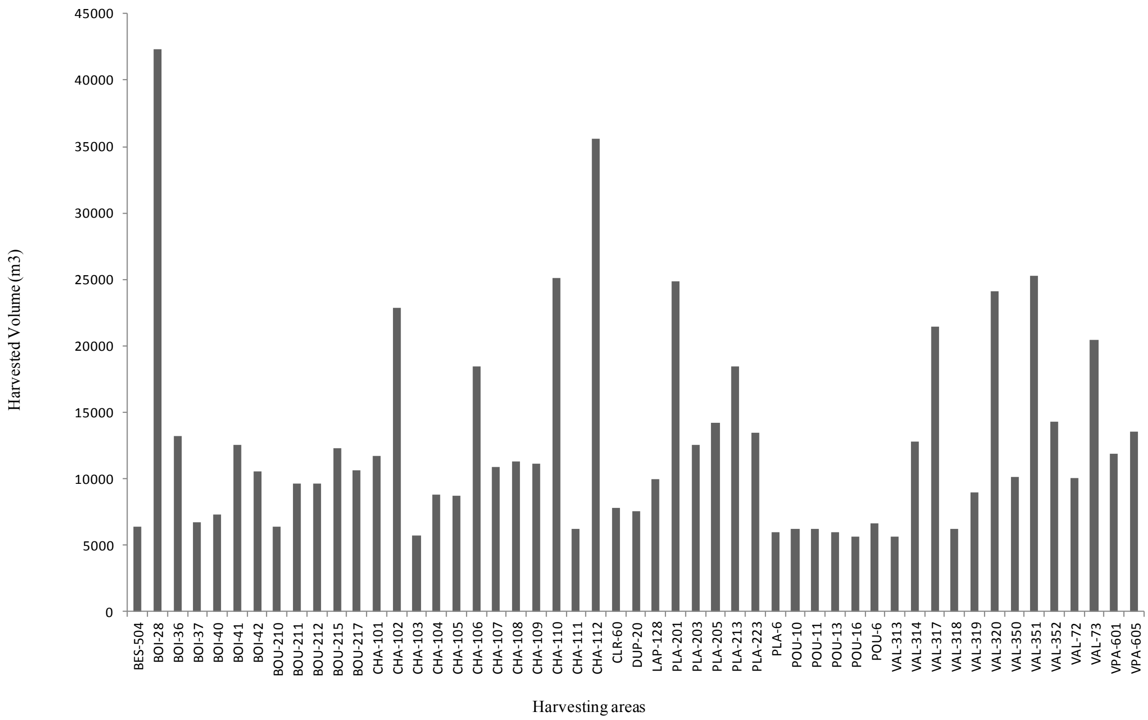

Figure 19 : Harvested volume (m^3) for selected harvesting areas

Figure 20 shows which type of logs are extracted from harvesting area. This shows aggregated data from variable $H_{b,r,f,t}$ (volume of logs *f* obtained from harvesting area *b* using system *r* in period *t*). The user can also visualize the results for each different harvesting area.

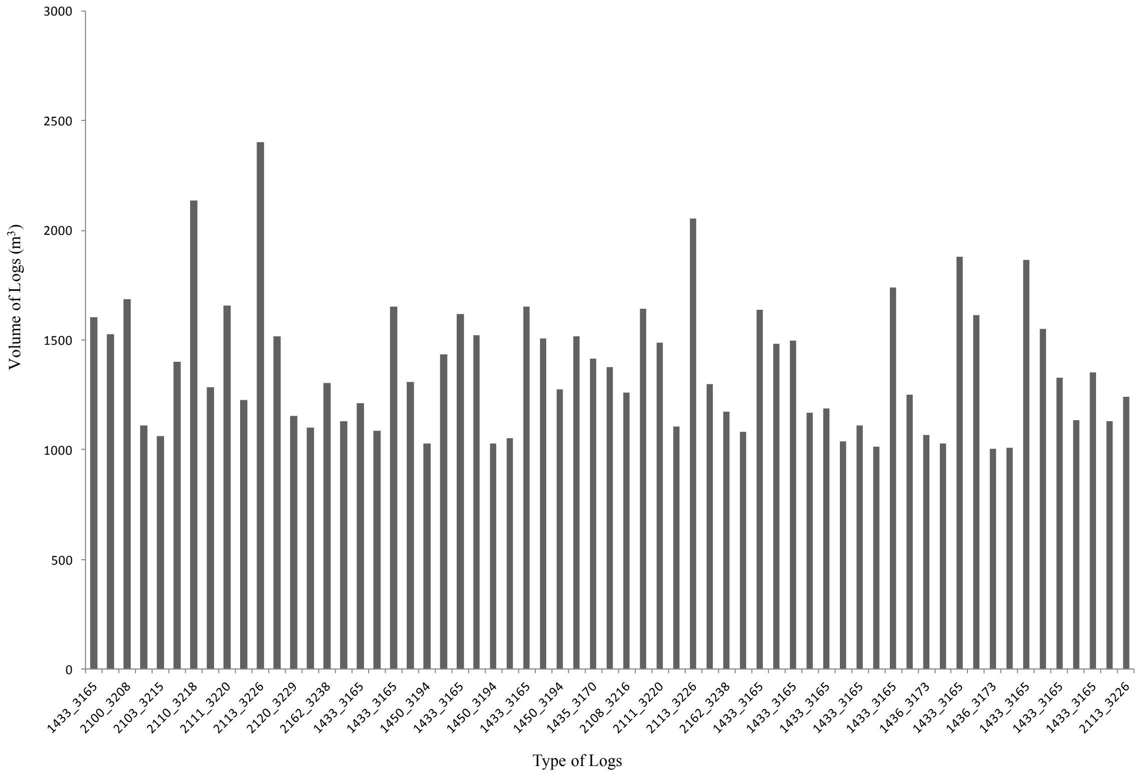

Figure 20 : Volume of the logs (m^3) obtained from all harvesting areas

Figure 21 shows the volumes of different types of log transported to a given mill. This comes from variable $Q_{b,f,u,t}$ (volume of log *f* transported between harvesting area *b* and mill *u* in period *t*).

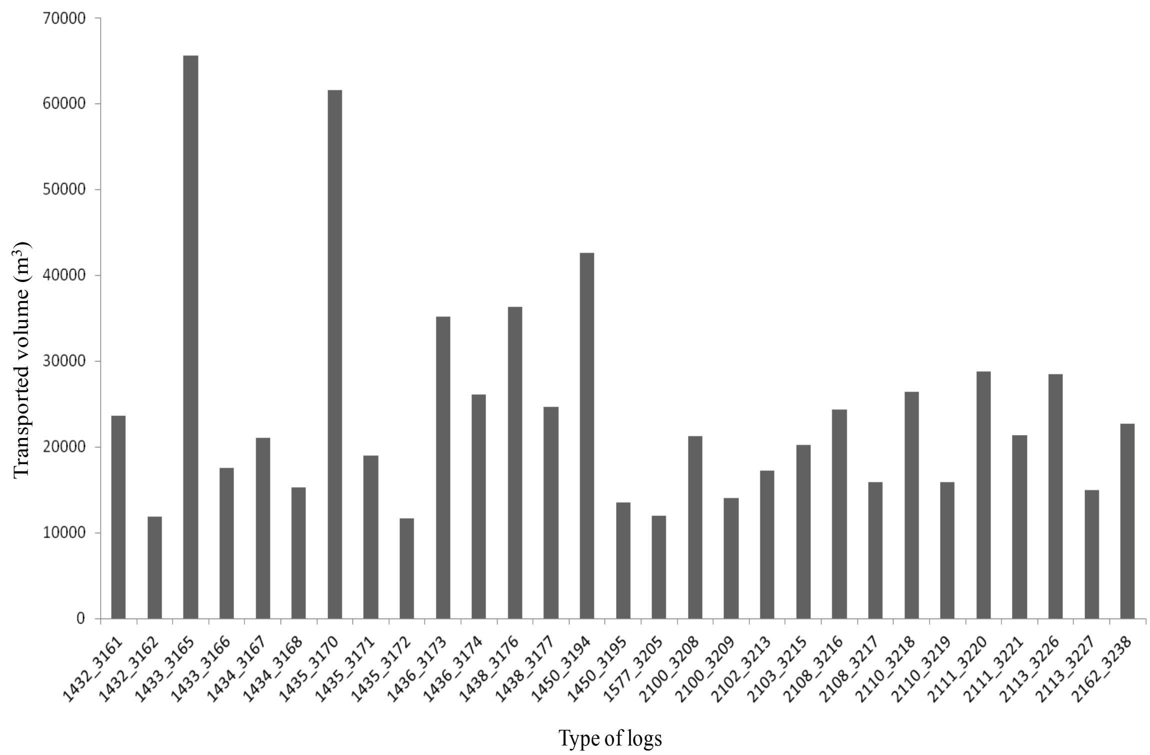

Figure 21 : The transported volume of the logs to one mill

Figure 22 shows which type of log is consumed by mills. This comes from variable $X_{f,n,u,t}$ (volume of log *f* consumed by the mill *u* configured in mode *n* during period *t*). Again, the user can configure the system to display aggregated or detailed results.

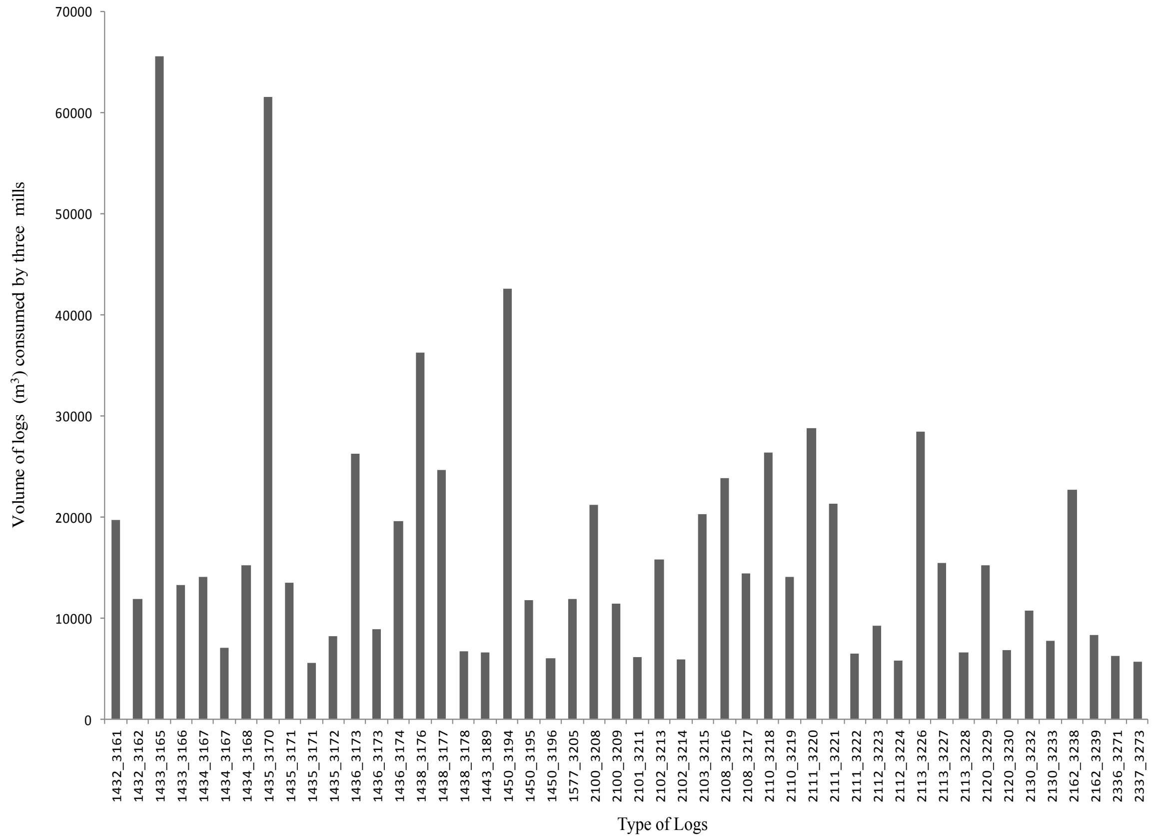

Figure 22 : The total volume of logs (m^3) consumed by three mills

Finally, charts like the one depicted in Figure 23 allow the user to see the quantity of lumber *p* manufactured by mill *u* configured in mode *n* during period *t* (variable $Z_{p,n,u,t}$).

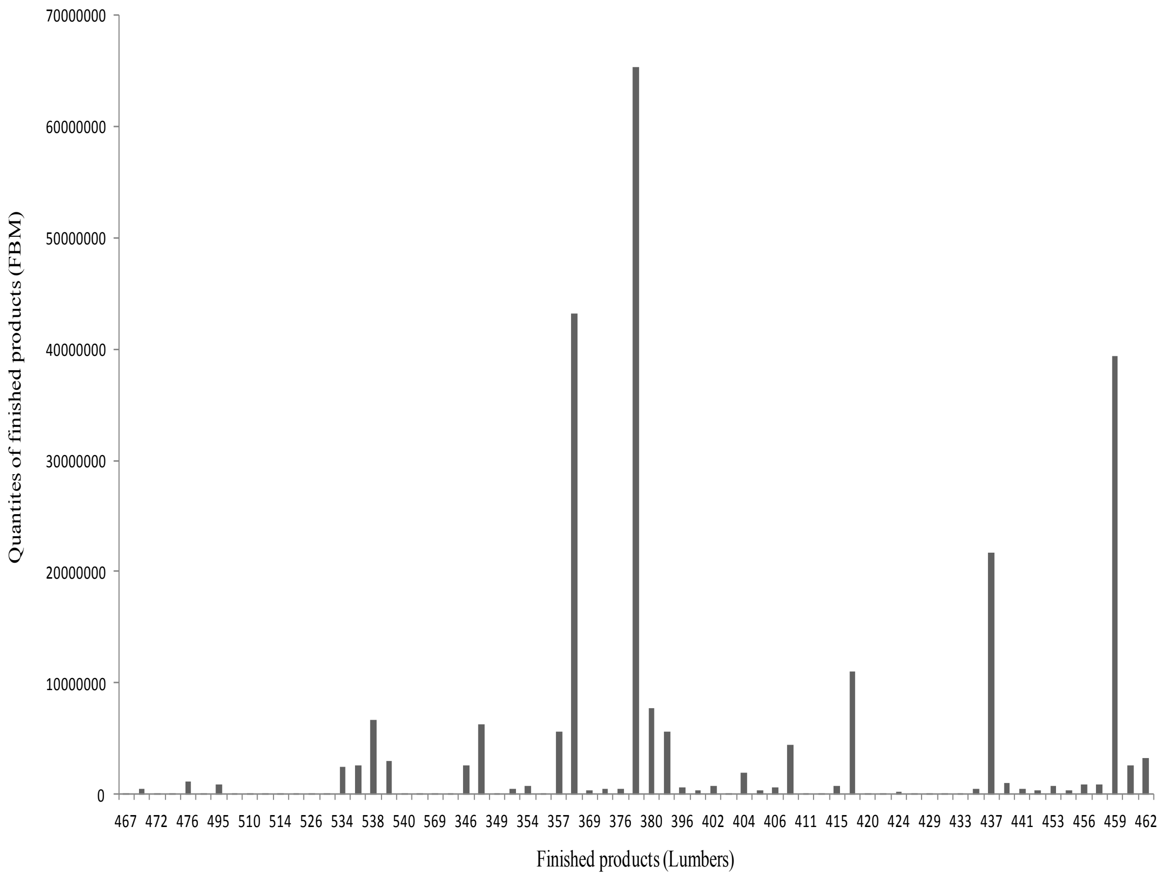

Figure 23 : Quantity of finished products manufactured by mills

4.2.3 Comparison with the plan obtained using a heuristic simulating manual planning

We compared the optimal solution obtained using our model with other solutions obtained using a heuristic simulating what a human planner could have performed.

In industry, traditional tactical planning is done by assigning a mill to its nearest harvesting areas. We developed a heuristic approach that emulates this. It goes as follows:

1- *Randomly select one mill.*

2- *Assign the nearest harvesting areas to the selected mill until maximum capacity of this mill is reached.*

3- *Select another mill and then go back to step #2.*

Since the total initial volume of harvesting areas is greater than the total capacity of the three mills, it will be necessary to ignore the remaining harvesting areas. Using this heuristic, we will obtain a different plan according to the sequence in which we select the mills. As we have three different mills (named B, L and T), there are six (3! = 6) different plans that can be generated according to the following mills sequence: BLT, BTL, TLB, TBL, LTB and LBT.

Finally, in industrial practice, only one harvesting mode is selected for a given forest. We generated plans for the two harvesting modes, but in the next section we present results only for the mode that provided the best results.

4.2.4 Results and discussion

In this section the heuristic plans are compared with the optimal results from *LogiOpt* in order to demonstrate the performance of our solution. Table 5 reports results for the six plans obtained using the heuristic and the solution obtained using *LogiOpt*.

As expected, the optimal plan is better than the result of the heuristic plans, because the heuristic only tries to minimize transportation costs and moreover applies a greedy scheme.

The first performance measure is the value of the objective function (profit). *LogiOpt* shows a 48% improvement in comparison with the best heuristic plans (Table 5 and Figure 24). This is achieved using a smaller volume of wood (Figure 25 and Table 5). This volume in *LogiOpt* is about 8% less than that of the best heuristic plan.

Moreover, the results show that the total volume of transported logs in *LogiOpt* is 7% less than that of the best heuristic plans (Figure 26 and Table 5).

Table 5 : Results for different performance measures (solutions obtained with the heuristic versus LogiOpt)

	Solutions obtained using the heuristic						Optimal solution (LogiOpt)	Improvement (in comparison with the best solution provide by the heuristic)
Profit ($)	5 928 458	6 377 837	5 928 458	5 935 826	6 377 837	6 349 317	13 079 711	↑ 48 %
Total Transported volume (m^3)	1 028 402	1 013 607	1 028 402	1 026 878	1 013 607	1 013 232	956 562	↓ 7%
Total harvested volume (m^3)	1 076 118	1 060 139	1 076 118	1 074 701	1 066 139	1 059 989	990 147	↓ 8%
Volume of produced finished product (FBM)	248 002 189	246 893 310	248 002 189	247 738 148	246 893 310	246 721 480	250 500 000	↑ 1%
Percentage of used mill capacity (FBM)	99%	98.5%	99%	98.9%	98.5%	98.5%	100%	↑ 1%

In *LogiOpt,* the total quantity of finished products is 1% more than this variable in the best heuristic plans (Figure 27 and Table 5). However, in heuristic plans, the differences between maximum and minimum transported volume and quantities of finished product are 3% and 0.5 % respectively.

In addition to this, (Figure 28 and Table 5), *LogiOpt* use 100% total mill capacity (FBM) while heuristic plans use 99% of these capacities.

Finally, comparing the results shows that the number of harvested areas in *LogiOpt* is about 40% less than in the best heuristic plan.

To conclude, the higher value of profits on the one hand, and the lower harvested volumes on the other hand, confirm the better performance of LogiOpt in comparison to the heuristics simulating manual planning.

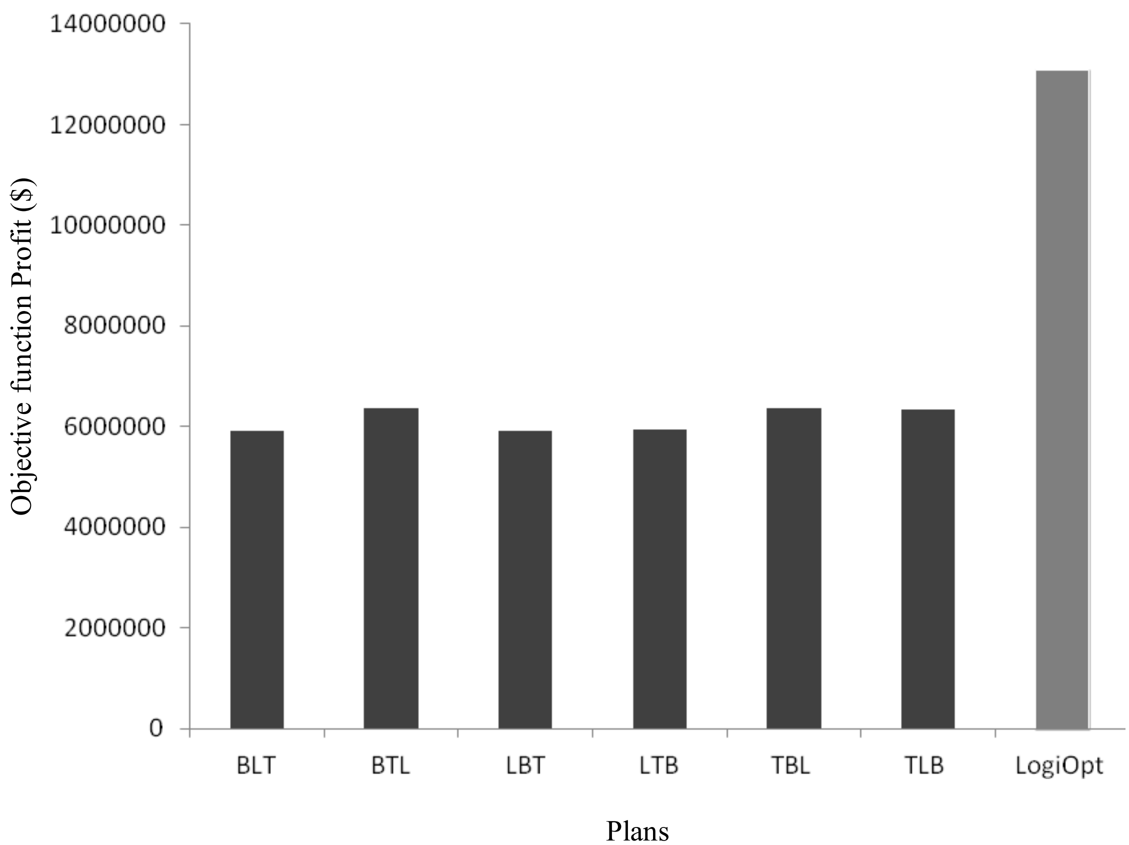

Figure 24 : Comparing the value of the objective function (profit) in different heuristic plans with LogiOpt

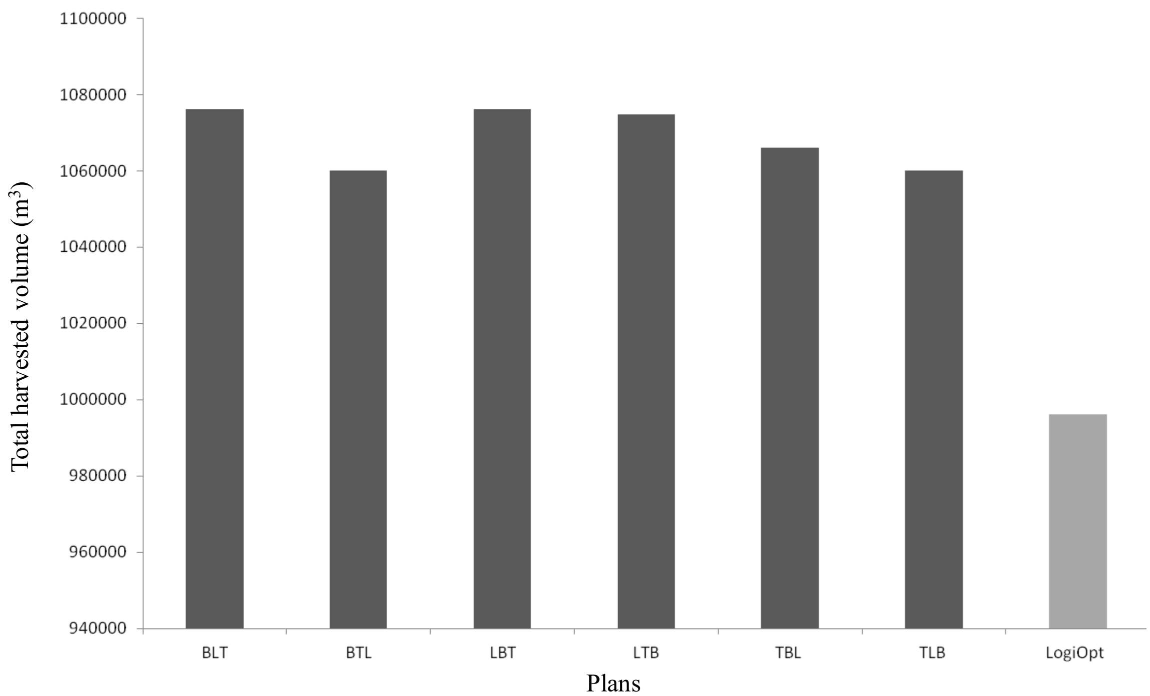

Figure 25 : Comparing the total volume harvested in different heuristic plans with LogiOpt

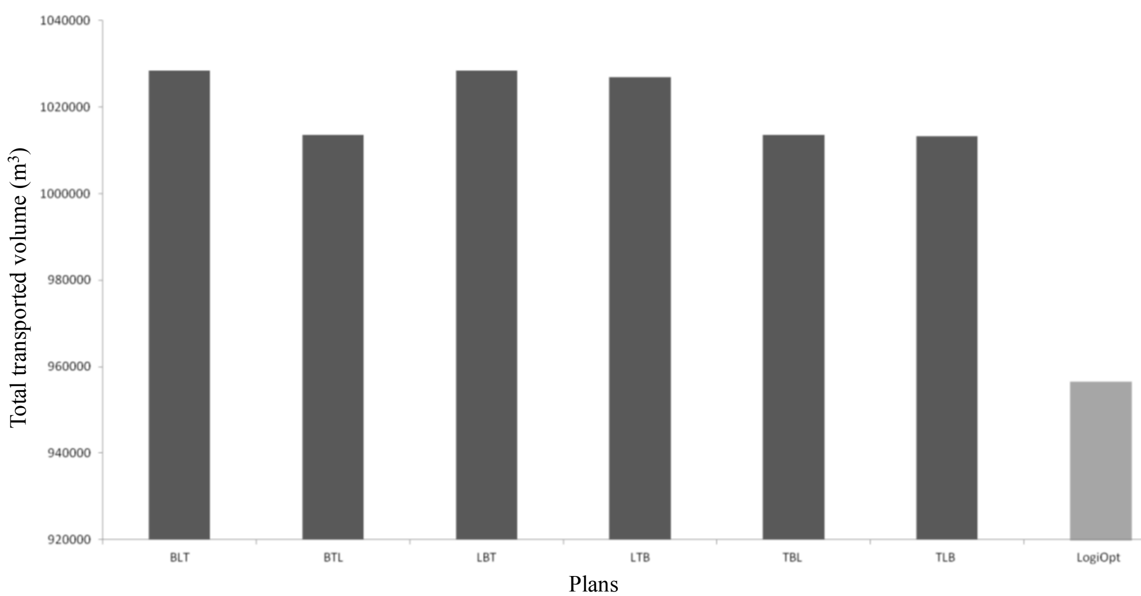

Figure 26 : Comparing the total volume transported in different heuristic plans with LogiOpt

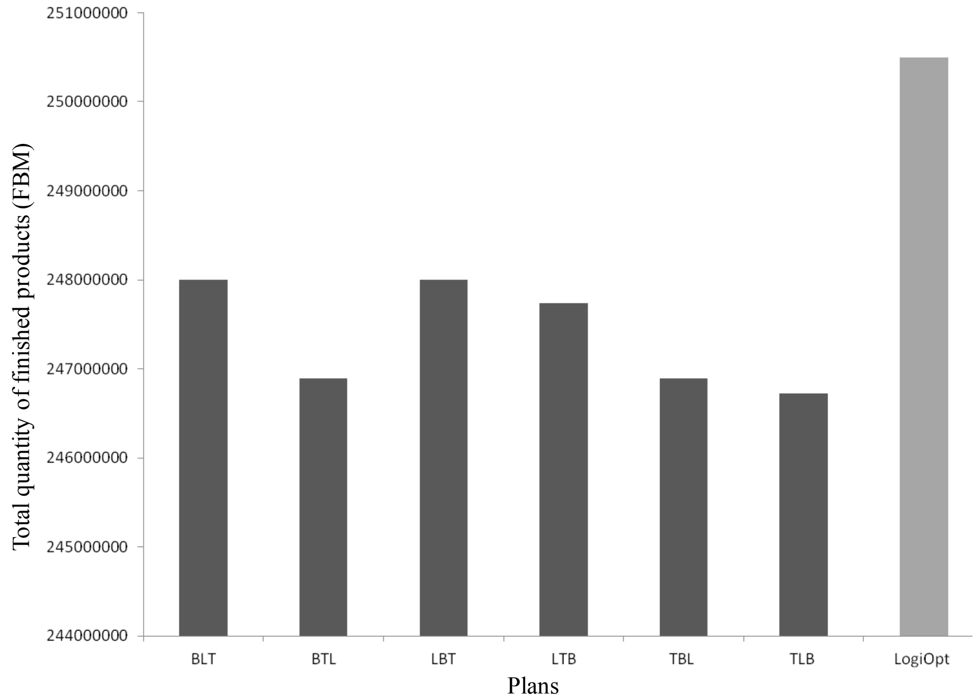

Figure 27 : Comparing the total quantity of finished products in different heuristic plans with LogiOpt

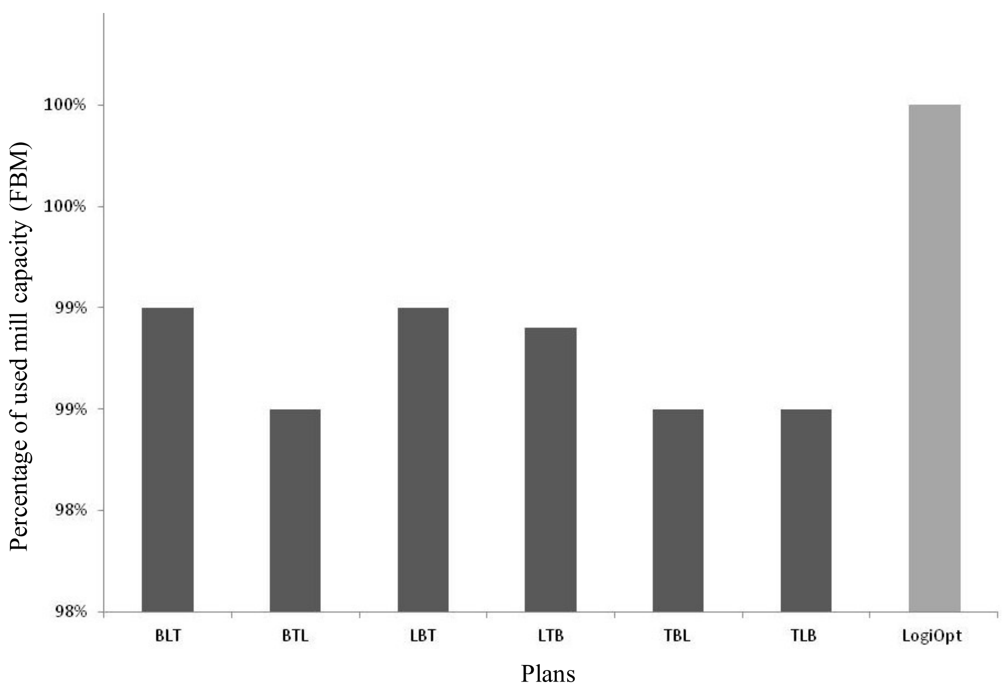

Figure 28 : Comparing the total mill capacity (FBM) in different heuristic plans with LogiOpt

Chapter 5. Conclusion

This project enabled managers to define optimal integrated tactical plans in the forest products industry. This work has the following original features: the proposed system models the supply chain as a whole (from harvesting areas to finished products) and allows an integrated optimization of forest and industry operations.

Moreover, the combinatorial nature of the problem is taken into account by our approach (i.e., the final products depend on the selected harvesting area, the harvesting system, the selected mill and its configuration). All of this is made possible because of our integration with a harvesting simulator (FPInterface) and a sawmilling simulator (Optitek). This coupling of simulation and optimization is of great interest from a scientific and an industrial perspective.

Some advantages of the proposed system (*LogiOpt*) are:

1- Decision-making process is based on mathematical modeling so it can provide optimal plans.
2- *LogiOpt* can evaluate automatically all possible scenarios in order to determine tactical plan.
3- Optimal plan is chosen according to data obtained from the logistics network, a harvest simulator and a sawmilling simulator.
4- The decision maker can evaluate their own tactical plans in comparison with the optimal solution.

To validate the proposed model, an industrial case involving three sawmills was used. The results of *LogiOpt* were compared with the results obtained using a heuristic. *LogiOpt* performs better in wood allocation between sawmills, harvesting in fewer harvesting areas while using lower quantity of wood with better output. Consequently, *LogiOpt* generated considerably more profits than the heuristic plans.

However, despite the good performance of the mathematical model, there are some researches that is still needed to be ready for an industrial application.

First of all, the results for several years should be computed and analyzed. Furthermore, the model accuracy could be improved by adding some parameters and elements of problems (demand, inventory costs, etc.).

Finally, in order to provide *LogiOpt* for industrial use, there are some more steps which should be taken. The optimization module should be better connected to FPInterface to provide a user-friendly experience.

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