SUPPLY CHAIN MANAGEMENT OF THE CANADIAN FOREST PRODUCTS INDUSTRY UNDER SUPPLY AND DEMAND UNCERTAINTIES: A SIMULATION-BASED OPTIMIZATION APPROACH

by

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Supply Chain Management of the Canadian Forest Products Industry under Supply and Demand Uncertainties: A Simulation-Based Optimization Approach

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Keywords: AnyLogic^{TM}, decision support system, integrated production planning, inventory management, merchandizing yard, meta-heuristic search algorithm, operational and tactical planning decisions, OptQuest engine optimization solver.

ABSTRACT

The Canadian forest products industry has failed to retain its competitiveness in the global markets under stochastic supply and demand conditions. Supply chain management models that integrate the two-way flow of information and materials under stochastic supply and demand can ensure capacity-feasible production of forest industry and achieve desired customer satisfaction levels. This thesis aims to develop a real-time decision support system, using simulation-based optimization approach, for the Canadian forest products industry under uncertain market supply and demand conditions. First, a simulation-based optimization model is developed for a single product (sawlogs), single industry (sawmill) under demand uncertainty that minimizes supply chain costs and finds optimum inventory policy parameters (*s, S*) for all agents. The model is then extended to multi-product, multi-industry forest products supply chain under supply and demand uncertainty, using a pulp mill as the nodal agent. Integrating operational planning decisions (inventory management, order and supply quantities) throughout the supply chain, the overall cost of the supply chain is minimized. Finally, the model integrates production planning of the pulp mill with inventory management throughout the supply chain, and maximizes net annual profit of the pulp mill.

It was found that incorporation of a merchandizing yard between suppliers and forest mills provides a feasible solution to handle supply and demand uncertainty. Although the merchandizing yard increases the total daily cost of the supply chain by $11,802 in the single industry model, there is a net annual cost saving of $17.4 million in the multi-product, multi-industry supply chain. Under supply and demand uncertainty without a merchandizing yard, the pulp mill is only able to operate at 10% of its full capacity and achieve a customer satisfaction level of 9%. The merchandizing yard ensures pulp mill running capacity of 70%, and customer satisfaction level of at least 50%. However, the merchandizing yard is economically viable only, if the sales price of pulp is at least $680 per tonne. Efficient and effective management of inventory throughout the supply chain, integrated with production planning not only ensures continuous operation of forest mills, but also significantly improves the customer satisfaction.

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1.1 Introduction

One of leading manufacturing sectors and largest net exporter of Canada, the forest products industry, has been in crisis for the past few decades due to new trends in globalization and recent economic challenges (Gaudreault et al. 2011). In the last decade, the market value of Canada's forest products substantially declined as a result of the decrease in North American housing starts, falling lumber prices and a fluctuating Canadian dollar (Forget et al. 2008). Demand has also decreased for pulp and paper due to the global recession, and for newsprint as a result of declining readership and advertising shifts to the internet. It has been suggested that the competitiveness of the Canadian forest products industry can be improved through diversification and aggressive pursuit of new markets (Frayret et al. 2007). Although diversification of the forest resource-based industry presents many opportunities in the emerging bio-economy, these opportunities are dependent on the coordinated involvement of the entire supply chain network.

Supply chain networks are a system of distributed facilities/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 (Chatfield et al. 2006). The forest products supply chain is similar to other industries, in the sense that the forest-based biomass material flows from forests (usually harvested and collected by forest contractors), to primary production facilities (lumber and pulp industry), to secondary facilities (value-added forest industry), and finally through a network of distributors to individual customers. However, the forest products supply chain networks are characterized by disassembly of the raw-material (tree), unlike the conventional supply chains, which have a convergent product structure of assembly of different materials. Different parts of the tree are utilized for making several products along the production process in the forest industry (Figure 1-1). It has been observed that from a mature tree, 17% of the tree material is utilized for production of saw logs for lumber/specialty products, 74% of the tree material is used for production of pulpwood, which includes 14% for production of engineered products and 60% for pulp/paper products production, and the remaining 9% of the tree is logging residue that can be used for the production of heat/electricity. Moreover, the properties of wood are highly varied within a tree and between trees of the same species (Panshin and De Zeeuw 1980), which make the whole production planning and management process very complex. With the shifting forest management paradigm from volume-based to value-based, optimal utilization of wood fibre has become important for value addition in wood supply chains.

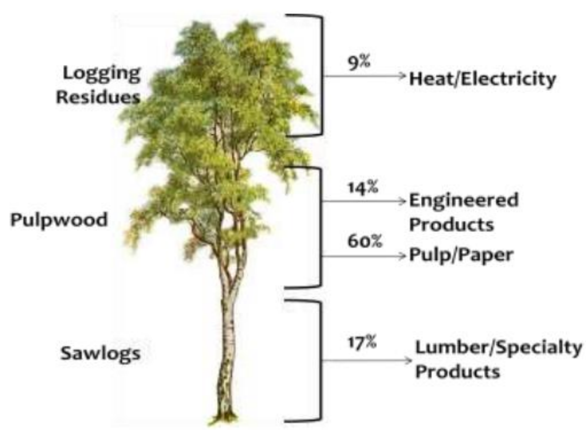

Figure 1-1: Tree utilization by the forest products industry (Shabani et al. 2013).

In this context, the one-way market push model of the forest products industry in Canada cannot improve its competitiveness, as it does not incorporate market demand signals and the information flow is restricted, and does not flow in many directions along and across the supply chain. The industry needs a supply chain management system that shares information promptly among different facilities and agents throughout the supply chain network about demand, availability, wood/fibre characteristics and quality, cost and value at each level, and quickly interacts with other agents of the supply-chain for harmonized real-time production planning and inventory management. The information flows start from market demand, and traces back up the supply chain through all distribution channels – manufacturing, processing raw material, procurement and inventory control, and vice versa. The two-way modeling of a series of value generating activities, both upstream (market to mill to tree) and downstream (tree to mill to market), with the available cost, quality and value data on each value chain level, can provide an improved decision support system and capitalize on the comparative advantages of the Canadian forest products industries. A real-time operational decision support system based on a two-way material and information flow (Figure 1-2) is thus required to deal with order promising and demand fulfillment for a given production facility. The real-time production planning and inventory management of each facility in the supply chain network for final order promising and demand fulfillment is governed by product prices, and operations management efficiency of each unit in the facility. So, the real-time planning and management of two-way flows of materials and information related to quality, yields and costs of inputs/outputs will help in improving the competitiveness of the forest products industries in the global market.

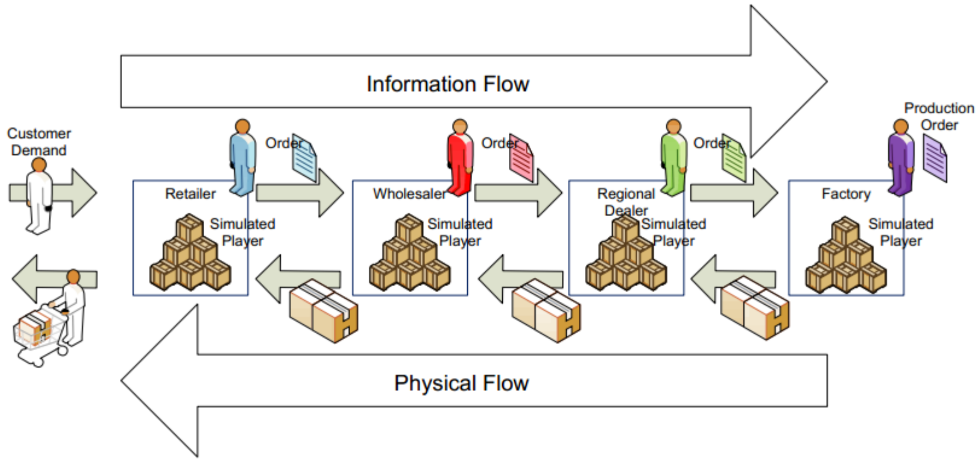

Figure 1-2: Information and Physical Flow Supply Chain Network (Anna 2006).

Further, there are potential constraints related to inbound logistics (warehousing of raw materials), operations management, and outbound logistics (warehousing and distribution of finished goods, marketing and sales). The Canadian forest products industry is at present facing challenges with uncertainties both in future feedstock supply (due to changing regulations and policies) and forest products demand (due to prevailing volatilities in the business environment with constantly changing customer expectations). The uncertain supply and market demand of the Canadian forest products industry is based on economic growth, changing government regulations and policies, global trade liberalization policy, new environmental policies, and forest management policies of different countries. Therefore, an operational decision support tool that uses dynamic supply chain management for two major activities, production planning in primary and secondary manufacturing and inventory management throughout the supply chain, is required. This will help the forest products industry to change their input/output activities according to the market signals and minimize the loss caused due to frequent interruptions in supply. The firms can thereby maximize their profit margin for a given level of market demand by changing their capacity-feasible production plan and optimally overseeing the reactivity and contingency involved. Lack of quality data is one of the biggest limitations for operational modeling of supply chain networks at different stages of the value chain. The supply chain systems can only work efficiently if quality data are available, which enhance the forecasting capability of company activities. Moreover, the supply chain management data must be continuously re-evaluated and refined to match reality. Similarly, absorption of technology, like the use of sophisticated software, is another pivotal factor for efficient supply chain control in value chain networks of the forest products industry.

The modeling of supply chain management for multiple agents in forest industries is a complex problem, because it involves identifying the best possible fibre utilization strategies from multiple options of value creation based on fluctuating market conditions. The best strategy in the face of conflicting requirements would be to first obtain the best market information that includes prices of forest products in different markets, cost associated with transportation of input materials and finished products, costs associated with the factors of production, and then match fibre attributes with end products that best utilize the quality of the available fibre. Figure 1-3, presents a broad outline of the forest products supply chain, involving: forest operations (forest harvesting), transportation of logs and other biomass as raw material for forest products, inventory control (including merchandizing yards and in-plant inventory), primary and secondary manufacturing of forest products, and final delivery to the markets.

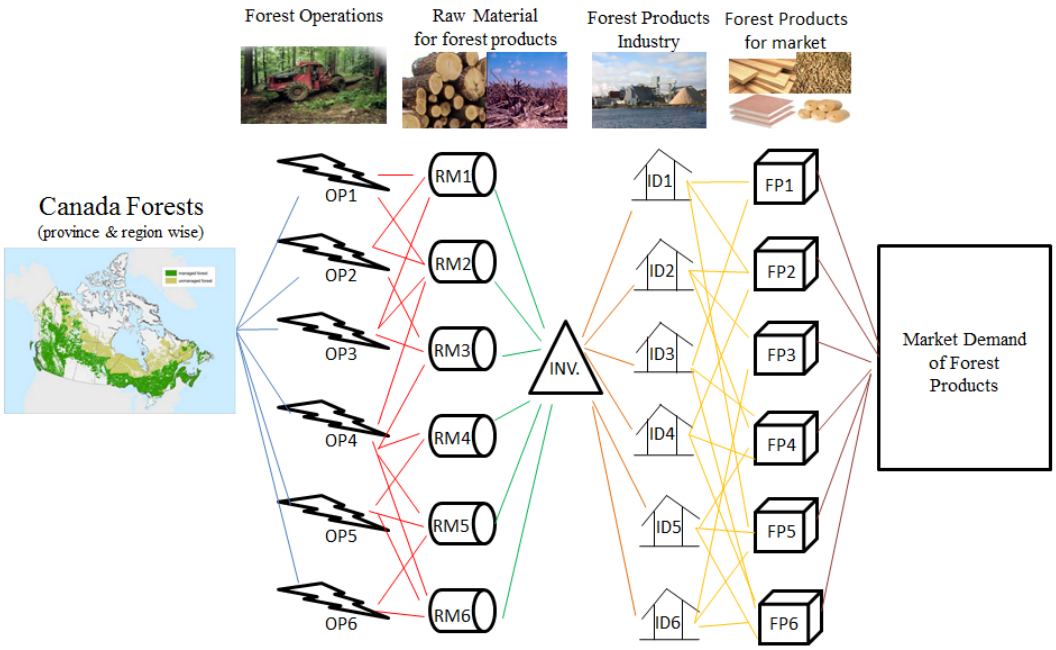

Figure 1-3: Forest Products Industries Supply Chain Network.

Further, each allowed combination of the paths in Figure 1-3, defines an alternative process that produces a specific mix of output products. There is a need to define a process flow diagram for each end product specifying the processes involved in order to design a planning system. Moreover, in order to remain competitive in the global market place, an emerging challenge for the forest products industries is to find ways to manage the inventories (raw materials, intermediate goods and finished goods) and production plans, so as to reduce costs and improve customer satisfaction. The best way to achieve this goal is to integrate inventory management and production planning with supply chain management decision models, so that decisions at the operational level can be determined simultaneously for lower costs and higher customer satisfaction. Although supply chain management design problems, inventory management and production planning have been studied extensively in recent years, most of the models consider inventory management and production planning problems separately in supply chain management design. Therefore, there is a need for a planning system that integrates supply chain network design model with inventory management and production planning under uncertain supply and demand conditions. The planning system should take into account the fact that due to co-production, one batch of raw materials will fulfill many customer orders, and the capacity to fulfill an order is not only linked to the co-product output mix associated with the process, but also to the order in which the process can be done. Therefore, for each agent, it is an integrated planning and inventory management problem. Forest products can be broadly classified into: (i) solid wood products like, lumber, plywood, oriented strandboard, particleboard, fibreboard, hardboard, insulation board, softwood veneer, cross-laminated timbers, composites, hybrid construction materials; (ii) wood pulp products like mechanical pulp, chemical pulp, kraft pulp, dissolving pulp; (iii) paper and paper products like, kraft paper, linerboard, boxboard, newsprint, groundwood, freesheet, tissue, new value-added paper products; (iv) wood based energy products like, pellets, liquid fuels; (v) value-added products like, shingles, cabinet work, windows, doors, millwork, engineered wood; (vi) bio-chemical or green chemical products from biorefining like, lignin, hemicelluloses; and (vii) total turn-key solutions.

There are three levels of decision making in forestry supply chain management: (i) strategic level (long-term planning), which includes selection of suppliers, transportation routes, manufacturing facilities, production level, warehouses, long-term harvest planning, plant location, investment decisions, road construction; (ii) tactical level (medium-term planning), which includes plans to meet actual demand like, annual harvest planning, production planning, inventory management, road upgrade; and (iii) operational level (short-term planning), which includes supply chain plans like short-term process control, such as monthly production plans and inventory management. The operation research models can deal with a wide range of problems ranging from long-term strategic forest management problems to very short-term operational problems. The focus here is to deal with short-term operational problems.

Simulation models have been used for understanding the dynamics of the supply chain and in determining the outcome of different scenarios. Simulation models can accommodate a large amount of variability and are usually easier to comprehend by end-users. In classical thinking, there are three types of simulation: discrete event, continuous and Monte Carlo (Nance 1993). The discrete event simulation utilizes a mathematical/logical model of a physical system that portrays state changes at precise points in simulated time. Customers waiting for service, inventory management and military combat are typical domains of discrete event simulation. Continuous simulation uses equations of physical systems and do not require the explicit representation of state and time relationships. Examples of such simulation systems are found in ecological modeling, ballistic re-entry, or large-scale economic modeling. Monte Carlo simulation utilizes models of uncertainty. Its application is found in solving non-probabilistic problems through the creation of a stochastic process that satisfies the relations of the deterministic problem. The nature of the state change and the time at which the change occurs in the forest products industry mandates precise description, and as such in this research proposal, the focus is on developing a discrete event simulation model. As supply chain networks are becoming more and more global, process coordination is considered crucial for successful business management. Information sharing becomes a key-point at each level of the supply chain network. As there are several analogies between a company in a business network and an agent, the multi-agent system paradigm is the most suitable approach for modeling supply chain networks. The integration of a discrete event simulation model with an agent-based optimization model can handle both nonlinear and stochastic elements.

Cost-based measures have been the predominant performance metric in tackling forest products supply chain problems (Vila et al., 2009, Ahmed and Sahinidis, 1998). The primary cost components in the forest products supply chain problem include harvesting, transportation, inventory (holding and stock out), manufacturing and ordering costs. Essentially, the major focus of supply chain network design problems has been the trade-off between these costs (Frayret et al., 2007). However in older literature, there is no focus on managing optimal inventory policy for the whole system, ensuring capacity-feasible production. This is because the supply chain problem becomes very complex in multi-level inventory models with uncertain supply and demand, especially when the production capacity requirements are also included in the model. Moreover, a common approach in the literature for tackling the modeling complexities of the forest products supply chain problem has been to simplify the situation by breaking a large problem into smaller sub-problems, and deal independently with either the supply side or demand side (Stadtler, 2008). However, such approaches may produce two locally optimal solutions that minimize supply chain costs in isolation, not necessarily resulting in a global optimum solution. On the other hand, integrated supply chain management problems may turn into large complex optimization problems requiring sophisticated solution methods to solve. However, advances in technology with high speed processors and the emergence of new sophisticated solution techniques to solve large nonlinear mathematical models help in dealing with increasingly larger and more complex integrated planning problems (Aazron et al. 2008). Optimization models have been commonly used in operations management to solve supply chain problems in the forest products industry (Stadtler, 2005). Optimization models use mathematical programming approaches to find a feasible and optimal solution to the supply chain problem such as designing a transportation network, or locating a new plant (Ahmadi and Azad, 2010). Optimization models can be integrated with simulation models, which allow the decision makers to see the performance of the supply chain over time under various scenarios and help them understand the inter-relationships between different model components (Jung et al., 2004). Optimization models are mostly centralized, while simulation models can more easily represent decentralized decision-making (Jung et al., 2004). Simulation-based optimization models have been used for supply chain management in the manufacturing industries, mainly because of their ability to incorporate uncertainty into the optimization problems (Mele et al., 2006, Fu, 2002). However, there is no integrated simulation-based optimization model that integrates operational planning with inventory management decision of supply chain agents in the forest products industry.

1.1.1 Research Objectives

The general purpose of this research is to develop real-time operations management decision support tools for the supply chain management of the Canadian forest products industry to meet uncertain wood fiber supply and market demand conditions. The proposed decision support tool, based on a simulation-based optimization modeling approach, constantly uses information from multiple agents throughout the supply chain. The flow of information starts from market demand (order promising and demand fulfillment) and tracks back up the supply chain through all agents including retailers, wholesalers, secondary manufacturers (paper, textile, and other value-added forest products mills), primary (pulp and lumber) mills, merchandizing yard and suppliers. The simulation-based optimization models are used to integrate production planning with inventory management decisions in a forest industry supply chain under stochastic supply and stochastic market demand conditions. The specific objectives are:

1. To provide a comprehensive review of the literature related to supply chain management models in general and forest products supply chain management models in particular. The review focuses on
    a) Supply chain networks optimization models,
    b) Simulation models, and
    c) Integrated simulation-based optimization models.
2. To minimize the overall supply chain costs in a single product (sawlog) supply chain, under demand uncertainty, by
    a) Incorporating a merchandizing yard between the suppliers and the sawmill, and
    b) Integrating inventory planning throughout the supply chain.
3. To minimize the overall supply chain cost in a multi-product, multi-industry forest products supply chain, under supply and demand uncertainty, by
    a) Incorporating a merchandizing yard between the suppliers and the pulp mill, and

b) Integrating operation-planning decisions (order quantity, inventory planning, and supply quantity) throughout the supply chain.

4. To maximize the net annual profit of a nodal agent (pulp mill) in a multi-product, multi-industry forest products supply chain, under supply and demand uncertainty, by

    a) Incorporating a merchandizing yard between the suppliers and the pulp mill, and

    b) Integrating production planning of the pulp mill with inventory management decisions throughout the supply chain, to ensure capacity-feasible production of the pulp mill and desired customer satisfaction levels.

1.1.2 Thesis Outline

This thesis is a compilation of four peer-reviewed articles.

1. Shahi, S., R. Pulkki, 2013. Supply chain network optimization of the Canadian forest products industry: A critical review. American Journal of Industrial and Business Management 631-643. http://dx.doi.org/10.4236/ajibm.2013.37073
2. Shahi, S., R. Pulkki, 2015. A simulation-based optimization approach to integrated inventory management of a sawlog supply chain with demand uncertainty. Canadian Juornal of Forest Research 45: 1313-1326. http://dx.doi.org/10.1139/cjfr-2014-0373
3. Shahi, S., R. Pulkki, M. Leitch, and C. Gaston. 2016. Integrating operational planning decisions throughout the forest products industry supply chain under

supply and demand uncertainty. Paper re-submitted to International Transactions in Operational Research on Jan. 23, 2016, ITOR-Jan-16-OA-0027

4. Shahi, S., R. Pulkki, M. Leitch, and C. Gaston. 2016. Integrating production planning with inventory management decisions in forest industry supply chain under demand and supply uncertainty. Paper submitted to Canadian Journal of Forest Research on Nov. 3, 2015, cjfr-2015-0438

Each of these articles, forming a chapter of this thesis, addresses one of the specific research objectives. Chapter 2 comprehensively reviews the literature related to supply chain models used both in general and specifically in the forest products industry. The optimization models used in the forest products industry literature use information from multiple agents (market demand attributes, flexible wood procurement and manufacturing processes, and resource characteristics), and share this information at each level in the supply chain network. However, the modeling of two-way flow of information (market to forests and vice-versa) for order promising and demand fulfillment through all facilities including manufacturing, processing, raw material procurement and inventory control is missing. The studies that focus on optimization are mostly deterministic in nature and do not account for uncertainty both in supply of wood fibre and market demand of forest products. Simulation and optimization models have been independently used for supply chain management in the past. The literature lacks an integrated approach that combines simulation and optimization models throughout the supply chain network of the Canadian forest products industry. Therefore, there is a need to develop simulation-based optimization models that will help in providing an operational planning tool that meets industrial expectations and provides much better solutions than current industrial practice.

Chapter 3 develops a simulation-based optimization supplier model for a single-product (sawlogs), single-industry (sawmill) supply chain. The simulation model integrates the two-way flow of information and materials under stochastic demand of the sawmill production unit. The dynamic optimization model finds optimum inventory policy parameters (s, S) that minimize total inventory cost for the three supply chain agents – sawmill storage, merchandizing yard, and forest management unit. The model is used to analyze a real sawmill case study in Northwestern Ontario, Canada. It was found that the merchandizing yard absorbs shocks of uncertain demand from sawmill production unit and reduces idle time, but increases the total cost of the supply chain. The optimized model predicts that only three and a half days of inventory is required at the sawmill storage. The simulation-based optimization model was limited to the upstream side of the forest industry supply chain, and did not include supply uncertainty.

Chapter 4 develops a decision support tool for integrating operational planning decisions (order quantity, inventory planning, and supply quantity) of multi-product, multi-industry forest products supply chain under supply and demand uncertainty. The pulp mill is considered as the nodal agent in a multi-product, multi-industry forest products supply chain, and the simulation-based optimization model minimizes the overall cost of the supply chain. It was found that there is a net annual cost saving by including a merchandizing yard in the supply chain. The merchandizing yard not only absorbs supply shocks for the pulp mill, but also reduces the safety stocks on the downstream side.

Chapter 5 further extends the multi-product, multi-industry simulation-based optimization model by integrating production planning of the pulp mill and inventory management decisions throughout the supply chain, under demand and supply uncertainty. The advanced supply chain management model ensures capacity-feasible production of the pulp mill and can significantly improve customer satisfaction levels. It was found that the supply and demand uncertainty causes a net annual loss to the pulp mill, as the pulp mill was only able to operate at 10% of its full capacity and a customer satisfaction level of 9% could be achieved. However, by incorporating a merchandizing yard in the supply chain, the pulp mill running capacity increases to 70%, and customer satisfaction level to at least 50%. The merchandizing yard is only viable for certain threshold levels of pulp price, shortage and transportation costs. The model also demonstrates the impact of reduction in supply caused by small, medium, and large suppliers.

Chapter 6 presents the general conclusions of the thesis. The theoretical contributions of the thesis are highlighted along with implications for supply chain management, research limitations and recommendations for future research.

CHAPTER 2
Supply chain network optimization of the Canadian forest products industry: A critical review

ABSTRACT
The Canadian forest products industry has failed to retain its competitiveness in the global markets because of the under-utilization of its resources. Supply chain optimization models can identify the best possible fibre utilization strategies from multiple options of value creation based on fluctuating market conditions in the forest industries. This paper comprehensively reviews the literature related to supply chain models used both in general and specifically in the forest products industry. The optimization models use information from multiple agents (market demand attributes, flexible wood procurement and manufacturing processes, and resource characteristics), and share this information at each level in the supply chain network. However, the modeling of two-way flow of information (market to forests and vice-versa) for order promising and demand fulfillment through all facilities including manufacturing, processing, raw material procurement and inventory control is missing. The studies that focus on optimization are mostly deterministic in nature and do not account for uncertainty both in supply of raw materials and demand of forest products. Simulation and optimization models have been independently used for supply chain management in the past. The literature lacks an integrated approach that combines simulation and optimization models throughout the supply chain network of the Canadian forest products industry. Further studies should focus on developing simulation-based optimization models that will help in providing an operational planning tool that meets industrial expectations and provides much better solutions than current industrial practice.

Keywords: Agent-based optimization; Discrete-event simulation; Forest products industry; Two-way information flow; Uncertainty

2.1 Introduction

One of the leading manufacturing and export sectors of Canada, the forest products industry, has been in crisis for the past few decades due to new trends in globalization and recent economic challenges [1]. In the last decade, the market value of Canada's forest products substantially declined as a result of the decrease in North American housing starts, falling lumber prices and a fluctuating Canadian dollar [2]. Demand has also decreased for paper and pulp due to global recession, and for newsprint as a result of declining readership and advertising shifts to internet. It has been suggested that competitiveness of the Canadian forest products industry can be improved through diversification and aggressive pursuit of new markets [3]. Although diversification of forest resource-based industry presents many opportunities in the emerging bio-economy, these opportunities are dependent on coordinated involvement of the entire supply chain network.

Supply chain networks are a system of distributed facilities/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 [4]. The forest products supply chain is similar to other industries, in the sense that the forest-based biomass material flows from forests (usually collected by forest contractors), to primary production facilities (lumber and pulp industry), to secondary facilities (value-added forest industry), and finally through a network of distributors to individual customers. However, the forest products supply chain network are characterized by disassembly of the raw-material (tree), unlike the conventional supply chains which have a convergent product structure of assembly of different materials (Figure 2-1). Different parts of the tree are utilized for making several products along the production process in the forest industry. It has been observed that from a mature tree, 17% of the tree material is utilized for production of saw logs for lumber and specialty products, 74% of the tree material is used for production of pulpwood, which includes 14% for production of engineered products and 60% for production of pulp and paper products, and the remaining 9% of the tree is logging residue that can be used for the production of bioenergy [5]. Moreover, the properties of wood are highly varied within a tree and between trees of the same species, which make the whole production planning and management process very cumbersome. With the shifting forest management paradigm from volume-based to value-based, optimal utilization of wood fibre has become important for value addition in wood supply chains.

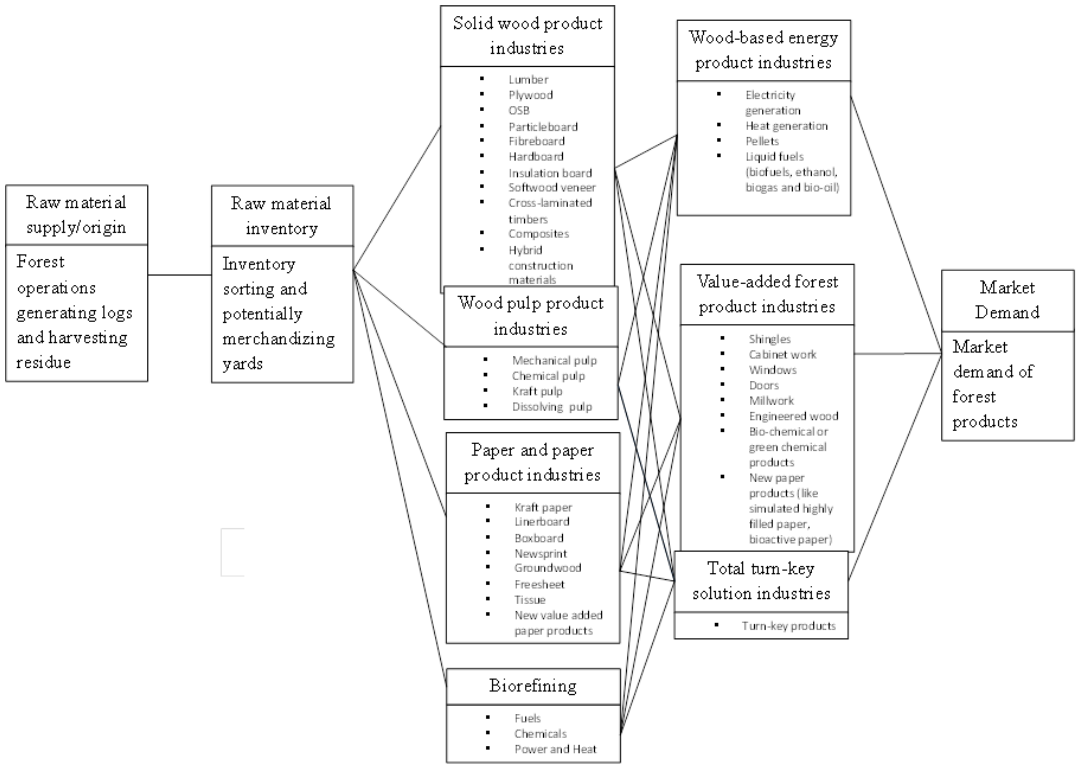

Figure 2-1: Forest Products Industries Supply Chain Network

In this context, the one-way market push model of the forest products industry in Canada cannot improve its competitiveness, as it does not incorporate market demand signals and the information flow is restricted, and does not flow in many directions along and across the supply chain. The two-way modeling of a series of value generating activities, both upstream (market to mill to tree) and downstream (tree to mill to market), with the available cost, quality, yield and value data on each value chain level, can provide with an improved decision support system and capitalize on the comparative advantages of the Canadian forest products industry. Further, there are potential constraints related to inbound logistics (warehousing of raw materials and their sequencing for manufacturing), operations management, outbound logistics (warehousing and distribution of finished goods, marketing and sales), and post-sale service. These constraints lead to uncertainties both in future feedstock supply (due to changing global trade regulations and environmental policies) and forest products demand (due to prevailing volatilities in the business environment with constantly changing customer expectations).

Operations management tools that optimize three major activities: harvesting, transportation and production (including inventory) have been used in primary and secondary manufacturing industries. The focus of these models has been to maximize profit margin for a given level of market demand by changing production plans and optimally overseeing the reactivity and contingency involved. However, the modeling of supply chain optimization for multiple agents in forest industries is a complex problem, because it involves identifying the best possible fibre utilization strategies from multiple options of value creation based on fluctuating market conditions. There are very few studies in optimization modeling that consider uncertainties in demand and supply in forest products industries, and none that consider uncertainties in both demand and supply.

Lack of quality data is one of the biggest limitations for operational modeling of supply chain networks at different stages of the value chain. Moreover, the supply chain management data must be continuously re-evaluated and refined to match reality at each stage, thereby requiring models that can handle large variability in data. Simulation models have been used in some industries that can accommodate a large amount of variability and are usually easier to comprehend by end-users. Three types of simulation models (discrete event, continuous and Monte Carlo) have been used for understanding the dynamics of the supply chain and in determining the outcome of different scenarios [6].

As supply chain networks are becoming more and more global, process coordination is considered crucial for successful business management. Information sharing becomes a key-point at certain levels of the supply chain network [7]. As there are several analogies between a company in a business network and an agent, the multi-agent system paradigm has been found to be the most suitable approach for modeling supply chain networks [1]. The agent-based modeling approach is, however, lacking in the forest products industry. Moreover, to handle both nonlinear and stochastic elements the integration of an agent-based simulation model with an optimization model is required. Such an integrated dynamic environment allows for the evaluation of new technologies, like collaborative planning, forecasting and replenishment, and quantifies the demand variation from the point-of-sale to the suppliers (called bullwhip effect), in the supply chain network management.

The purpose this paper is to provide a comprehensive review of the literature related to supply chain models in general and forest products supply chain models in particular. More specifically, the review focuses on: (i) supply chain networks optimization models; (ii) simulation models; and (iii) integrated simulation-based optimization models.

2.2 Supply Chain Network Optimization Models

Supply chains are networks that connect the raw material sources to finished products consumers through manufacturing activities and distribution channels [8, 9, 9a].

The research literature on supply chain management is rapidly growing, offering different classifications of supply chain models. Depending on the operational level of the problem, supply chain models are broken down into strategic, tactical or operational hierarchies [10, 11, 11a]. Strategic planning is at the highest level and the supply chain models at this level are concerned with broad-scale decisions over long periods of time that give a firm competitive advantage over its competitors [10]. The strategic planning supply chain models identify the types of actions that need to be taken, but do not plan the implementation steps for those actions [11, 11a]. An example of a strategic planning decision would be deciding the location of a manufacturing facility in a production-distribution network. On the other hand of the spectrum is operational planning, concerned with regular operations of the supply chains, with time spans ranging from a day to a few weeks. For example, scheduling truck routes for transporting logs from specific harvest sites to specific destinations is an example of operational planning [10]. Tactical supply chain models can provide a link between the two ends of the decision level spectrum. Tactical models translate the strategies into appropriate operational level targets [11, 11b]. These models ensure that the strategic goals are feasible at the operational level. For example, harvest scheduling at the strategic level may identify some area of a certain age class that needs to be harvested on a land base [11]. A tactical supply chain model then provides more spatial details about specific stands that should be harvested in a specific order.

Supply chain models have also been classified into centralized and decentralized models based on how decisions are made [12]. In centralized supply chain models, all procurement, production and distribution decisions are made by a central unit, considering the state of the entire system. This ensures a higher level of control and collaboration among all supply chain members and a globally optimum decision. Traditionally, many of the models in the supply chain management literature have utilized centralized decision making. However, sometimes it is not realistic to assume that all decisions can be controlled centrally, especially if the supply chain members do not belong to the same organization. Each firm may aim to maximize its benefits without considering the impact on the whole system. Moreover, different firms may not be willing to share their cost and price information with others. In such cases, decentralized models are more appropriate [12]. Decentralized supply chain models allow individual supply chain members to make decisions based on their own goals, while still operating in the same environment that inevitably affects all members [12]. This reflects the decision making process in many real world systems and simultaneously decreases the model complexity, particularly in the case of larger supply chains that may be very difficult to model with centralized modeling techniques [12].

Finally, another approach to classify supply chain models is based on the modeling approach and solution method [12, 12a]. Under this classification scheme, supply chain models can be broadly categorized into optimization and simulation models. Optimization models use mathematical programming approaches to find a feasible and optimal solution to the supply chain problem such as designing a transportation network, or locating a new plant [13]. Alternatively, simulation models allow the decision makers to see the performance of the supply chain over time under various scenarios and help them understand the inter-relationships between different model components [13]. Optimization models are mostly centralized, while simulation models can more easily represent decentralized decision making [13]. Simulation and optimization have also been combined for supply chain management in the manufacturing industries. In fact, simulation based optimization has become a popular approach, mainly because of its ability to incorporate uncertainty into optimization problems [14-16].

2.2.1 Supply Chain Network under Uncertainty

Supply chain networks have numerous sources of demand and supply uncertainty at different levels. However, most of the existing supply chain models are deterministic and do not account for any uncertainty [17-19]. The few supply chain models that account for uncertainty follow different approaches. One part of the effort has been oriented through control theory in which uncertainty is modeled as disturbances in a dynamic model [20, 21]. Another approach deals with uncertainty through fuzzy programming at the strategic level [22]. A third group and the biggest one include statistical analysis-based methods in which it is assumed that the uncertain variable follows a particular probability distribution [23, 23a]. Most research studies in the third group apply an adaptive strategy in which the supply chain controls the risk exposure of its assets by constantly adapting its operations to unfolding demand realizations [24, 25]. Literature also reveals that the most extensively studied source of uncertainty has been demand [26-28]. However, uncertainty could be related to many other factors such as raw material supply, production capacity, transportation and processing times, which are other important factors that could seriously affect the planning decisions.

Uncertainty in supply chain models cannot be handled by deterministic optimization, and stochastic programming is one of the ways to address this challenge [29-31, 31a]. Although fast optimization algorithms exist, realistic problems involving stochasticity with sample size of up to 60 scenarios need several hours to be solved [8, 32]. Sometimes, the stochastic programming problems are too large to solve to optimality and the conclusions are to be based on near-optimal solutions [33, 34]. Stochastic programming models have been used for designing production-distribution networks in the lumber industry also, but these work efficiently only for moderate size problems, and are much more difficult to solve to optimality for large scale problems [35, 36].

2.2.2 Forest Products Industry Supply Chain Models

There has been a lot of emphasis on supply chain management in the forest industry as a result of consolidation of upstream and downstream companies [37, 38]. The studies focus on each of the operational areas in the forest industry separately, examining the effect of different management scenarios on the performance of individual companies as well as the entire sector in different regions and countries. It is believed that the supply chain in the forest industry can be substantially improved if the analysis integrates all the different steps of wood flow from the forest to the customer [39, 40]. Although such an analysis would be extremely complicated, even a small improvement in efficiency could result in large financial gains, considering the large volume of wood flowing in a supply chain. For example, a study on Quebec mills, showed that by effectively managing all nodes in a supply chain, the overall cost can decrease [37]. Another study in the Chilean sawmill industry found that internal supply chain management would increase the profitability of the sawmills by approximately 15% [38]. Ronnqvist [39] conducted an extensive review of literature to define the set of decisions that need to be made in a wood products supply chain, and concluded that operations research (OR) and especially optimization can be used as decision support tools in forestry. A few other review papers also emphasize the importance of incorporating uncertainty and environmental issues in forestry supply chain optimization models [39, 41]. D'Amours et al. [42] further argued that there is a need for more research on integrating the forest management activities with the forest products supply chains.

A summary of studies on forest product industries supply chain network optimization models is shown in Table 2-1. Optimization studies in forestry have mainly focused on individual areas such as harvest scheduling and forest planning [43-45], sawmill operations [46, 47], and transportation [48, 49]. However, in recent years modeling the entire supply chain that combines tactical and operational level decisions has received more attention [39, 41, 42, 50, 51]. Most of the studies in the forest products industry supply chain networks optimization have used linear programming (LP) or mixed-integer programming (MIP) models [9, 38, 40, 52-56]. These models have been used to minimize the net present value of the total cost [57], for combined facility location and shipping route problem for pulp mills [9, 52, 58], and for modeling a network of biomass energy production facilities [53, 53a]. However, it was found that in general the problems solved with LP and MIP models usually include several over-simplifications in order to keep them solvable. These strategic models are useful only for the case of vertically integrated companies that manage all supply chains members in a centralized manner. However, if the objective is to model independent firms that belong to the same supply chain, then these centralized model structures are not sufficient. This modeling approach also does not include any uncertainty in the model to represent the supply chains realistically.

Table 2-1: Summary of studies on forest product industries supply chain network optimization models.

Author	Year-Region	Forest product application	Optimization model approach
Gaudreault et al. [1]	2010- Eastern Canada	Drying and finishing operations in softwood lumber facility	Process planning and scheduling based on mixed integer programming (MIP) and on constraint programming (CP)
Shabani et al. [5]	2013- General review	Forest biomass for bioenergy production	A review of deterministic and stochastic mathematical models
Vila et al. [9]	2006- Quebec, Canada	International production-distribution network for softwood lumber industry.	Generic mathematical programming model based on MIP.
Hultqvist and Olsson [34]	2004- Sundsvall, Sweden	Roundwood supply chain for a pulp or paper mill	Deterministic equivalent of the stochastic scenario optimization model, solved as a convex mixed integer quadratic model
Vila et al. [35]	2009- Eastern Canada	Lumber industry production-distribution network	Two-stage stochastic programming model using a sample average approximation method based on Monte Carlo sampling technique
Vila et al. 2007 [36]	2007-Quebec, Canada	Lumber industry international production-distribution networks	Two-stage stochastic programming model based on Monte Carlo sampling technique
Singer and Donoso [38]	2007- Santiago, Chile	Production and inventory planning of sawmill industry	Combined production and inventory planning optimization model
Ronnqvist [39]	2003- Canada	Wood-flow in forest industry (saw mills and pulp and paper mills)	Linear and nonlinear optimization models covering wide-range of planning periods

Table 2-1 Continued

Bredstrom et al. [40]	2004- Scandinavia	Pulp mills supply chain management	Mixed integer optimization models using novel constraint branching heuristic
D'Amours et al. [42]	2008- Quebec	Forest products industry supply chains	An overview of different planning problems
Weintraub et al. [43]	1994- General	Forest spatial planning	Linear program with a column generation approach
Borges et al. [44]	1999- Minnesota, USA	Forest management spatially scheduling problem	Dynamic programming
McDill et al. [45]	2002- USA	Forest harvest scheduling	Mixed integer linear programming
Maness and Adams [46]	1991- USA	Optimal bucking and sawing policies	Linear programming
Ronnqvist and Ryan [48]	1995- New Zealand	Sawmills and pulpmills transportation schedules	Combination of heuristic, linear optimization relaxation, and branch and bound approaches
Weintraub et al. [49]	1995- Santiago, Chile	Forest harvest scheduling and transportation planning	Mathematical programming and heuristic models
Gunnarsson et al. [52]	2006- Sweden	Pulp products terminal location and ship routing	Mixed integer programming model
Chauhan et al. [55]	2009- Quebec	Timber procurement system	Mixed integer optimization models
Troncoso and Garrido [57]	2005- Chille	Saw mill strategic planning model (forest facilities location and freight distribution)	Mixed-integer dynamic optimization model

Table 2-1 Continued

Gunnarsson et al. [58]	2007- Sweden	Pulp mill integrated transportation, production and distribution planning	Mixed integer optimization model for the entire supply chain
Lonnstedt [71]	1986- Sweden	Forest management strategic planning	Mathematical long-term forest sector model
Beaudoin et al. [74]	2007- Quebec, Canada	Forest products industry supply chain tactical planning	Mixed integer programming model

2.3 Simulation Models

Simulation is the process of designing a computer model of a real system and conduct experiments with this model to understand its behaviour or to evaluate strategies to its operations [59]. Simulation models give support to the decision-making, allowing the reduction of risks and costs involved in a process. Simulation models can accommodate the variability in input data more readily (e.g. different log diameters in a saw mill) and are usually easier to comprehend by end-users [60].The discovery of computational modeling and simulation has become the third pillar of Science, alongside theory and experimentation [61]. Science turns to simulation, when the models become too complicated or exact mathematical solutions are not possible [62]. The significance of simulation depends on the validity of the data, the model and the process [61]. Simulation models have also been used in understanding the dynamics of supply chains and in determining the outcome of different scenarios [63, 63a].

Within the area of supply chain management, the earliest attempts to use dynamic simulation was reported by Forrester [64], who strove to perform a dynamic simulation of industrial systems by means of discrete time mass balances and non-linear delays. However, due to the complexity of the models and the computer limitations at that time, the work only covers small academic examples. Frayret et al. [3] presented a generic architecture to implement distributed advanced planning and scheduling (APS) systems with simulation capabilities. APS systems provide companies with algorithms and models for planning their activities from raw material procurement to distribution [12]. The performance of this APS tool under different scenarios was further studied and validated by Lemieux et al. [65]. Simulation models have also been combined with genetic algorithms and MIP models to consider strategic decisions regarding facility location and partner selection for supply chain design problems [66, 66a]. The literature on simulation tools and techniques used for supply chains distinguishes between three different approaches: discrete-event simulations, system dynamics, and agent-based models [63].

2.3.1 Discrete Event Simulations

In discrete-event simulation (DES) models, the activities within the supply chain are represented through individual events that are carried out at separate points in time according to a schedule [63, 67, 68]. DES models are the most powerful simulation tools to consider complex stochastic systems. Numerous software packages for discrete-event simulation are available, both very specialized ones for a specific part of the supply chain, and general ones with a high functionality in modeling and visualization of supply chains [56, 69]. One such example is the Supply Net Simulator, which allows simulating the behavior of individual members in a supply chain network [70].

DES models have been used to model supply chain networks in the forest products industry [71-74, 74a]. While many of these studies focus on individual stages of production and distribution, some have included the entire supply chain. For example, Lonnstedt [71] simulated the forest sector in Sweden to study the dynamics of cost competitiveness in the long term, and suggested policy changes, such as lowering taxes or interest rate to increase investment in the industry. Randhawa et al. [73] developed a discrete-event object-oriented simulation environment that could be used to model sawmills with various configurations. Lin et al. [75] studied the benefits of producing green dimension parts directly from hardwood logs by comparing four mill designs using simulation. Baesler et al. [76] used simulations to identify bottlenecks and factors that affect productivity (number of logs per day) in a Chilean sawmill, and concluded that there is a potential for a 25% increase in production. Beaudoin et al. [74] combined a deterministic MIP and Monte Carlo sampling methods to support tactical wood procurement decisions in a multi-facility company, and showed that their proposed planning process achieved an average profitability increase of 8.8% compared to an approach based on a deterministic model using average parameter values.

2.3.2 System Dynamics

System Dynamics (SD) modeling is mainly used for simulating continuous systems (as opposed to discrete event simulation) [77]. An SD model is characterised by feedback mechanism and information delays to help explain the behaviour of complex systems [77]. In SD modeling, real-world systems are represented in terms of stock variables (e.g., profit, knowledge, number of people), and the information flow between these stock variables. Interacting feedback loops link the stock and flow variables. The resulting model is a system of differential equations and its dynamic behaviour is due to the structure of feedback loops [77].

SD approach has been combined with OR techniques to model supply chains and further refined to study its dynamics [78, 79]. Angerhofer and Angelides [80] have reviewed the literature on SD modeling in supply chain management, and concluded that SD can be used in combination with different techniques to study inventory management, demand amplification and international supply chain design. Very few studies have used SD to model the forest industry supply chains. Schwarzbauer and Rametsteiner [81] used SD to analyze the potential impact of sustainable forest management (SFM) certification on forest products in the Western European forest sector. Fjeld [82] developed the "wood supply game" based on the Sterman Beer Game [83, 84] as educational material for students in forest logistics courses. The game included four stages in the supply chain from the forest to the lumber or paper retailer. Demand on the end customer was decided based on a random draw and the game demonstrated the distortion of demand as it moved upstream through the supply chain (the bullwhip effect). Jones et al. [85] modeled the supply chain of the Northeastern US lumber industry using the SD approach to answer policy questions on its economic and environmental sustainability. Jones et al. [85] showed the capacity of the lumber mills could potentially exceed the available timber resources, however, feedback mechanisms are required to ensure the sustainability of lumber mill operations. It should be noted that SD models are better suited for getting an aggregate views of the system and policy questions at a strategic level. The modeled system is evolved as a result of equations that link stock and flow variables together and it is not always possible to identify individual behaviour of people or firms.

2.3.3 Agent-Based Models

Agent-based modeling (ABM) makes use of individual behaviour and characteristics to create a bottom-up system, where each member optimizes its own operations in the sense of an advanced planning system [86]. ABM aims to investigate how the players within the supply chain interact under changeable policies and rules to create a stable state for all supply chain members [86]. ABM has attracted a great deal of attention during recent years for the purpose of decentralized planning. Each member of the supply chain, who is autonomous or semi-autonomous, is considered as an agent. Each agent uses predefined characteristics, decision rules and objectives in order to interact with each other, and tries to maximize its own utility, but does so in an environment where all other agents are present [2]. The main advantages of multi-agent systems are their ability to model decentralised complex systems easily, offering increased flexibility without losing efficiency, and providing learning systems that improve over time with better decisions [16].

ABM is being increasingly used for supply chain management in a number of manufacturing industries for production planning [52, 87-94]. The flexibility of ABM allows for the incorporation of uncertainty through a combination of statistical analysis methods in the modeling approach [95]. These statistical methods assume that the uncertain variables follow a particular probability distribution and repetitive sampling from these distributions generates a set of possible realizations or scenarios. The deterministic discrete-event simulator is then run for each of these scenarios, providing a set of output variables. The probability distribution of the performance measure, constructed form the output variables, is used to assess different supply chain configurations.

ABM has also been used in forest industries supply chain modeling [2, 3, 12, 37, 65, 82, 87, 96]. Each entity (mill, wholesaler or retailer) is represented as an intelligent agent that has a specific behaviour (ordering scheme) and also the option of collaborating with other agents in decision making [17]. The results of these studies show that the lowest cost of the supply chain was associated with highest collaboration of agents. Collaboration and information sharing is not only good for the whole supply chain, but it is also better for each individual entity. Lumber industry supply chains have been analyzed using multi-behaviour agents [2], where the agents are either reactive (have a predefined action for every possible state of the environment) or deliberative (use past knowledge about the environment to make decisions). Comparing the performance of single-behaviour and adaptive (multi-behaviour) agents under different business environments, Forget et al. [96] found that performance gains are possible if agents adjust their behaviour in every situation instead of using a single strategy over the entire time horizon. Because of their flexibility and being less complicated compared to large centralized stochastic programming models, agent-based models are helpful tools for both strategic and operational planning under uncertainty [52, 91, 97]. Table 2-2 provides a summary of studies on forest product industries supply chain network simulation models.

Table 2-2: Summary of studies on forest product industries supply chain network simulation models.

Author	Year - region	Forest product application	Simulation model approach
Forget et al. [2]	2008-North America	Lumber industry supply chains	Agent-based planning simulation platform
Moyaux et al. [37]	2004-Quebec, Canada	Sawmill wood supply	Simulation model to study the impact of global supply chain behaviour
Lemieux et al. [65]	2009-Eastern Canada	Lumber industry integrated planning and scheduling system	Multi-agent based simulation model
Randhawa et al. [73]	1994-Oregon, USA	Sawmill design and analysis	Discrete-event object-oriented simulation model
Lin et al. [75]	1995-General	Log-to-dimension manufacturing system	Fortran-based simulation model
Schwarzbauer and Rametsteiner [81]	2001-Western Europe	Forest products markets and certification	System dynamics simulation model
Jones et al. [85]	2002-Northeastern United States	Sawmill industry	Dynamic simulation model

2.4 Integrated Simulation-Based Optimization Models

Simulation models do not prescribe an optimal design for the supply chain, which necessitate the use of optimization models [95]. The optimization model translates all interdependencies of the supply chain members into a mathematical program to identify improvements that can be made in a supply chain with regards to a certain performance measure (an objective function such as total profits or order fulfillment rate) [95]. Supply chain optimization models prescribe a plan for production and distribution activities of supply chain members that is optimal, meaning that no alternative plan can further improve the value of the objective function [66, 98]. In this category of supply chain models, the optimization problem (either deterministic or stochastic) is constructed based on all the constraints and variables of the problem. However, as the size of this optimization problem grows under uncertainty, finding an exact optimal solution becomes difficult and in many cases, approximation techniques and heuristics are needed to find a near-optimal solution.

Integrated simulation-based optimization models are an attractive combined strategy to address optimization under uncertainty [14]. It deals with the situation in which the analyst would like to find which of many possible sets of input parameters lead to optimal performance of the represented system. Most of today's simulators include possibilities to do a black-box parameter optimization of the simulation model. Opt Quest is one such optimization toolbox containing different meta-heuristics algorithms designed to optimize configuration decisions from different simulation runs [99], where the simulation model is only used for the evaluation of the objective value under different scenarios. Many of the simulation-based optimization processes, being complicated, need a considerable amount of technical expertise on the part of the user, as well as a substantial amount of computation time. This is closely related to the fact that some of these techniques are local search strategies and may be strongly problem dependent [95, 95a]. In the context of simulation-based optimization models, the ability to find high quality solutions early in the search is of critical importance, as evaluating the objective function entails repeatedly running the simulation model [100]. Evolutionary algorithms have been commonly used for this purpose to optimize multi-modal, discontinuous and differential functions. The main advantage of evolutionary approaches over other meta-heuristics approaches is that these are capable of exploring a larger area of the solution space with a smaller number of objective function evaluations [95].

The genetic algorithms of simulation-based optimization models in the supply chain networks are supported through mathematical programming [101-103]. However, these studies mostly deal with strategic decisions, for instance combinatorial operation research problems such as multi-stage facility location, rather than tactical or operational ones. Although, there are a few studies that used simulation-based optimization techniques in different industries [16, 52, 91, 92] there are none to our knowledge that combine agent-based modeling with optimization techniques and also deal with uncertainty in the forest products industry. A summary of studies on forest product industries supply chain network integrated simulation-based optimization models is presented in Table 2-3.

Table 2-3: Summary of studies on forest product industries supply chain network integrated simulation-based optimization models.

Author	Year - region	Forest product application	Integrated model approach
Frayret et al. [3]	2007-Quebec, Canada	Lumber industry distributed planning and scheduling systems	Combined agent-based technology with constraint programming
Todoroki and Ronnqvist [47]	2002-New Zealand	Sawmills.	Dynamic optimization model with log sawing simulation system, AUTOSAW
Daugherty et al. [53]	2007-Central Oregon and Northern California	Bioenergy production	Forest vegetation simulator and mixed-integer optimization model
Baesler et al. [76]	2004-Chile	Sawmills	Discrete event simulation model
Forget et al. 2009 [96]	2009-Quebec, Canada	Lumber production planning platform	Agent-based simulation model and mixed integer programming model

2.5 Conclusions

The purpose of this review paper was to comprehensively review the literature related to supply chain models, and identify those models which would best address the needs for the Canadian forest products industry. It was found that the supply chain models used in the forest products industry mostly address either the production planning/scheduling or inventory management problems. Such supply chain models have been used to optimize isolated harvesting, transportation, and production, planning and distribution in the sawmill and pulp and paper industries. Not only do these optimization models focus on a few operations, but also do not capture uncertainty in market demand and raw material supply, and lack in the two-way flows of information and materials. The second class of supply chain models use simulation approaches and deals with stochastic natures existing in the forest products industry's supply chain. However, these simulation models only capture the system dynamics of large-scale systems in the supply chain network, and do not provide any optimized solutions.

Therefore, there is a need for an integrated simulation-based optimization modeling approach for the Canadian forest products industry supply chain network that considers uncertainty in both demand and supply. This integrated model would act as a supply chain template in order to further develop operational decision support tools for inventory management and production planning/scheduling. The integrated model of Canadian forest products industries will further help in evaluating collaborative planning, forecasting and replenishment, and the demand variations in the industry's supply chain networks.

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CHAPTER 3
A simulation-based optimization approach to integrated inventory management of a sawlog supply chain with demand uncertainty

Abstract

This paper develops a simulation-based optimization supply chain model for supplying sawlogs to a sawmill from a forest management unit. The simulation model integrates the two-way flow of information and materials under stochastic demand of the sawmill production unit. The dynamic optimization model finds the optimum inventory policy (s, S) that minimizes total inventory cost for the three supply chain agents – sawmill storage, merchandizing yard, and forest management unit. The model is used to analyze a real sawmill case study in Northwestern Ontario, Canada. It was found that the merchandizing yard absorbs shocks of uncertain demand from sawmill production unit and reduces idle time, but increases the total cost of the supply chain by $11802 (about 42%). The optimized model predicts that only three and a half days of inventory is required at the sawmill storage. The simulation-based optimization supplier model will help in decision making at the tactical and operational level in the forest products industry supply chain through two-way flow of information and materials.

Keywords: AnyLogic™, Forest products industry, Inventory policy (s, S), Merchandizing yard, Meta-heuristic search algorithm, Northwestern Ontario, OptQuest engine optimization solver.

3.1 Introduction

Inventories exist throughout the supply chain in any production system, in the form of raw materials, work in progress or finished goods. Considering only the supply of raw materials to the production unit, inventories exist with the supplier, at the distribution yard and at the storage of the production facility (Ganeshan and Ganeshan 1999). All these inventories are related to each other, as the level of inventory at each location is determined by demand at the downstream site (Ganeshan and Ganeshan 1999). Managing these inventories at an optimal level makes economic sense, as carrying these inventories can cost anywhere from 20% to 40% of their annual value (Ganeshan and Ganeshan 1999). Inventory management refers to making coordinated decisions about inventory levels at each location in the supply chain, incorporating sources of uncertainty and designing proper supply chain performance measures (Lee and

Billington 1992). The supplier side of forest products industry supply chain in Canada is characterized by the pull system, where production managers make the inventory decisions (order quantity, reorder point) based on their local conditions (Federgruen 1993, Song et al. 2014). Normally, the production manager places an order as soon as the demand for raw material occurs (Ganeshan and Ganeshan 1999).

Global competition and economic threats to the Canadian forest products industry have encouraged companies to improve their performance by reducing inventory and exchanging information promptly throughout the supply chain (Forget et al. 2008). On one hand, the new global economy offers new business opportunities for the Canadian forest products industry, but on the other it challenges them to optimize their business processes in order to remain competitive (Ding et al. 2005). The real competition is not between individual organizations, but between their competing supply chains, which are looking for effective means to help companies reduce costs and improve responsiveness to customers (Ding et al. 2005). Generally, supply chain planning processes occur at strategic, tactical and operational levels (Ding et al. 2005). Strategic optimization problems in a supply chain include long term decisions such as facility location, whereas tactical and operational decisions cover shorter period and short term arrangements, such as inventory control policy and order quantity decisions (Ding et al. 2005). The real challenge in supply chain planning is to make correct tactical decisions while taking the operational performances into consideration (Ding et al. 2005). Integrated inventory management with information sharing between different locations can help deal with such challenges, maintaining agility and synchronization in the supply chain (Forget et al. 2008, Murphy 1987).

The value of the trees removed from forests could be enhanced if the wood were effectively evaluated and sorted (sawlogs, stud logs, peeler logs, post and pole, pulpwood and hog fuel) in log sort yards for quality and highest value before delivery to the next manufacturing destination (Han et al. 2009). Merchandizing yards, on the other hand, can provide additional benefits in the utilization and merchandizing of logs, wood and fiber (Dramm et al. 2004). Merchandizing involves scanning and bucking tree lengths or long log-lengths into logs and sorting according to the highest end use (Williston 1976). Merchandizing yards can be equipped with laser or X-ray scanning equipment and computerized log optimization software for maximum value recovery from logs based on diameter, length, taper, crook, sweep, rot, forks, branches (knots) and other defects. Interest in commercial merchandizing yards has increased in response to uncertainty in timber supply and the need to recover more value from the available resource (Dramm et al. 2002). They could also provide better utilization and improve value recovery of underutilized species (Dramm et al. 2004). However, past studies have indicated that costs for managing a merchandizing yard for small-diameter logs could outweigh the revenue generated by sorting and pre-processing those logs (Han et al. 2009). Merchandizing yards would still have operational and economic advantages if physical space precludes sorting at the forest landing, or where low volumes makes it unjustifiable to sort in the forest (Dramm et al. 2004). Moreover a log grader, with a good understanding of log specifications and markets, and/or the integration of modern laser or X-ray scanning with optimization algorithms, can make much better decisions at a merchandizing yard (Dramm et al. 2004). Therefore, the effectiveness of a merchandizing yard can only be judged through an integrated inventory management system in a supply chain. An integrated inventory management system will be a synthesis of the inventory analysis at the mill storage, merchandizing yard and forest landing (Ganeshan and Ganeshan 1999). The central premise here is that the lowest inventories result, when the entire supply chain is considered as a single system (Ganeshan and Ganeshan 1999).

Although supply chain planning has improved the performance of many industries, the challenge of integrating the problems of different planning locations still remains (D'Amours et al. 2008). This is more so in the case of forest products industry supply chains, as these are generally composed of many divergent processes using different parts of the same raw material (i.e., trees) (D'Amours et al. 2008, Yanez et al. 2009). These varied processes make the task of integrating the procurement and production very complex, given that inventories at different locations are always bounded by trade-offs between holding and shortage costs in the supply chain (D'Amours et al. 2008, Yanez et al. 2009). Simulation has been used extensively to investigate issues related to the design and operation of production systems in forestry to estimate various sawmill performance parameters (Mobini et al. 2013, Beaudoin et al. 2012, Lebel 1997, Boosothonsatit et al. 2012, Yanez et al. 2009). However, the use of simulation modeling for inventory management is very limited in spite of high levels of raw material inventory in the forest industry (Beaudoin et al. 2012, Crespo Marquez et al. 2004).

Demand uncertainty can result in excess inventories or inability to meet production needs (Jung et al. 2004). Whereas, excess inventory leads to unnecessary holding costs, the inability to meet production needs results in shortage costs (in terms of reduced profits and potentially long-term loss of customers) (Jung et al. 2004). This trade-off between inventory holding cost and shortage costs can be posed as a multi-stage stochastic optimization problem in which the inventory levels and idle time are the key optimization variables (Jung et al. 2004). One such approach used in practice is ensuring a safety stock, which is a lower bound on the inventory level that is chosen so as to absorb some level of demand uncertainty (Jung et al. 2004). Although, safety stocks can be estimated using traditional inventory theory, in real world supply chains safety stock levels are dependent on probabilistic distribution of the demands (quantity and lead-times) (Jung et al. 2004). The most commonly used probability distribution of the demands is a normal distribution (Deuermeyer and Schwarz 1979). However, the use of uniform, gamma or Weibul distributions have resulted in lesser amount of safety stocks for the same level of service (Ganeshan and Ganeshan 1999, Sculli and Shum 1990, Kelle and Silver 1990, Guo and Ganeshan 1995, Ramasesh et al. 1991). Research in inventory management has been extended from the foundational work, such as the classical economic order quantity (EOQ) model and the optimal inventory policy (s, S), to the design of supply chains based on stochastic demand and real conditions experienced in the day-to-day operation (Jung et al. 2004). Simulation-based optimization, an active area in the field of stochastic optimization, has been used for decision making at tactical and operational levels (Jung et al. 2004, Ding et al. 2005, Shabani et al. 2013). However, the simulation-based optimization approach has not been used for integrated inventory management in the complex forest products industry supply chain. The optimization algorithm guides the search for improving the operational performance in a supply chain systematically, considering feedback from simulation evaluations (Ding et al. 2005). Optimal estimation of key performance indicators of the supply chain are provided as feedback for further searches, whereas, uncertainties related to demand and production are taken into account using simulation (Ding et al. 2005). Since operational planning problems need to be solved rapidly, heuristics and meta-heuristics methods are commonly used for optimization (Rönnqvist 2003). Commercial optimization software, such as OptQuest (produced by OptTek Systems, Inc.), use scatter search methodology coupled with tabu search strategies to obtain high quality solutions to optimization problems defined in highly complex systems (Laguna 2011).

Using the simulation-based optimization approach, the general purpose of this study is to develop an integrated inventory management supply chain model that minimizes the total inventory cost and idle time for supplying sawlogs from a forest management unit to a sawmill. The specific objectives are: (i) to develop a simulation model that integrates the two-way flow of information (demand and orders) and materials (supply and shipment) for the sawlogs supply chain, under stochastic demand of the sawmill, (ii) to find the optimum inventory policy (s, S) that minimizes total inventory cost (material handling, holding and shortage) for the forest management unit and sawmill, and idle time at sawmill, and (iii) to study the role of a merchandizing yard in reducing inventory cost and idle time in the forest products industry supply chain under demand uncertainty. We develop a base simulation-based optimization model, which considers only one supplier, one product (sawlogs) and one forest industry (sawmill). The model is developed using real parameters of a sawmill (name not disclosed for confidentiality purposes) in Northwestern Ontario. However, the model can be extended to all forest products supply chain having multiple suppliers, products and industries.

3.2 Problem Description

Typically in a forest products supply chain, the production unit needs forest fiber (raw material) to produce forest products in the most cost effective and efficient way as per customer demand. In the present forest products supply chain, the sawmill needs sawlogs from the forest management unit for the production of stud grade lumber. The total annual demand of sawlogs is 475000 m^3. However, the daily demand of sawlogs by the sawmill production unit is uncertain (the data for variation of daily demand is not known), and the quarterly demand of sawlogs varies from 110000 m^3 to 125000 m^3. Under this uncertain demand, a supply chain model is required that minimizes the total inventory cost and idle time for supplying sawlogs from the forest management unit to the sawmill. Although supply side uncertainty is a major problem that needs to be considered, we do not include it in the present model. The sawmill supply team is also interested in understanding the effectiveness of a merchandizing yard in reducing the total inventory cost in the supply chain and its usefulness for increasing the value of logs.

The simulation-based optimization approach is used to solve the multi-echelon integrated inventory management problem instead of a more traditional approach because of the multiple complexities involved in this problem. First, the supply chain problem is characterised by a two-way modeling approach, where information (demand) flows in the upstream direction and the material (shipment) flow in the downstream direction. Second, the demand of sawlogs from the sawmill storage agent and supply of logs from the forest management unit are both stochastic in nature. We only accounted for demand uncertainty in the present model. Third, the optimization problem involves integrating the inventory management at all three levels (sawmill storage agent, merchandizing yard and forest management unit) of the supply chain.

3.3 Methodology

3.3.1 Sawlogs Supply Chain Model

The sawlogs supply chain model consists of three agents – sawmill storage agent, merchandizing yard and forest management unit – supplying sawlogs to sawmill for the production of stud grade lumber. The model is built in AnyLogic™ software (Borshchev and Filippov 2004). Figure 3-1 shows this sawlogs supply chain model with and without a merchandizing yard. It is assumed that the sawmill operates 24 hours a day and the demand for sawlogs from production unit arrives with exponential inter-arrival times having a mean of 0.1 day.

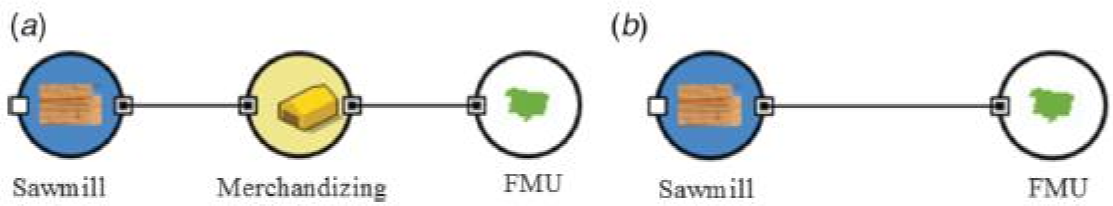

Figure 3-1: Sawlog supply chain model (a) with and (b) without merchandizing yard.

The supply chain model follows stationary (s, S) inventory policy, which is a minimum/maximum inventory policy, for all three agents. When the level on-hand falls below the minimum inventory, s, the agent generates a request for replenishment order that will restore the on-hand inventory to a target, or maximum inventory level, S. The reorder point in this inventory policy is the minimum, or trigger level, s. The reorder quantity restores the inventory back to the maximum inventory level, S. When a demand of sawlogs from production unit occurs, it is satisfied immediately as long as the inventory level of sawlogs at the sawmill storage agent is at least as large as the demand. In that case, the time required for the production unit to receive the entire order of sawlogs, $T = 0$. The new inventory level of sawlogs in the storage is equal to the old inventory level minus the demand size, resulting in a non-negative inventory level. If the demand exceeds the inventory level of sawlogs, the production unit takes the currently available inventory and the excess of demand over supply is backlogged and satisfied by a future delivery from the merchandizing yard. The new inventory level of sawlogs is equal to the old inventory level minus the demand size, resulting in a negative inventory level. In this case, T is the time from when the demand from production unit first arrives until that future time, when the production unit receives the remainder of their order. At the beginning of each day, the sawmill storage reviews its inventory and decides how much volume of sawlogs to order from the merchandizing yard. If the sawmill storage orders o_{sms} volume of sawlogs, it incurs an ordering cost of $K_{sms} + i_{sms}o_{sms}$, where K_{sms} is the order setup cost of the sawmill storage and i_{sms} is the order cost per m^3 of sawlogs by the sawmill storage agent, which includes the cost of shipping by the merchandizing yard. If there is no order by the sawmill storage, i.e., $o_{sms} = 0$, then no ordering cost is incurred. It is assumed that the order is sent to the merchandizing yard electronically and arrives immediately. The sawmill storage uses a stationary (s_{sms}, S_{sms}) inventory policy to decide how much to order is equation (3-1):

$$o_{sms} = \begin{cases} S_{sms} - I_{sms} & if \quad I_{sms} < s_{sms} \\ 0 & if \quad I_{sms} \geq s_{sms} \end{cases} \qquad [3\text{-}1]$$

where, s_{sms} is the minimum inventory level and S_{sms} is the maximum inventory level of the sawmill storage, I_{sms} is the inventory level of the sawmill storage at the beginning of the day. When a shipment of sawlogs arrives from the merchandizing yard, it is assumed that it is used immediately to satisfy any backlogged demand from the sawmill production. Assume that there is no travel time between the production unit and the sawmill storage, since they are at the same location. In order to compute T for a backlogged production unit demand, it is necessary for the production unit to have two attributes while idle in a backlog queue, i.e., original demand time and the current amount of volume of sawlogs backlogged. Let $I_{sms}(t)$ be the inventory level at the sawmill storage at time, t which could be positive, negative, or zero. Let $I^{+}_{sms}(t) = \max\{I_{sms}(t), 0\}$ be the amount of volume physically on hand in the inventory at time t, which will be non-negative. Let $I^{-}_{sms}(t) = \max\{-I_{sms}(t), 0\}$ be the backlog at time t, which will also be non-negative.

Let $O_{sms}(i)$ be the ordering cost incurred on the ith day {i.e., the time interval $(i-1,i)$ } by the sawmill storage for $i=1,2,......,n$, where n days is the simulation run length. Then the average ordering cost per day at sawmill storage is equation (3-2):

$$\overline{O}_{sms} = \frac{\sum_{i=1}^{n} O_{sms}(i)}{n} \qquad [3\text{-}2]$$

If the sawmill storage incurs a holding cost of h_{sms} per m^3 per day held in (positive) inventory, and a shortage cost of v_{sms} per m^3 per day in backlog. For n days simulation length period, the average volume of sawlogs (per day) held in inventory is equation (3-3):

$$\overline{I}^{+}_{sms} = \frac{\int_{0}^{n} I^{+}_{sms}(t)dt}{n} \qquad [3\text{-}3]$$

And the average volume of sawlogs (per day) held in backlog is equation (3-4):

$$\overline{I}^{-}_{sms} = \frac{\int_{0}^{n} I^{-}_{sms}(t)dt}{n} \qquad [3\text{-}4]$$

Therefore, the average holding cost of sawmill storage per day is equation (3-5):

$$\overline{H}_{sms} = h_{sms}\overline{I}^{+}_{sms} \qquad [3\text{-}5]$$

And the average shortage (or backlog) cost of sawmill storage per day is equation (3-6):

$$\overline{V}_{sms} = v_{sms}\overline{I}^{-}_{sms} \qquad [3\text{-}6]$$

Finally, the average total cost per day for the sawmill storage of maintaining its inventory, $\overline{C}_{sms}$ is equation (3-7):

$$\overline{C}_{sms} = \overline{O}_{sms} + \overline{H}_{sms} + \overline{V}_{sms} \qquad [3\text{-}7]$$

Let $I_{sms}(0)$ be the initial inventory level for the sawmill storage and that no order to the merchandizing yard is outstanding. The sawmill storage evaluates its inventory level at times $t = 0,1,.....,n-1,$ since the simulation is run over at $t = n$ days.

The inventory level of sawmill storage, I_{sms} is modeled as an integer variable. The inventory level of all agents of the sawlogs supply chain model represents the amount of sawlogs physically available with the agent. The sawmill storage orders sawlogs, receives shipments from the merchandizing yard and supplies the sawmill production unit for the production of stud grade lumber. Stochastic demand processing algorithm of the sawmill storage agent is shown in the flow chart (Figure 3-2). When a demand of sawlogs occurs from the production unit and if the sawlogs are on stock, these are immediately supplied, or for backlogged orders demand is met upon arrival of a shipment from the merchandizing yard. Figure 3-3 shows the flow chart for the order processing algorithm of the sawmill storage agent.

The merchandizing yard is included in the simulation model by defining its internal information (state) and parameters in the sawlogs supply chain. At the beginning of each day, the merchandizing yard first checks to see if there are any orders of sawlogs from the sawmill storage agent that need to be shipped, including one that might have just arrived. If so, it will ship in a First-In-First-Out manner any full orders of sawlogs for which it has enough inventory. Partial orders are not shipped. However, there is a random lead (or shipping) time, L_{my} of the merchandizing yard for the shipment to actually arrive at the sawmill storage, where L_{my} is assumed to be uniformly distributed on the interval [0.25, 0.5] day. The new inventory level of sawlogs at the merchandizing yard, I_{my}^{N}, is the old inventory level minus the volume of sawlogs shipped. Any order that is not shipped is backlogged.

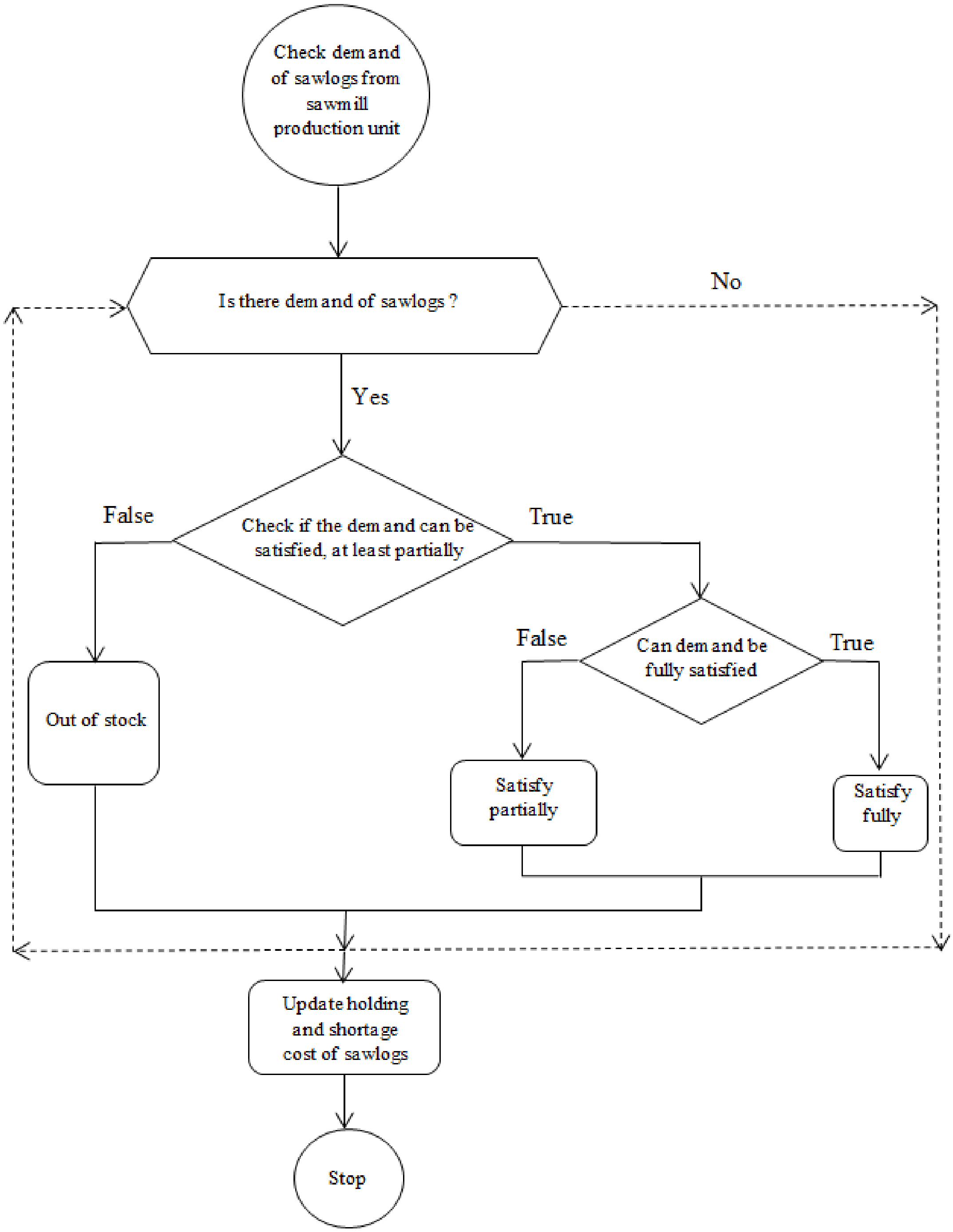

Figure 3-2: Stochastic demand processing flow chart of the sawmill.

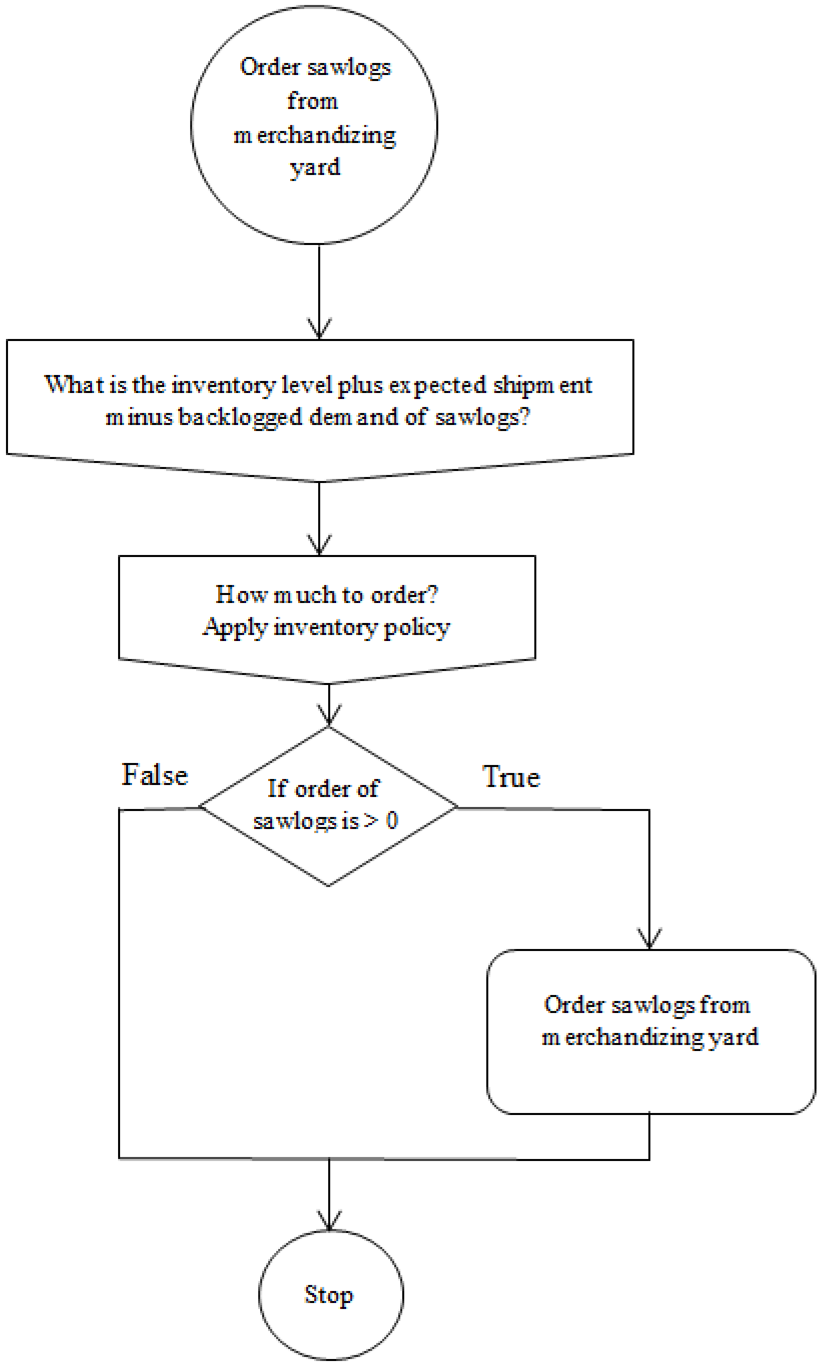

Figure 3-3: Order processing flow chart of the sawmill storage agent.

The merchandizing yard reviews its current inventory level, I_{my}^{N}, after shipping to the sawmill storage and decides how much volume of sawlogs to order from the forest management unit. If the merchandizing yard orders o_{my} volume of sawlogs, it incurs an ordering cost of $K_{my} + i_{my}o_{my}$, where K_{my} is the order setup cost and i_{my} is the order cost per m^3. Note that the total ordering cost O_{my} includes the cost of shipping by the forest management unit. If $o_{my} = 0$, no ordering cost is incurred. The order is sent to the forest management unit electronically and arrives immediately. The merchandizing yard uses a stationary (s_{my}, S_{my}) inventory policy to decide how much to order, in the same manner as sawmill storage. The average total cost per day for the merchandizing yard for maintaining its inventory, $\overline{C}_{my}$, is (equation 3-8):

$$\overline{C}_{my} = \overline{O}_{my} + \overline{H}_{my} + \overline{V}_{my} \qquad [3\text{-}8]$$

Where, h_{my} is the holding cost per m^3 per day and v_{my} is the shortage cost per m^3 per day in backlog. The calculation of $\overline{C}_{my}$ is analogous to the calculation of $\overline{C}_{sms}$ in Equation 3-7. Also, we assume that $I_{my}(0)$ is the initial inventory level for the merchandizing yard and that no order to the forest management unit is outstanding. The merchandizing yard evaluates its inventory level at times, $t = 0,1,\ldots..,n-1$.

The next step is to determine what events or conditions will cause the merchandizing yard object to trigger. The flow chart showing the order processing algorithm of merchandizing yard is shown in Figure 3-4. The three main triggers of the merchandizing yard are: (i) an order received from the sawmill storage agent, (ii) a shipment arrives from the forest management unit, or (iii) at the beginning of each day the incoming orders in the merchandizing yard are processed, sawlogs are shipped and an order to forest management unit is issued. The volume of sawlogs received is added to the inventory of the merchandizing yard. Once the shipment is sent, it logically leaves the merchandizing yard and does not affect its future activity.

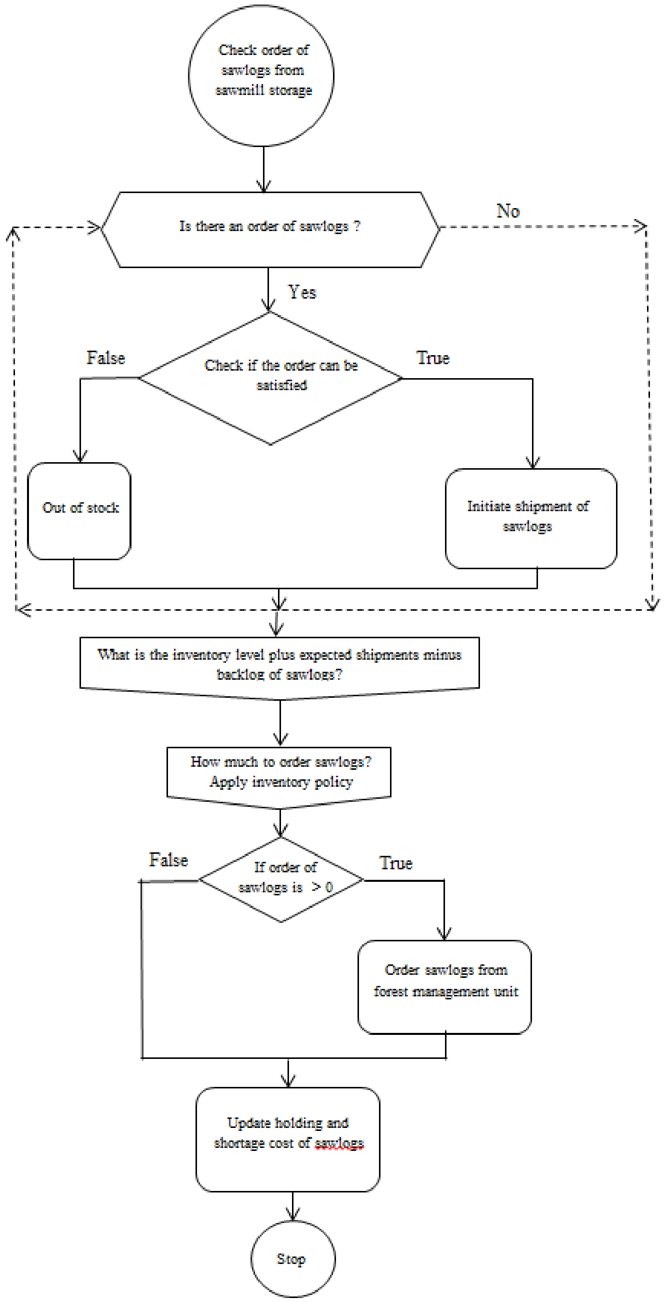

Figure 3-4: Order processing flow chart of the merchandizing yard.

At the beginning of each day, the forest management unit also checks to see if there are any orders from the merchandizing yard that need to be shipped, including one that might have just arrived. If so, it will also ship in a First-In-First-Out manner any full orders for which it has enough inventory. There is a random lead (or shipping) time, L_{fmu}, for the shipment to actually arrive at the merchandizing yard, where L_{fmu} is assumed to be or distributed on the interval [0.5, 1] day. The new inventory level at the forest management unit, I_{fmu}^{N}, is the old inventory level minus the volume of sawlogs shipped. Any order that is not shipped is backlogged. The forest management unit reviews its current inventory level, I_{fmu}^{N}, after orders are shipped to the merchandizing yard, and decides how much volume of sawlogs to harvest, assuming that trees are always available in forest management unit to produce sawlogs. If the forest management unit harvests HR_{fmu} volume of sawlogs, it incurs a harvesting cost of $K_{fmu} + i_{fmu}HR_{fmu}$, where K_{fmu} is the harvesting setup cost and i_{fmu} is the harvesting cost per m^3.

The forest management unit also uses a stationary (s_{fmu}, S_{fmu}) inventory policy, as sawmill storage and merchandizing yard, to decide how much to harvest. The state of the forest management unit is also defined by the inventory level, I_{fmu} and by its backlog order. The flow chart of the order processing algorithm of forest management unit is shown in Figure 3-5. The forest management unit is triggered by three main conditions: (i) an order is received from the merchandizing yard, (ii) the designated harvesting volume of sawlogs is finished, or (iii) at the beginning of each day, the incoming orders are processed, sawlogs are shipped and harvesting operation is setup, if needed.

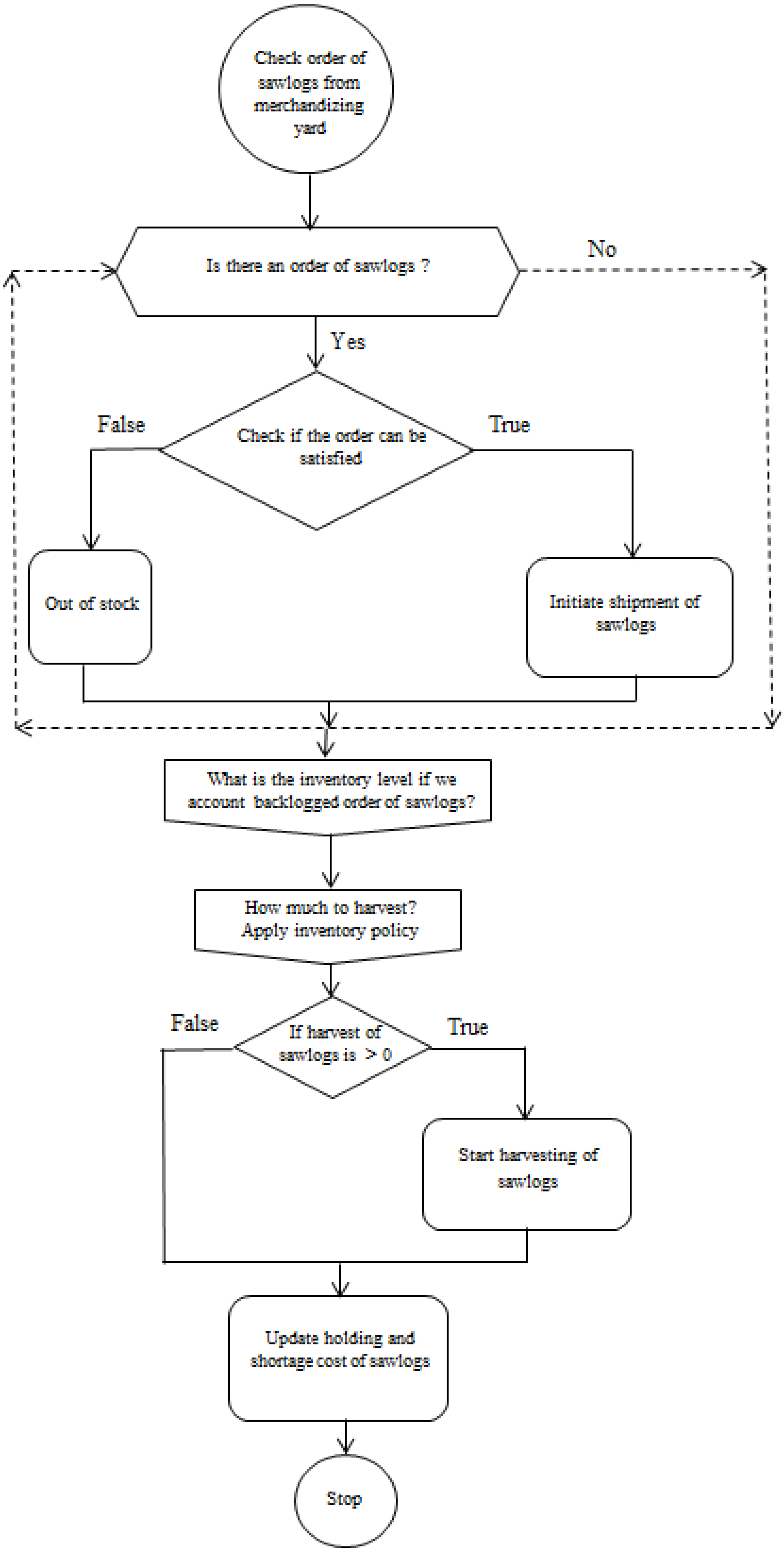

Figure 3-5: Order processing flow chart of forest management unit.

3.3.2 Simulation Model

The total annual demand of sawlogs for stud grade lumber production by the sawmill is 475000 m^3, with quarterly demand variation from 110000 m^3 to 125000 m^3. This data was obtained from the sawmill manager. According to the problem definition, the demand size takes several integer values with predefined probabilities in order to achieve the maximum annual demand of sawlogs of 475000 m^3. The daily demand of sawlogs is assumed to be a discrete random variable that takes on the values 110, 120, 130, 140 and 150 m^3 with respective probabilities of 0.2, 0.4, 0.2, 0.1 and 0.1. The demand of sawlogs occurs at a rate of 10 times per day, since the sawmill production unit approaches the sawmill storage agent with exponential inter-arrival times having a mean of 0.1 day (based on personal communication with the sawmill manager). Table 3-1 and Table 3-2 show the input parameters used for the integrated inventory management sawlogs supply chain simulation model with and without merchandizing yard, respectively. The minimum and maximum inventory parameters with each supply chain agent are assumed to be one-day (1260 m^3) and four days (5040 m^3) inventory, respectively. An initial inventory of 4000 m^3 is assumed at each location. The simulation model is first run with merchandizing yard and then without merchandizing yard to evaluate its role in reducing inventory cost and idle time in the forest products industry supply chain under demand uncertainty. In the absence of a merchandizing yard, the ordering, holding and shortage costs of the merchandizing yard are added to the sawmill storage agent. This is because the sawmill storage unit needs to place the orders for procuring sawlogs directly to the forest management unit in the absence of a merchandizing yard. Although, the ordering, holding and shortage costs of the merchandizing yard will differ from the sawmill storage cost, we assume these to be the same.

Table 3-1: Input parameters of the integrated inventory management sawlogs supply chain simulation model with a merchandizing yard.

Sawmill	
Initial inventory level	4000 m^3
Inventory re-order level, s	1260 m^3
Inventory re-order up to level, S	5040 m^3
Order setup cost	\$30
Order cost per m^3	\$3
Holding cost per m^3 per day	\$1
Shortage cost per m^3 per day	\$5
Merchandizing yard	
Initial inventory level	4000 m^3
Inventory re-order level, s	1260 m^3
Inventory re-order up to level, S	5040 m^3
Order setup cost	\$40
Order cost per m^3	\$4
Holding cost per m^3 per day	\$1.25
Shortage cost per m^3 per day	\$6
Forest management unit	
Initial inventory level	4000 m^3
Inventory re-order level, s	1260 m^3
Inventory re-order up to level, S	5040 m^3
Harvesting setup cost	\$50
Harvesting cost per m^3	\$5
Holding cost per m^3 per day	\$0.75
Shortage cost per m^3 per day	\$4

Table 3-2: Input parameters of the integrated inventory management sawlogs supply chain simulation model without a merchandizing yard.

Sawmill	
Initial inventory level	4000 m^3
Inventory re-order level, s	1260 m^3
Inventory re-order up to level, S	5040 m^3
Order setup cost	$70
Order cost per m^3	$7
Holding cost per m^3 per day	$2.25
Shortage cost per m^3 per day	$11
Forest management unit	
Initial inventory level	4000 m^3
Inventory re-order level, s	1260 m^3
Inventory re-order up to level, S	5040 m^3
Harvesting setup cost	$50
Harvesting cost per m^3	$5
Holding cost per m^3 per day	$0.75
Shortage cost per m^3 per day	$4

In the AnyLogic*TM* software, the cost is defined as a statistics object, which is either discrete or continuous type. Since, ordering and harvesting take place only if an order is placed, which is a discrete event, these costs are defined as discrete statistics object in the software while building the simulation model. Whereas, holding and shortage costs are defined as continuous statistics objects in the software, as holding and shortage cost are an integral of continuous changing value of the cost associated with sawlogs on stock and backlog, respectively at each supply chain agent. The values that are added to the holding cost are the inventory levels multiplied by the cost per m^3 per day. The shortage cost is defined in exactly the same way, but uses backlog multiplied by the shortage cost per m^3 per day. The holding cost is updated when a shipment arrives, whereas the shortage cost is updated when a new order arrives.

The supply chain agents in AnyLogic*TM* software are built as autonomous units capable of making decisions and having clearly defined interfaces with other agents in the model. The supply chain models use agent ports as interface points between two agents. Data can be transferred between two supply chain agents, when they are connected graphically through agent ports. For example, sawmill storage agent and merchandizing yard have two ports each, one for receiving orders and sending products and another for sending orders and receiving shipments. Whereas, the supplier, forest management unit, has only one port for receiving orders and shipping sawlogs (Figure 3-6).

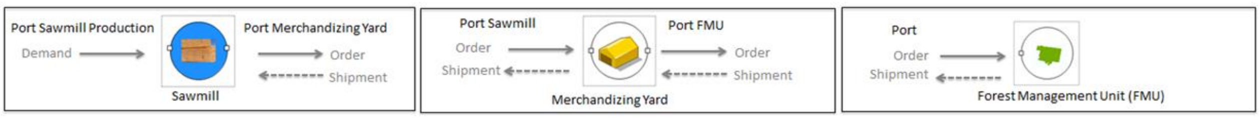

Figure 3-6: Information and material flow interface in supply chain.

The simulation model starts by checking daily demand from the sawmill production unit, which is a discrete random variable to account for uncertainty. A cyclic timeout event is created, which executes at the beginning of each day and invokes ordering or shipping policies of the supply chain agents. This stochastic demand is processed by the sawmill as shown in flow chart (Figure 3-2). Next, the order is processed as described in the order processing flow chart of the sawmill storage agent (Figure 3-3), the merchandizing yard (Figure 3-4), and the forest management unit (Figure 3-5). The two-way flow of information (stochastic demand and orders) and materials (supply and shipment) for the sawlog supply chain are integrated in the simulation model using three Java classes (demand, order and main object) in the AnyLogic^{TM} software. The demand java class defines the stochastic demand (volume of sawlogs) of the sawmill production unit. The order java class contains the order (volume of sawlogs being ordered) and the shipping address. The main object class is used to create a synchronized supply chain between the three agents – sawmill, merchandizing yard, and forest management (Figure 3-7). Synchronization of the supply chain model also defines when and in what order the supply chain agents will execute their shipping/ordering policies. Each simulation-based optimization run generates stationary inventory policy parameters (s, S) for each supply chain agent, based on minimum total daily cost of the entire supply chain.

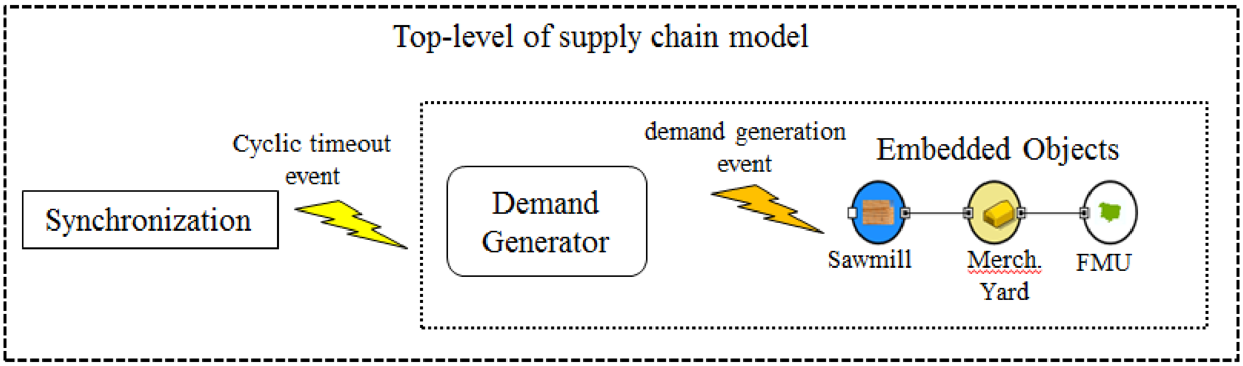

Figure 3-7: Synchronization of supply chain model.

The supply chain model is designed in such a way that there is no communication between the supply chain agents other than message exchange, so that the agents need not know anything about each other's internal structure. This enables independent development and implementation of sawmill storage agent, merchandizing yard and forest management units.

3.3.3 Optimization Model

The simulation model itself does not prescribe an optimal solution for the inventory management problem and requires integration with an optimization approach. An OptQuest engine optimization solver that uses meta-heuristic search algorithm is used to guide the search for optimum solutions (Olafsson 2006). Meta-heuristic search algorithm helps to optimize the stationary inventory policy parameters (s, S) for each agent, and the total daily cost (total of the average daily cost of the three agents) of the supply chain model. Traditional search methods work well with precisely known model data, and find local solutions around a given starting point (Kokash 2005). However, these methods fail when searching for global solutions to real world problems that contain significant amounts of uncertainty (Kokash 2005). Recent developments in optimization have produced efficient search methods capable of finding optimal solutions to complex problems involving elements of uncertainty.

The objective function of the optimization model is to minimize the total daily cost of the three agents in supply chain model, which includes the average total cost per day for the sawmill storage, $\overline{C}_{sms}$, the average total cost per day for the merchandizing yard, $\overline{C}_{my}$, and the average total cost per day for the forest management unit, $\overline{C}_{fmu}$. Mathematically, the objective function is represented as equation (3-9):

Objective function, $fun = Minimize\ (\overline{C}_{sms} + \overline{C}_{my} + \overline{C}_{fmu})$ [3-9]

The stationary inventory policy parameters (s, S) for each agent of the supply chain are the decision variables of the integrated inventory management supply chain model. The constraints (inventory order up to level, S is always greater than reorder level, s for all each supply chain agent) used in the optimization process are shown in Table 3-3. The input parameters (S, s) for each supply chain agent in the optimization model are shown in Table 3-4. Using the objective function to minimize the total daily cost of the entire supply chain (Equation 3-9), the meta-heuristic search algorithm helps to find the optimum stationary inventory parameters (s, S) for each agent in the supply chain (Figure 3-8). The meta-heuristic algorithm evaluates statistical outputs (mean daily cost of the entire supply chain and for each agent in the supply chain, Table 3-5) from the simulation model, analyzes and integrates these outputs with those obtained from previous simulation runs, and determines a new set of values to evaluate.

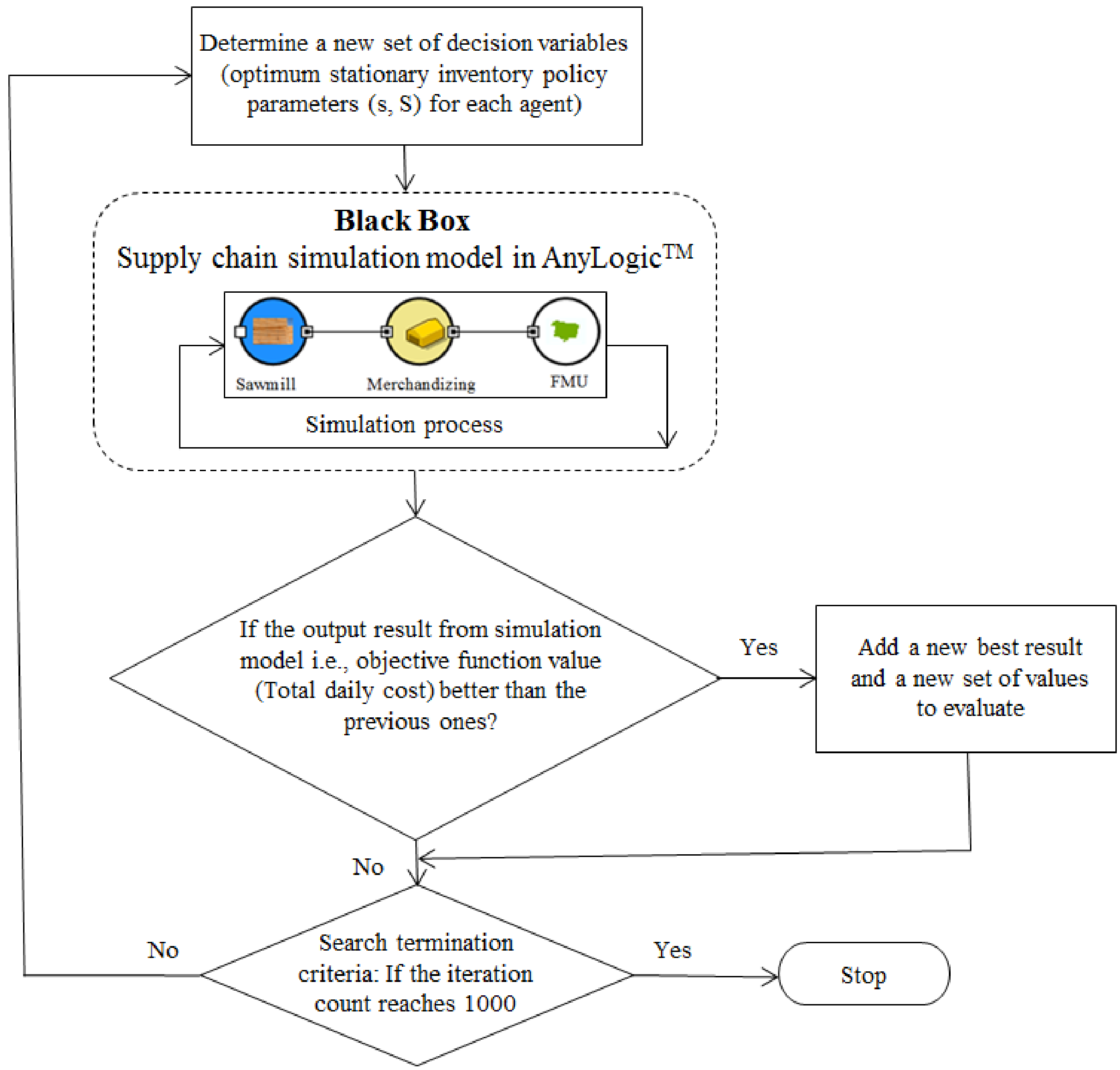

Figure 3-8: Flow chart of the meta-heuristic algorithm using OptQuest engine solver.

Table 3-3: Constraints of the supply chain optimization model.

No.	Constraint		
1	(S – s) for sawmill	≥	0.00
2	(S – s) for merchandizing yard	≥	0.00
3	(S – s) for forest management unit	≥	0.00

Table 3-4: Input parameters of the integrated inventory management optimization model.

Sawmill (s, S) policy parameters	
S (re-order up to level)	10000 m^3
s (re-order level)	0 m^3
Merchandizing yard (s, S) policy parameters	
S (re-order up to level)	10000 m^3
s (re-order level)	0 m^3
Forest management unit (s, S) policy parameters	
S (re-order up to level)	10000 m^3
s (re-order level)	0 m^3
Replications per iteration	10

Table 3-5: Results of the integrated inventory management simulation model.

	With a merchandizing yard	Without a merchandizing yard
Mean idle time	0.11 day	0.074 day
Mean daily cost	\$ 40004	\$ 28202
Sawmill		
Ordering cost per day	\$ 3673	\$ 8448
Holding cost per day	\$ 2169	\$ 4438
Shortage cost per day	\$ 654	\$ 1235
Merchandizing Yard		
Ordering cost per day	\$ 4909	
Holding cost per day	\$ 5365	
Shortage cost per day	\$ 8387	
Forest management unit		
Harvesting cost per day	\$ 6150	\$ 6048
Holding cost per day	\$ 3850	\$ 3786
Shortage cost per day	\$ 4911	\$ 4830

The meta-heuristic search algorithm uses adaptive memory to remember which solutions worked well before and recombines them into new and better global solutions. Since this technique does not use the hill-climbing approach of ordinary solvers, it does not get trapped in local solutions, and it does not get thrown off course by noisy (uncertain) model data. This is an iterative process that successively generates new sets of values. Not all of these values improve the objective function (total daily cost), but over time this process provides a highly efficient trajectory to the best solutions. The search process continues until meta-heuristic algorithm reaches some termination criteria, in this case a maximum number of simulations. In the present optimization process, the search process (optimization stop condition) terminates, when the iteration count reaches 1000. For each simulation, 10 replications are run as specified in Table 3-4. The replication option allows the optimization process to test the statistical significance between the mean of the objective function in the current simulation and the best value found in the previous simulations. The purpose is to weed out inferior solutions without wasting too much time on these. Optimization was performed using Intel® Core™ i7 CPU with 8 GB RAM. The overall flow chart of the simulation-based optimization process of the integrated inventory management supply chain model is explained in Figure 3-9.

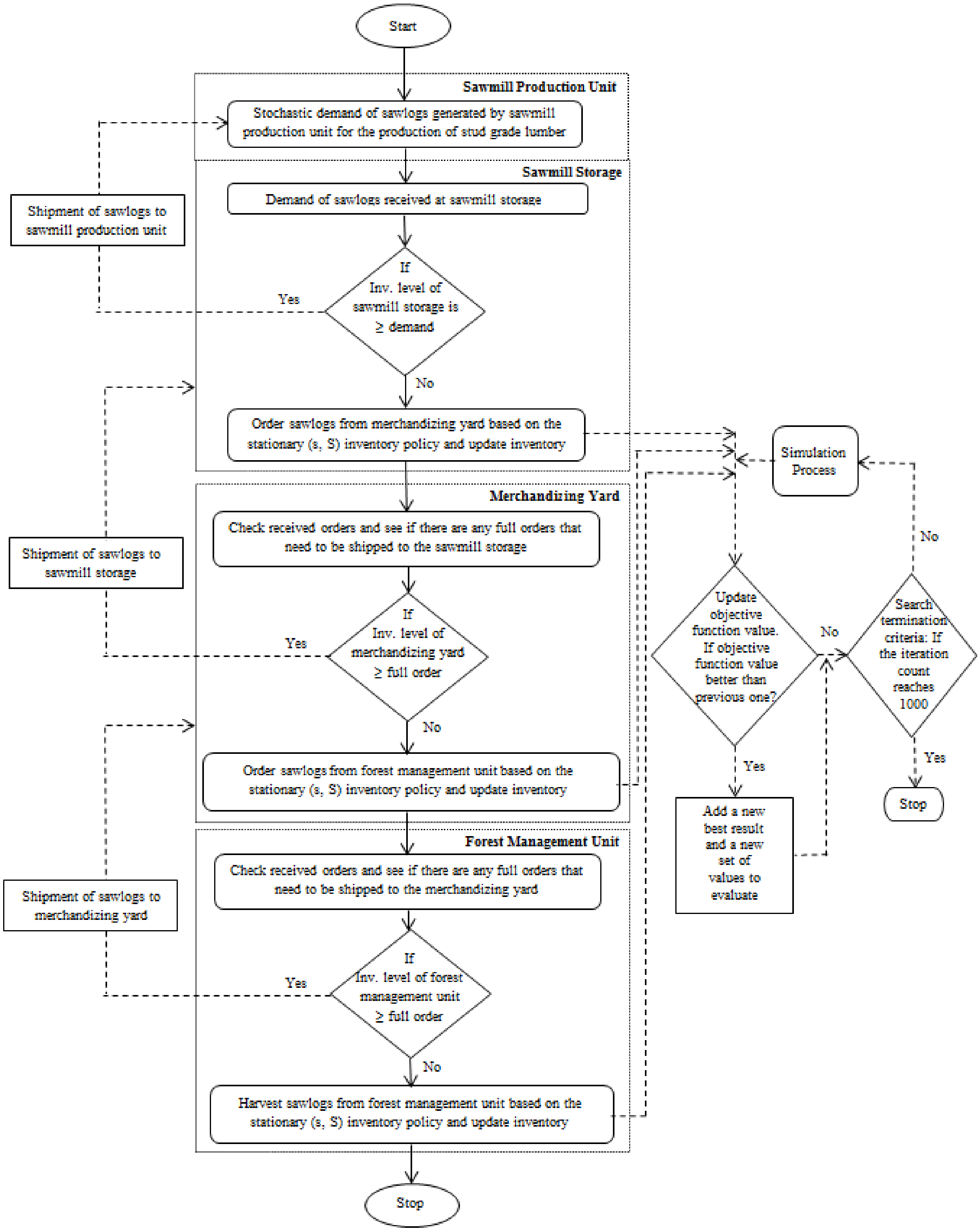

Figure 3-9: Flow chart of the simulation-based optimization process.

3.4 Results

3.4.1 Optimized Inventory Levels and Role of Merchandizing Yard

The results of the simulation model over one year planning horizon for inventory levels at sawmill storage agent, merchandizing yard and forest management unit with and without merchandizing yard are shown in Figure 3-10 and Figure 3-11, respectively. The simulation model calculates the dynamic (for each day) sawlogs inventory levels (m^3) at the sawmill storage agent, merchandizing yard and forest management unit over the planning horizon. The uncertainty in demand at the production unit causes fluctuations in the inventory level at each supply chain location. The simulated inventory level at the forest management unit is fairly even at 5040 m^3 (the re-order up to level, S specified in the model), other than the times, when the inventory level at the sawmill storage reduces to below zero level. The forest management unit first recuperates the inventory of merchandizing yard by holding extra inventory of sawlogs, represented by green peaks in Figure 3-10 and Figure 3-11. The inventory level at the merchandizing yard (represented by yellow lines in Figure 3-10) absorbs most of the shocks caused due to uncertain demand of the sawmill production unit and supplies sawlogs continuously to the sawmill storage unit, as long as it has inventory level up to its re-order point, s. Whereas, the forest management unit has to directly take the shocks caused due to uncertain demand of the sawmill production unit, in the absence of merchandizing yard (Figure 3-11). Table 3-5 presents the results of mean idle time and mean daily cost of the integrated inventory management simulation model with and without merchandizing yard. It is found that there is not much difference in the mean idle time between the two scenarios of with and without merchandizing yard. Table 3-5 also shows the breakup of the mean total cost per day for each supply chain agent. The mean daily cost is composed of ordering cost, holding cost and shortage cost for sawmill storage agent and merchandizing yard, and harvesting cost, holding cost and shortage cost for the forest management unit. The simulation model updates these statistics once a day.

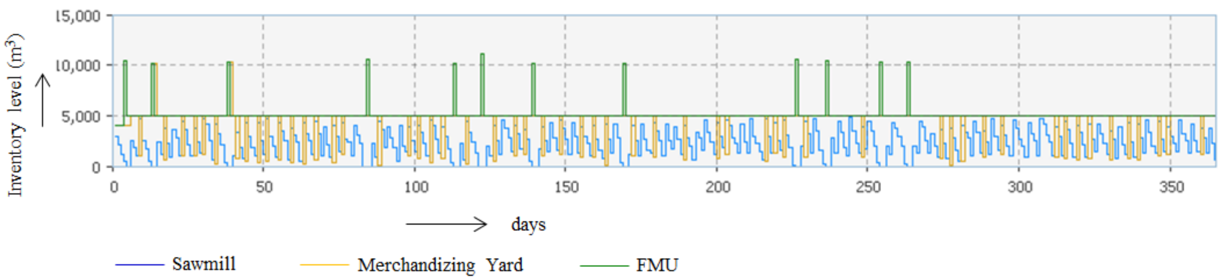

Figure 3-10: Simulated inventory levels over the planning horizon (with merchandizing yard).

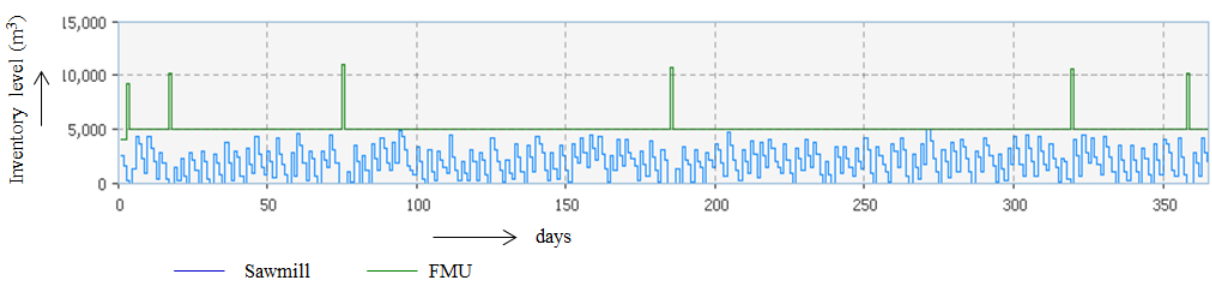

Figure 3-11: Simulated inventory levels over the palnning horizon (without merchandizing yard).

The results of the optimized mean daily cost of integrated inventory management supply chain model with and without merchandizing yard are shown in Figure 3-12 and Figure 3-13, respectively. The grey dots indicate the mean daily cost of the current objective function for a particular simulation run, and the blue line indicates the mean daily cost of the best feasible objective function. The blue line represents the Pareto optimal solution for the mean daily costs of the three supply agents taken together. The optimized mean total daily cost without merchandizing yard scenario is $5,823 lower as compared to the with merchandizing yard scenario.

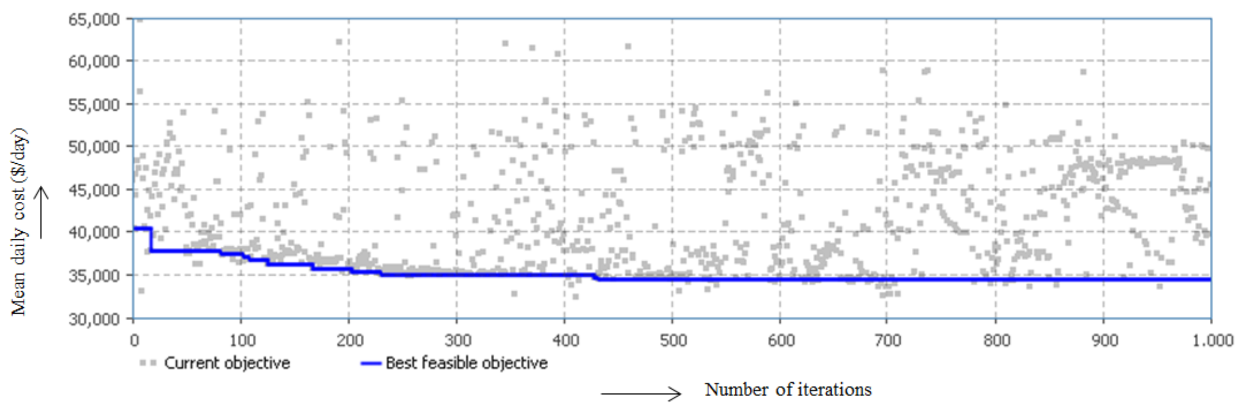

Figure 3-12: Optimization result of mean daily cost with merchandizing yard.

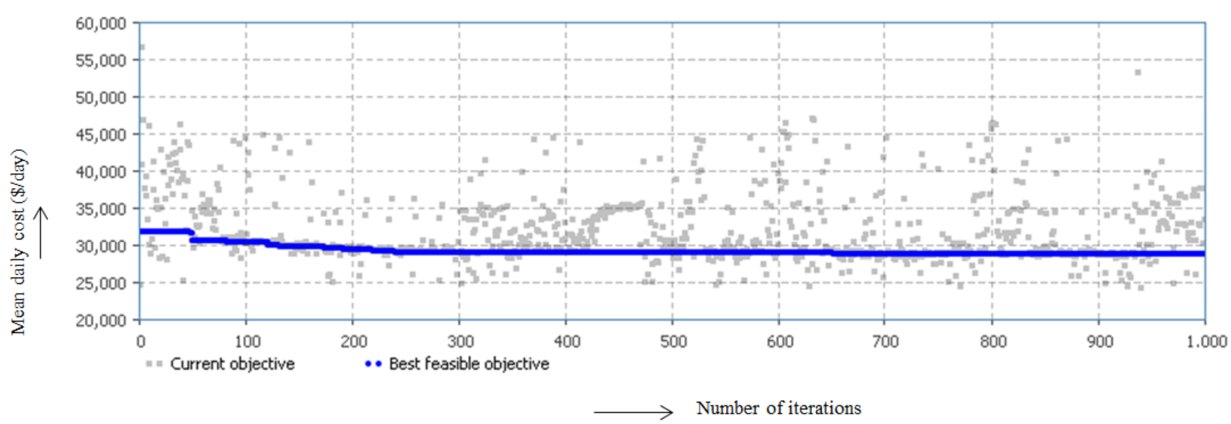

Figure 3-13: Optimization result of mean daily cost without merchandizing yard.

The results of the optimized integrated inventory policy, re-order level and re-order up to level (s, S), for each supply chain agent with merchandizing yard and without merchandizing yard scenario in comparison to a particular simulation are shown in Table 3-6. With an average (uncertain) demand of 1300 m^3 of sawlogs per day, the results show that the sawmill needs to keep about three days of inventory under the optimized inventory policy with merchandizing yard, and about three and a half days of inventory without merchandizing yard. The forest management unit is recommended to keep about two days of inventory in both scenarios. The merchandizing yard, which absorbs the shock due to demand uncertainty, should keep about two days of inventory for an optimized supply chain. The results also show that by following the optimized inventory policy (s, S), the mean daily cost reduces by $4518 and $4614 as compared to the current simulation scenario, with and without merchandizing yard scenarios, respectively.

Table 3-6: Results of the integrated inventory policy (s, S) of the optimization model.

	With a merchandizing yard		Without a merchandizing yard	
Parameters	Current	Optimized	Current	Optimized
Sawmill				
Re-order up to level, S	4830 m^3	3629 m^3	7956 m^3	4496 m^3
Re-order point, s	3978 m^3	3337 m^3	1006 m^3	3953 m^3
Merchandizing yard				
Re-order up to level, S	4345 m^3	2883 m^3		
Re-order point, s	3820 m^3	2803 m^3		
Forest management unit				
Re-order up to level, S	4506 m^3	2799 m^3	6009 m^3	2770 m^3
Re-order point, s	3963 m^3	1954 m^3	2259 m^3	2440 m^3
Number of iterations	1007	624	1000	897
Mean daily cost ($/day)	38967	34449	33240	28626

The simulation-based optimization model developed in this study was used for a single product and singly forest industry (sawmill) scenario. It was found that the merchandizing yard, although absorbing shocks of uncertain demand from sawmill production unit and reducing the mean idle time, in fact increases the mean daily cost of the supply chain. In the absence of merchandizing yard, although the total mean daily cost of the integrated inventory management of the supply chain agents reduces, the mean daily cost of sawmill storage agent more than doubles. Majority of this increase in cost at the sawmill storage agent comes from ordering and holding costs. In the absence of a merchandizing yard, the sawmill storage agent has to order and hold larger inventory of sawlogs, thereby adding to its cost. The amount of inventory held at the sawmill storage agent, without a merchandizing yard scenario, is about six days of inventory, whereas the optimized model result predicts that only three and a half days of inventory is required. Therefore, it was found that the merchandizing yard is not efficient for a single product (sawlogs) and single forest industry (sawmill) scenario. However, if multiple products and multiple industries are considered in the supply chain model, the merchandizing yard is expected to show substantial savings in mean daily cost for all supply chain agents.

3.4.2 Sensitivity Analysis

It is observed that with merchandizing yard scenario, the mean daily cost is higher by \$11802 (42%) as compared to the without merchandizing yard scenario. Merchandizing yard is responsible for 47% of the mean daily cost of \$40004, as it absorbs the shocks caused due to uncertain demand of the sawmill production unit. In the absence of merchandizing yard, although there is a decrease in the total mean daily cost, the total cost (ordering, holding and storage) of the sawmill storage goes up by 117%. The ordering cost of the sawmill storage agent increases, as it has to place large number of orders to the forest management unit. The holding cost at the sawmill storage increases, as the sawmill storage holds a larger inventory in the absence of merchandizing yard from the supply chain. The shortage cost at the sawmill storage agent increases in the absence of merchandizing yard, as any shortage of sawlogs at sawmill production unit has to be directly met from the forest management unit. Sensitivity analysis of holding and shortage costs at sawmill storage agent were conducted in order to analyze their effect on mean daily costs of the sawmill storage agent as compared to the merchandizing yard (Figure 3-14 and Figure 3-15). It is found that a holding cost of more than \$4.25 per m^3 or a shortage cost of more than \$31 per m^3 at the sawmill storage unit would make it unsuitable to eliminate the merchandizing yard from the supply chain, as the mean daily cost of sawmill storage agent becomes higher than that of the merchandizing yard.

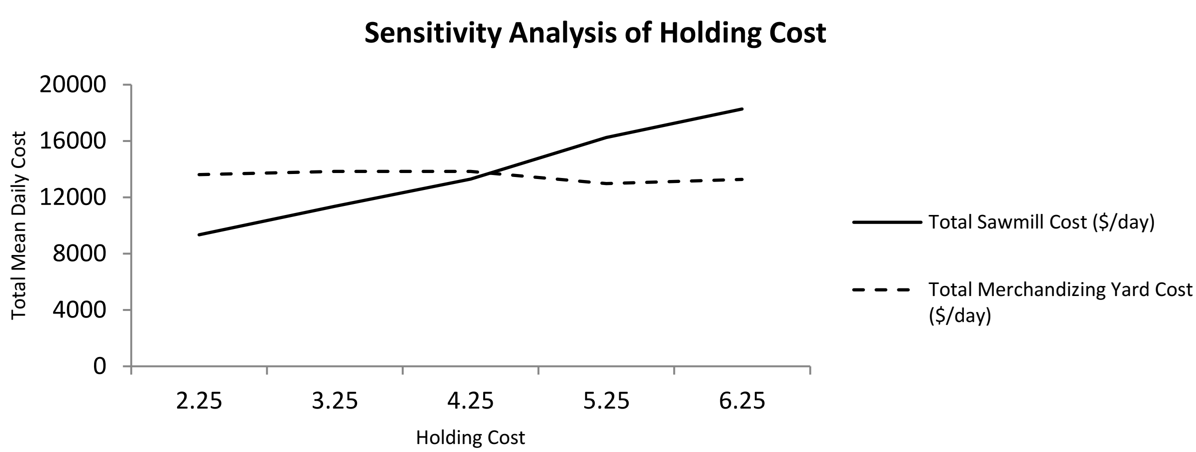

Figure 3-14: Sensitivity analysis of the holding cost at sawmill storage.

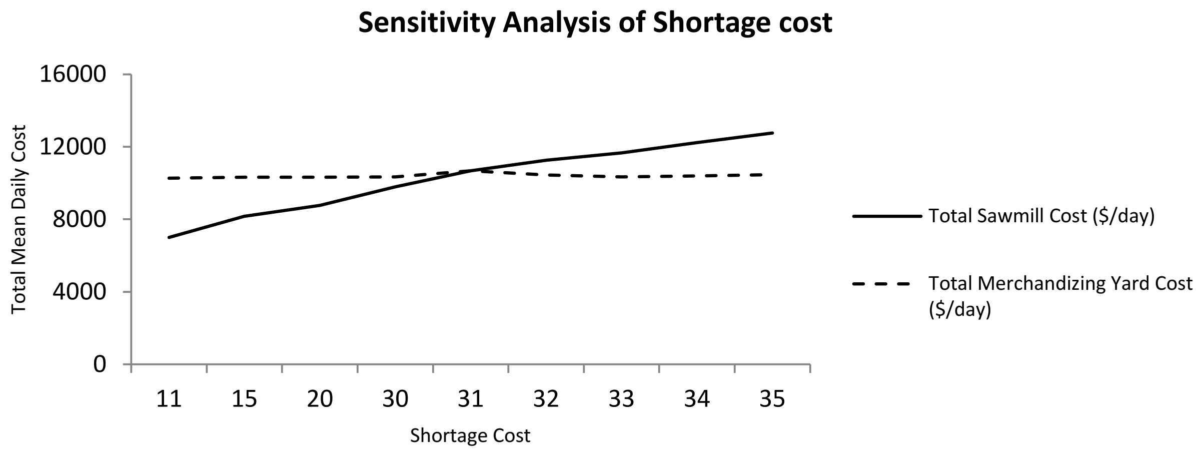

Figure 3-15: Sensitivity analysis of the shortage cost at sawmill storage.

3.5 Conclusions

Sawmills are spending a substantial portion of their costs in procuring raw material (sawlogs). This is evident from the large amount of sawlogs inventory held at many forest products industries across Canada. A simulation-based optimization supply chain model is developed, which optimizes the mean daily cost in procuring sawlogs for sawmill, manufacturing stud grade lumber, from a forest management unit, and helps in integrated inventory management of the supply chain agents. The supply chain model incorporates the two-way flow of information and materials between all the elements of the supply chain. The supply chain models is used for testing the effectiveness of a merchandizing yard in the supply chain, and in reducing idle time and mean daily cost. The simulation model output results show that the presence of merchandizing yard in the supply chain, in fact, increased the mean daily cost, although it absorbs shocks from uncertain demand of the sawmill production unit and reduced idle time in the supply chain. The optimization model output results show that the daily cost of procurement can be substantially reduced if optimum inventory policy (s, S) is followed for each supply chain agent. The merchandizing yard was not found to be efficient for a single product (sawlogs) and single forest industry (sawmill) scenario. The underlying assumptions do not limit the use of this model for other sawmills. However, the input parameters need to be adjusted to make the results applicable to other sawmills. Moreover, this base model can be used as a foundation for advanced integrated inventory management models that incorporate multiple products and multiple industries in the supply chain model, to understand the effectiveness of the merchandizing yard in reducing the mean daily cost for all supply chain agents in multiple industries and products scenario. In addition, future research should incorporate supply side uncertainties in the supply chain model.

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CHAPTER 4
Integrating operational planning decisions throughout the forest products industry supply chain under supply and demand uncertainty

Abstract

In the face of both supply and demand uncertainty, the forest products industry needs advanced supply chain management models that can significantly improve their competitiveness in global markets. This paper aims to provide a decision support tool for integrating operational planning decisions with inventory management of all agents in a multi-product forest industry supply chain under supply and demand uncertainty. A pulp mill is considered as the nodal agent and an integrated simulation-based optimization model is developed, which minimizes the cost of the entire supply chain for different customer satisfaction levels, while material and information flow both upstream and downstream of the pulp mill. The incorporation of a merchandizing yard helps in managing risks associated with supply and demand uncertainty in the forest products industry supply chain. There is a net annual cost saving of $17.4 million by including a merchandizing yard in the supply chain. However, the merchandizing yard is viable only if the shortage cost is above $6.80 per m^3. The merchandizing yard not only absorbs supply shocks for the pulp mill, but also reduces the safety stocks on the downstream side. This integrated supply chain model can be used for operational planning decisions that minimize overall cost for any agent in the supply chain.

Keywords: forest products industry, integrated operational planning decisions, simulation-based optimization, supply and demand uncertainty, supply chain management.

4.1 Introduction

Supply chain management has substantially improved the performance of many industries and helped these industries gain sustainable competitive advantages (Cardoso et al. 2013). The Canadian forest products industry, being heavily dependent on the export market, also needs to ensure its cost competitiveness through proper supply chain management. In the forest products industry, the material flow starts from standing trees in forests and continues with harvesting, bucking, sorting, transportation, and ends with different customers as products such as pulp, paper and rayon (textile) fibre, lumber and dimensional parts (Bredström et al., 2003; Carlsoon and Rönnqvist, 2005). Supply chain management tools have been used to optimize three major activities: harvesting, transportation and production in the forest products industries (D'Amours et al., 2008). The focus of these models has been to maximize profit margins for a given level of market demand by changing production plans and optimally overseeing the reactivity and contingency involved. Very few studies have focused on optimization modeling under uncertainties in demand and supply in the forest products industries, and none have considered uncertainties in both demand and supply (D'Amours et al., 2008; Shahi and Pulkki, 2013). Therefore, the challenge of integrating different supply chain decisions in the forest products industry still remains. This is especially the case when the procurement, production, distribution and sales activities need to be harmonized for independent business agents (e.g., contractors, sawmills, pulp and paper mills, wholesalers, retailers), with their suppliers and customers (Weintraub and Romero, 2006; Shahi and Pulkki, 2013).

The forest products industries have many interconnected supply chain agents that are constrained by their divergent processes (Stadtler, 2005). For example, the forest products supply chain may include the suppliers, who harvest and supply a mix of tree species from the forest management units, the merchandizing yards which convert these trees into logs or chips, the sawmills that transform the sawlogs into lumber or dimension parts, the pulp and paper mills that use the wood chips to create paper or rayon fiber used in textile industries, and the wholesalers and retailers which supply the final products to customers (Carlsson et al., 2006). The varied activities of the forest products industry supply chain agents makes the task of integrating the procurement, production, distribution and inventory management of multiple agents very complex, given that these activities are always bounded by tradeoffs between reducing logistics costs and improving customer satisfaction levels (Carlsson et al., 2008).

Forest products industry supply chain agents traditionally make operational decisions (e.g. harvesting and supply planning, production scheduling, transportation planning) in a hierarchical sequence due to the number of products, processes, suppliers, customers and time periods (Fahimnia et al., 2013a). However, these decisions are reliant on demand and supply, which in turn are highly stochastic in nature (Gaudreault et al., 2011; Church, 2007). The supply of biomass from forests is uncertain to a greater extent, because of the involvement of several products or assortments (saw logs, pulp logs, wood chips and hog fuel) and no detailed information of volume for each product is available at the planned harvest areas (Alonso-Ayuso et al., 2003). Whereas, uncertainty in demand is brought about by external factors, such as continuously changing market conditions and customer expectations (Jung et al., 2004). The hierarchical nature of operational decisions by multiple-agents in the supply chain may result in multiple conflicting and infeasible solutions (Grossi and Kunreuther, 2005; Christopher and Peck, 2004), necessitating the need for integrated multi-level decision-making, despite the inherent modeling complexities (Esmaeilikia et al., 2014; Fahimnia et al., 2013a; Fahimnia et al., 2013b, Fahimnia et al., 2013c). Interest in commercial merchandizing yards has increased in response to uncertainty in timber supply and the need to recover more value from the available resource (Dramm et al., 2002, 2004). Merchandizing involves scanning and bucking tree lengths or long log-lengths into logs and sorting according to the highest end use (Williston, 1976). However, past studies have indicated that costs for managing a merchandizing yard for small-diameter logs could outweigh the revenue generated by sorting and pre-processing those logs (Han et al., 2009, Shahi and Pulkki, 2015). Therefore, the effectiveness of a merchandizing yard for an integrated forest products supply chain system needs to be analyzed (Ganeshan and Ganeshan, 1999).

Customer satisfaction can be achieved if the right kinds of products are delivered to the customers in the right quantity and at the right time. The decisions of all agents in the overall supply chain are impacted with changing customers' demand. This necessitates the need for a flexible supply chain system and dynamic tools for better planning and control. Therefore, the development of robust supply chain management models and methods are an important prerequisite for producing efficient solutions in the complex and dynamic forest industry supply chains. In addition to the customer satisfaction level, cost-based measures have been the predominant performance metric in tackling forest products supply chain problems (Vila et al., 2009, Ahmed and Sahinidis, 1998). The primary cost components in the forest products supply chain problem include harvesting, transportation, inventory (holding and stock out), production and ordering costs. Essentially, the trade-off between these costs is a major task in supply chain network design problems (Frayret et al., 2007). Optimization models have been commonly used in operations management to solve supply chain problems in the forest products industry (Stadtler, 2005). Optimization models can be integrated with simulation models, which allow the decision makers to see the performance of the supply chain over time under various scenarios and help them understand the inter-relationships between different model components (Jung et al., 2004). Optimization models are mostly centralized, while simulation models can more easily represent decentralized decision-making (Jung et al., 2004). Simulation-based optimization models have been used for supply chain management in the manufacturing industries, mainly because of their ability to incorporate uncertainty into the optimization problems (Mele et al., 2006, Fu, 2002). However, there is no integrated simulation-based optimization model that integrates the operational decisions of all supply chain agents in the forest products industry.

The purpose of this paper is to develop simulation-based optimization models that integrate the supply chain decisions of all agents in the forest products industry with two-way flow of information and materials under stochastic supply and demand. The specific objectives are to use these models to: (i) optimize overall supply chain costs under supply and demand uncertainty, (ii) understand the impact of supply and demand uncertainty on customer satisfaction levels and overall supply chain costs, and (iii) study the role of a merchandizing yard in managing risks associated with supply and demand uncertainty, and conduct sensitivity analysis of cost parameters associated with setting up and working of a merchandizing yard.

4.2 Wood fiber flow in a forest products supply chain

Figure 4-1 illustrates multiple levels in a forest products industry supply chain, with a pulp mill as the nodal agent and with a merchandizing yard between the suppliers and the mills. Forest products supply chains have large networks through which wood fiber from the forest is transformed into products demanded by the customer. On the upstream side of the pulp mill, the production network is linked to a procurement network that starts in the forest management unit, and on the downstream side of the pulp mill, the production network is linked to a distribution network that ends with the customers. The procurement network involves suppliers providing a set of products to multiple industries (pulplogs and wood chips to pulp mill, sawlogs to sawmills, hardwood logs to hardwood products industry, and hog fuel for bioenergy plants). The suppliers, who are independent contractors, are responsible for harvesting and distribution activities. Harvesting includes cutting, delimbing and bucking the trees into logs of specific dimensions and quality, usually at the forest landing. Bucking and sorting operations can also be done in a merchandizing yard. Logs of different sizes and quality from the forest landing or merchandizing yard are then transported to the mills, as per their demand. The pulp mill supplies pulp to paper and textile mills, which eventually fulfill product demands at multiple customer locations through wholesalers and retailers. Different modes of transportation (trucks and trains) are used to transport various products from one agent to the other in the supply chain.

The production activities in the mills vary according to the products being produced. For example, different recipes are used for making pulp in the pulp mills, and different bucking and sawing patterns are used in the sawmills (Wood handbook 2010, Bowyer et al. 2003, Panshin and De Zeuuw 1980). At each stage of the production process, some by-products are produced along with the main products. For example, wood chips and saw dust from sawmills are used in the pulp mill for producing pulp and bioenergy, whereas black liquor from pulp mill is used in biorefineries for producing bio-chemicals (Bowyer et al. 2003). The pulp logs and wood chips are converted into pulp in the pulp mill, which is then transformed either into paper in the paper mill or into rayon in the textile mill. Sawmills transform sawlogs into lumber or dimension parts as per the market demand. The hardwood industries convert hardwood logs into boards and panels, which are further used to produce engineered wood products. Panels are produced from wood flakes, which are dried, glued and pressed together under high temperature and pressure (Bowyer et al. 2003). The engineered wood products are used as structural members (flooring or roofing systems) both in residential and commercial buildings. Customers of all these products exhibit different buying practices, which are influenced by a number of external factors including housing starts, mortgage rates, exchange rate, price and quality of the products, and availability of substitutes. A typical pulp mill owns many paper and textile mills on the downstream side and is highly dependent on suppliers on the upstream side. Therefore, there is a need for greater integration and optimization of the cost of the entire supply chain.

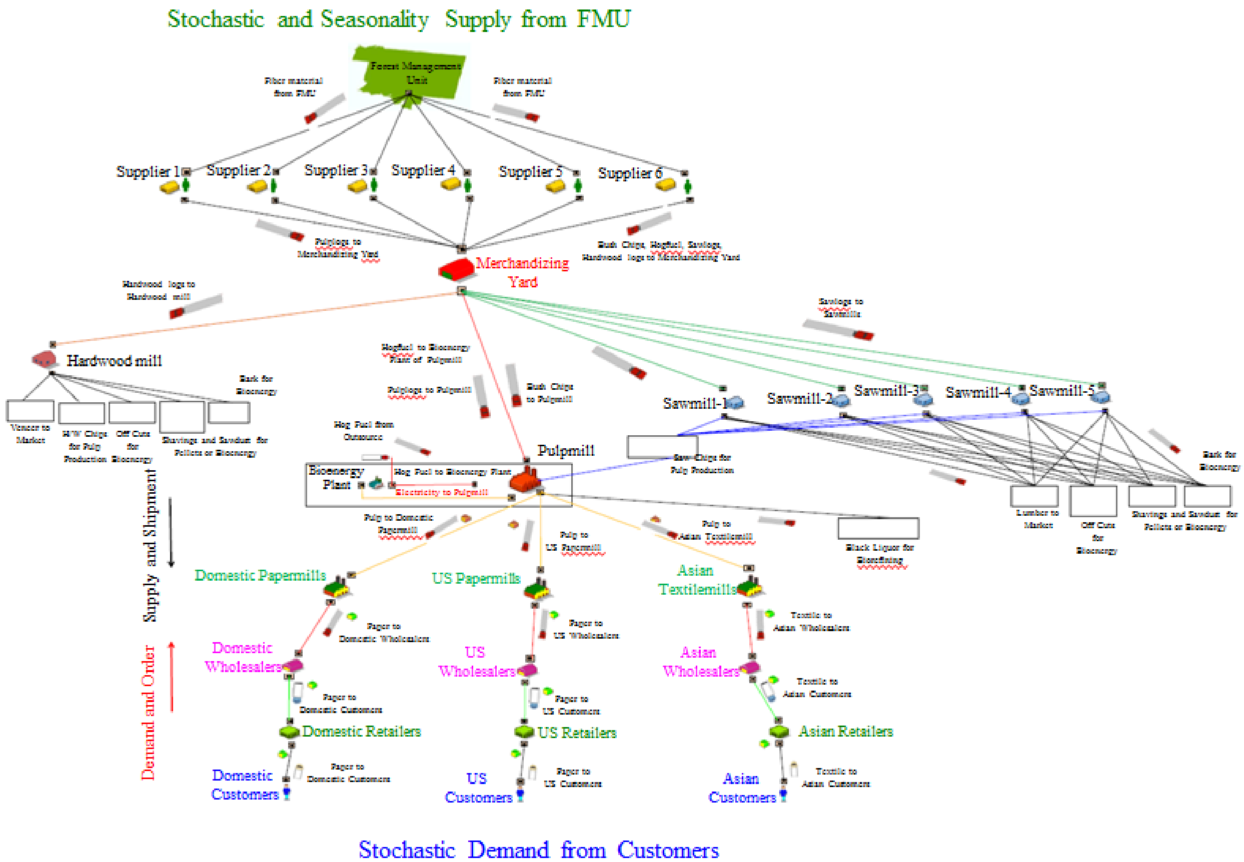

Figure 4-1: Integrated forest products industry supply chain

4.3 Supply and demand uncertainty

The forest products industry has to make supply chain decisions under constantly changing (dynamic) information about supply and demand. However, most models proposed in the literature are not only static, but also deterministic in nature, which do not consider any supply or demand stochasticity (D'Amours et al., 2008). Uncertainty may arise in a system either due to incomplete understanding of the system because of the inherent complexity involved, or due to random changes in parameters of the system (Vose, 2008). Therefore, the approaches used for dealing with uncertainties in supply chain management vary according to the uncertainty in stochastic parameters. The higher the uncertainty, the greater is the difficulty in attributing probabilities to the possible outcomes of a decision. Researchers have used fuzzy sets and possibilities (Zadeh, 1978), belief functions (Shafer, 1990), and rough sets (Pawlak, 1991) to handle uncertain modeling paradigms.

Supply uncertainty is not only caused by random variation in the business-as-usual (BAU) scenario, but by extreme events such as natural disasters (fire or blow down), weather conditions, and operational problems associated with harvesting contractors. The impact of random variation in supply is relatively minor, and it can be modeled using standard probability distributions. However, extreme events are difficult to predict and may have serious consequences on the supply of wood fiber to mills, which makes them much harder to model in the supply chain management process. We considered both types of supply uncertainty, randomness and extreme events, in the wood fibre supply network from forest management units to the mills. The randomness in supply is modeled using a probability distribution. Based on the limited historical data obtained from the pulp mill, the best-fitted probability distribution (Poisson distribution) was determined for supply, which expresses the probability of a given number of events (supply of wood fibre) occurring in a fixed interval of time, when these events occur with a known average rate and independent of the time since the last event. We studied the impacts of extreme events by restricting the supply of all three categories of suppliers on the total cost of the supply chain. We studied the role of merchandizing yards in absorbing shocks (both random and those related to the extreme events) caused due to supply uncertainty. Since variation in supply also impacts customer satisfaction, we analyzed the impact of extreme events on customer satisfaction levels.

Both short and long-term demand uncertainties affect the supply chain system (Gupta and Maranas, 2003). Short-term demand uncertainties may include day-to-day variations, and cancelled/rushed orders, whereas, long-term demand uncertainty refers to seasonal demand variations occurring over longer periods of time. Failure to account for demand fluctuations could either lead to unsatisfied customers, translating to loss of market share or excessively high inventory holding costs (Petkov and Maranas, 1997). Both these situations are highly undesirable in current global market competition, where profit margins are limited. A major source of demand uncertainty in the forest products supply chain is the large variation in the product prices and inventories, which results in large variations in the sales volume. This requires high inventories to be maintained at all times, until the market has found a new equilibrium (Carlsson and Rönnqvist, 2005). When several countries are involved, additional factors such as exchange rates, transfer prices, tariffs, tax regulations and trade barriers further add to demand uncertainty (Martel et al., 2005). Based on the historical data for the demand of paper in the domestic and the US markets, and the demand for textiles in the Asian markets, we used Poisson probability distribution to account for short-term demand uncertainty. The long-term demand uncertainty is analyzed by varying the demand of paper and textile in domestic and export markets.

4.4 Problem description

The nodal agent (pulp mill) in the forest products supply chain (Figure 4-1) needs a regular supply of wood fibre (pulp logs) for un-interrupted production of pulp under both stochastic supply and demand conditions. The supply of pulp logs to the pulp mill is done by three categories of suppliers (small, medium and large). The small, medium and large suppliers supply 18%, 36%, and 46% of the annual demand of the pulp mill, respectively. Although, there is a known average annual rate of pulp logs that the suppliers supply to the pulp mill, there is huge variability in monthly supply. In addition to the pulp logs, the suppliers also supply saw logs, bush chips and hog fuel to different mills in the supply chain that produce multiple by-products, which are further used by other mills. Therefore, there is information (demand and order quantity) and material (supply quantity of multiple products) flowing in both (upstream and downstream) directions in the supply chain. Since the demand of products by customers is also stochastic in nature, there is a trade-off between inventory holding costs and shortage costs for the entire supply chain.

4.5 Integrated supply chain model specification

The integrated supply chain model consists of multiple agents – suppliers of wood fibre from the forest management units, merchandizing yard, primary forest industries (pulp mill, sawmills, and hardwood mills), secondary forest products industries (paper and textile, veneer and panels, lumber and dimensional parts mills), wholesalers, retailers, and customers. The by-products of the secondary forest products industries are either routed back to the pulp mill, or to biorefineries. The model is built in Oracle® software. The supply chain model follows stationary (*s, S*) inventory policy, which is a minimum/maximum inventory policy, for all agents. The re-order point in this inventory policy is the level *s*, and the re-order quantity restores the inventory back to the level *S*. Each agent starts with a beginning inventory level (I_{beg}) and beginning backlog order position (BL_{beg}) for each month. The agent compares its minimum inventory level (*s*) with the difference between the beginning inventory level and the beginning backlog position, and retains the higher of the two as its initial inventory level (I_{int}) for the month. The next step calculates the initial backlog order position (BL_{int}), which is decided as in equation [4-1]:

$$BL_{\text{int}} = \begin{cases} BL_{beg} - I_{beg} + I_{\text{int}} & if \quad BL_{beg} \geq I_{beg} - s \\ 0 & if \quad BL_{beg} < I_{beg} - s \end{cases} \qquad [4\text{-}1]$$

As the supply of material (S_{new}) is received from the upstream agent in respect of the previous month's order, the agent updates its new inventory level (I_{new}) for the month as in equation [4-2]: $I_{new} = I_{\text{int}} + S_{new}$ [4-2]

Next the agent checks its demand received (D_{rec}) from the downstream agents, and updates the new demand (D_{new}) by adding the initial backlog order position (BL_{int}) as in equation [4-3]: $D_{new} = D_{rec} + BL_{int}$ [4-3]

The quantity supplied (Q_{sup}) to the downstream agent is decided by first comparing the new inventory level (I_{new}) with the minimum inventory level (s), and then with the new demand (D_{new}+s) as in equation [4-4] and [4-5].

$$Q_{sup} = \begin{cases} Check(D_{new} + s) & if \quad I_{new} \geq s \\ 0 & if \quad I_{new} < s \end{cases} \tag{4-4}$$

$$Q_{sup} = \begin{cases} D_{new} & if \quad I_{new} > D_{new} + s \\ I_{new} - s & if \quad I_{new} \leq D_{new} + s \end{cases} \tag{4-5}$$

The model then updates the ending inventory level (I_{end}) and ending backlog order position (BL_{end}) of the supply chain agent as in equation [4-6] and [4-7], respectively.

$$I_{end} = I_{new} - S_{qn} \tag{4-6}$$

$$BL_{end} = D_{new} - S_{qnt} \tag{4-7}$$

Finally, an order for supply (O_{sup}) is placed to the upstream agent based on inventory levels (s, S) as in equation [4-8]: $O_{sup} = \begin{cases} 0 & if \quad I_{end} \geq s \\ S - I_{end} & if \quad I_{end} < s \end{cases}$ [4-8]

The total annual ordering cost of the pulp mill receiving unit is given in equation [4-9].

$$O_{pulpmill\ (ru)} = \sum_{i=1}^{12} o_{pulpmill\ (ru)}(i) \tag{4-9}$$

Where, $o_{pulpmill\ (ru)}(i)$ is the ordering cost incurred in the i^{th} month by the pulp mill receiving unit. Let $I^{+}(t) = \max\{I\ (t), 0\}$ be the amount of volume physically on hand in the inventory at time t, and $I^{-}(t) = \max\{-I\ (t), 0\}$ be the backlog at time t, where $I(t)$ is the inventory level at the pulp mill receiving unit at time, t (in months), which could be positive, negative, or zero. If the pulp mill receiving unit incurs a holding cost of $ho_{pulpmill(ru)}$ per m^3 per month, a handling cost of $ha_{pulpmill(ru)}$ per m^3 per month held in (positive) inventory, and a shortage cost of $v_{pulpmill(ru)}$ per m^3 per month for the backlogged orders in (negative) inventory, then the total annual holding, handling and shortage cost of pulp logs for the pulp mill receiving unit are: $HO_{pulpmill\ (ru)} = \sum_{i=1}^{12} ho_{pulpmill\ (ru)}(i)I^{+}$, $HA_{pulpmill(ru)} = \sum_{i=1}^{12} ha_{pulpmill(ru)}(i)I^{+}$,

$V_{pulpmill\ (ru)} = \sum_{i=1}^{12} v_{pulpmill\ (ru)}(i)I^{-}$, respectively.

Finally, the total annual cost for the pulp mill receiving unit, $TC_{pl(ru)}$ is given in equation [4-10]: $TC_{pl(ru)} = O_{pulpmill(ru)} + HO_{pulpmill(ru)} + HA_{pulpmill(ru)} + V_{pulpmill(ru)}$ [4-10]

Using the same logic, the total annual cost for the pulp mill supply unit, $TC_{pl(su)}$ is obtained from the model. The supply unit also incurs a transportation cost for shipping pulp to the downstream mills given by equation [4-11]: $TR_{pulp} = \sum_{i=1}^{12} tr_{pulp}(i)Q_{pulp}$ [4-11]

Where, the pulp mill supplies Q_{pulp} tonnes of pulp per month to the paper and textile mills, and incurs a transportation cost of tr_{pulp} per tonne. The total annual cost for the pulp mill supply unit, $TC_{pl(su)}$ is given by equation [4-12]:

$$TC_{pl(su)} = O_{pulpmill(su)} + HO_{pulpmill(su)} + HA_{pulpmill(su)} + V_{pulpmill(su)} + TR_{pulp} \quad [4\text{-}12]$$

The total annual production cost for the pulp mill is calculated from the total production, pr_{pulp} tonnes of pulp per month, and production cost of pc_{pulp} per tonne, using the equation [4-13]: $PR_{pulp} = \sum_{i=1}^{12} pr_{pulp}(i)pc_{pulp}$ [4-13]

The costs in equations [4-10], [4-12] and [4-13] are added together to obtain the total annual cost, TC_{pl} for the pulp mill, given in equation [4-14]:

$$TC_{pl} = TC_{pl(ru)} + TC_{pl(su)} + PR_{pulp} \qquad [4\text{-}14]$$

The total annual costs of other supply chain agents, are calculated in the same manner as explained for the pulp mill, except for supplier, where harvesting costs are also added.

4.5.1 Model parameters

The total annual demand of paper is 42,000 tonnes in the domestic market, 240,000 tonnes in the US market, and the annual demand of textiles in the Asian market is 72,000 tonnes, with monthly random demand variations. The total annual supply of wood fibre from the forest management units is 1,650,000 m^3, with random monthly supply variations by the suppliers (data obtained in consultation with the pulp mill managers). The demand of paper in the domestic and the US market, and the demand of textiles in the Asian market follow a Poisson distribution with a known monthly average of 3,500 tonnes, 20,000 tonnes, and 6,000 tonnes, respectively. The cost parameters of the suppliers are shown in Table 4-1. The suppliers harvest trees from the forest management units and convert these into pulp log (54%), saw logs (18%), bush chips (13%), hardwood logs (15%), and hog fuel (13%). It is assumed that the saw mills are of different capacities, and the suppliers supply 10% of their harvested saw logs to saw mill 1, 15% to saw mill 2, 20% to saw mill 3, 25% to saw mill 4, and 30% to saw mill 5. The saw mills convert the saw logs to lumber (50%), saw chips (25%), offcuts (10%), shavings and saw dust (10%), and bark (5%). The hardwood mills convert the hardwood logs to veneer (50%), hardwood chips (25%), offcuts (10%), shavings and sawdust (10%), and bark (5%). The pulp recovery is assumed to be 50% from pulp logs, and 15% from bush and saw chips. In addition, 10% (of total pulp production) black liquor is also produced from the pulp mill. The production cost of pulp in the pulp mill is assumed to be $600 per tonne, if the pulp mill is running at more than 20% of its full production capacity, and $1,000 per tonne otherwise. This is because higher fixed costs at less than 20% running capacity increase the overall production cost. The pulp mill distributes its production to the paper and textile mills, with 11% of pulp production supplied to domestic paper mills, 67% to US paper mills, and rest 22% to Asian textile mills. The average sales price of pulp to the paper and textile mills is assumed to be $1,140 per tonne. The paper and textile mills convert 75% of the pulp received into paper and textiles. The cost parameters of all supply chain agents are shown in Table 4-1.

Table 4-0-1: Cost parameters of the integrated supply chain model agents

Costs	Suppliers ($/m3)	Merchandizing yard ($/m3)	Pulp mill ($/m3)	Paper/Textile mills ($/m3)	Wholesalers ($/tonne)	Retailers ($/tonne)
Harvesting cost	7.00					
Ordering cost			5.00	4.50	3.50	2.50
Holding cost	4.50	6.50	5.50	3.50	2.50	1.50
Shortage cost	4.75	6.75	5.75	3.75	2.75	1.75
Handling cost	6.00	8.00	7.00	5.00	4.00	3.00
Transportation cost	6.75	7.00	7.75	5.75	4.75	3.75
Production cost			8.00	8.00		

4.5.2 Simulation model

The simulation model starts by generating stochastic monthly demand of paper from the domestic and the US customers, and stochastic monthly demand of textile from the Asian customers. The supply chain agents of each product receive the monthly demand from the customers, and based on their inventory level either supply the desired quantity of product to the customers or place an order to the upstream agent. All the agents in the supply chain maintain their inventory levels using the stationary inventory policy (*s, S*). The supply chain agents are built as autonomous units capable of making decisions and having clearly defined interfaces with other agents in the model.

4.5.3 Optimization model

The simulation model itself does not prescribe an optimal solution for the integrated operational planning and inventory management problem and requires integration with an optimization approach. An OptQuest engine optimization solver that uses meta-heuristic search algorithm guides the search for optimum solutions (Olafsson 2006). The objective function of the optimization model is to minimize the overall cost of the entire supply chain, including suppliers, merchandizing yard, pulp mill, paper and textile mills, wholesalers, and retailers. Mathematically, the objective function is represented as equation [4-15]: Objective function: Minimize total cost (TC) of the entire supply chain,

$$TC = \sum_{m=1}^{12} \sum_{t=1}^{3} \sum_{s=1}^{2} \sum_{k=1}^{6} \left(tC_{r_{mt}} + tC_{w_{mt}} + tC_{p_{ms}} + tC_{tm} + tC_{pl_m} + tC_{my_m} + tC_{s_{mk}} \right) \qquad [4\text{-}15]$$

where; m =1, ..., 12 indicate twelve months of the year.

$tC_{r_{mt}}$ = total monthly supply chain cost of all retailers ($t = 1, 2, 3$ indicates domestic, the US and the Asian retailers)

$tC_{w_{mt}}$ = total monthly supply chain cost of all wholesalers ($t = 1, 2, 3$ indicates domestic, the US and the Asian wholesalers)

$tC_{p_{ms}}$ = total monthly supply chain cost of all paper mills ($s = 1, 2$ indicates domestic, the US paper mill)

tC_{tm} = total monthly supply chain cost of Asian textile mills

tC_{pl_m} = total monthly supply chain cost of the pulp mill

tC_{my_m} = total monthly supply chain cost of the merchandizing yard

$tC_{s_{mk}}$ = total monthly supply chain cost of all suppliers ($k = 1, \ldots, 6$ indicates two small, two medium and two large suppliers)

such that a specified customer satisfaction level (90% in case of business as usual scenario) is achieved. The decision variables for this optimization model are order quantity, inventory policy parameters (s, S), and supply quantity of all supply chain agents. The constraints (*S* is always greater than s for each supply chain agent) are used in the optimization process.

The meta-heuristic algorithm evaluates statistical outputs (total cost for each agent in the supply chain) from the simulation model, analyzes and integrates these outputs with those obtained from previous simulation runs, and determines a new set of values to evaluate. The meta-heuristic search algorithm uses adaptive memory to remember which solutions worked well before and recombines them into new and better global solutions. The search process continues until meta-heuristic algorithm reaches some termination criteria, in this case a maximum number of simulations (1000 iteration counts). For each simulation, 10 replications are run. Optimization was performed using Intel® *Core™ i7 CPU* with *8 GB RAM*. The overall flow chart of the simulation-based optimization process in the integrated supply chain model is shown in Figure 4-2.

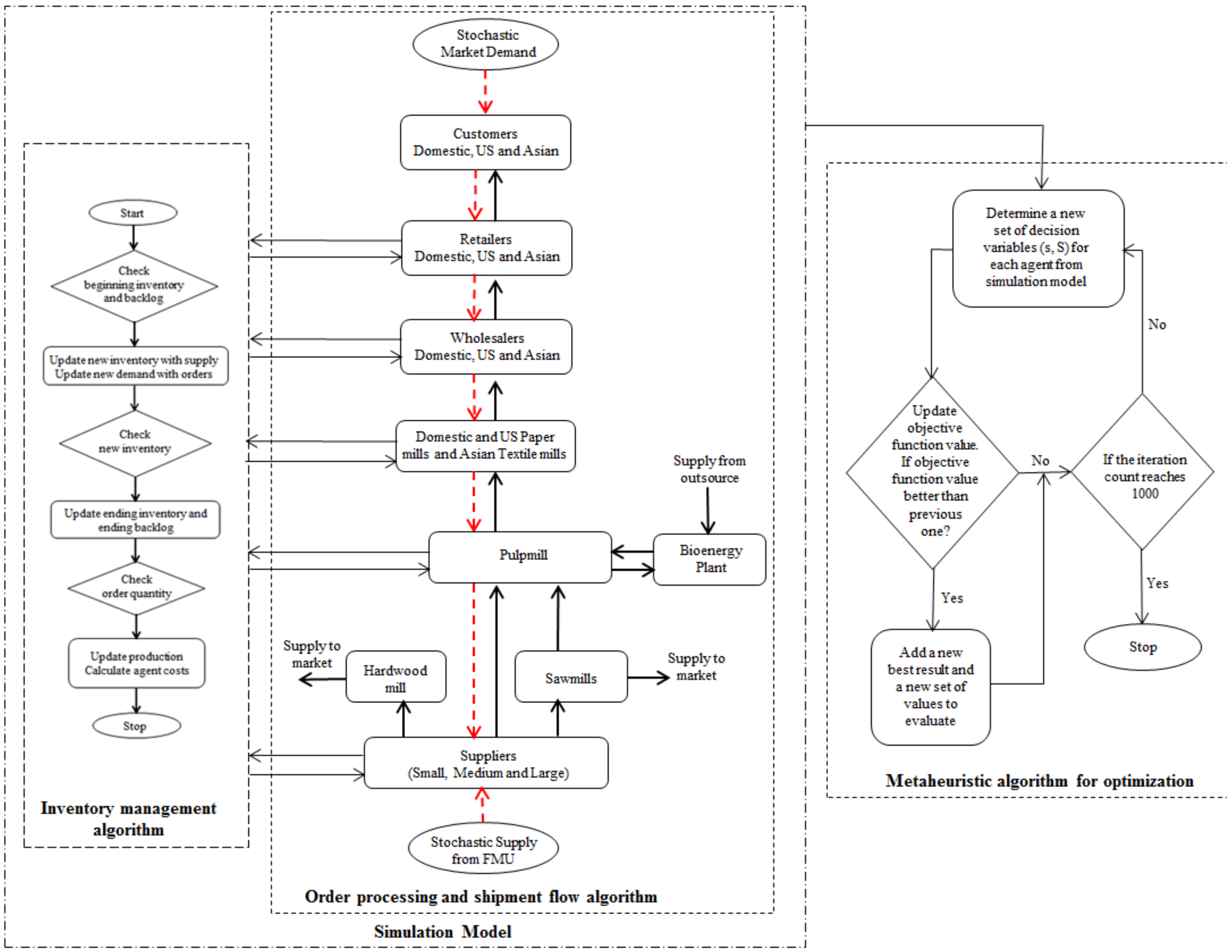

Figure 4-2: Overall flow chart of the simulation-based optimization process in the integrated supply chain model. material flow ⟶ information flow - - ->

4.6 Results and Discussion

4.6.1 Optimizing overall supply chain costs under uncertainty

The optimization model converges to a total annual cost of the entire supply chain to $201,848,723, including a cost total annual cost for the pulp mill of $86,211,511. The results of the optimization model, focusing on minimizing the cost of only the pulp mill show a saving of $5,163,846 (about 6%) for the pulp mill. However, this reduction in cost for the pulp mill increases the supply chain costs of the downstream paper and textile mills by about 5%. This is because, the decrease in inventory holding and its associated costs in the pulp mill, increases the ordering and transportation costs (by 25.3%) of the downstream paper and textile mills, as these have to place multiple orders to fulfill the fluctuating market demand. Therefore, it is not in the best interest of the entire supply chain to focus on optimizing the cost of a single agent (in this case the pulp mill), rather the focus of the integrated optimization model should be to minimize the cost of the entire supply chain. The rest of the analysis is performed by considering the entire supply chain, and minimizing the cost of the integrated supply chain that includes all agents both upstream and downstream to the pulp mill.

4.6.2 Impact of supply and demand uncertainty on customer satisfaction levels

The results show that disruption in supply by the suppliers has a direct impact on the customer satisfaction level and costs of all supply chain agents. With 80% reduction in supply of wood fibre by the small supplier, the customer satisfaction (which is 90% in the BAU scenario) of all three types of customers (domestic, the US customers and the Asian customers) is not affected. However, the model gives an infeasible solution at 90% customer satisfaction, if there is 80% reduction in supply of wood fibre by the medium or large suppliers. The model produces feasible solutions only, if the customer satisfaction is reduced to 75% for reduction in supply by medium suppliers, and to 70% for reduction in supply by large suppliers (Figure 4-3). Therefore, small wood fibre suppliers do not substantially affect the customer demand or satisfaction levels. The introduction of supply uncertainty by medium and large wood fibre suppliers has a direct impact on customer satisfaction.

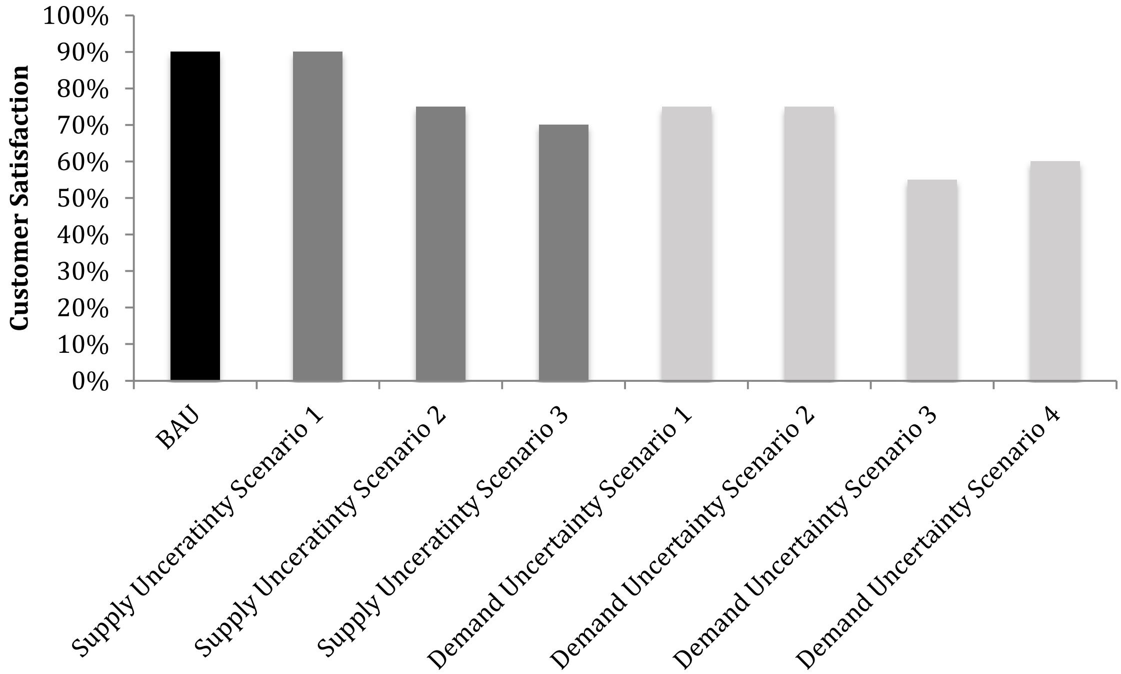

Figure 4-3: Effect of supply and demand uncertainty on customer satisfaction

SU Scenario 1: 80% reduction is supply by small suppliers
SU Scenario 2: 80% reduction is supply by medium suppliers
SU Scenario 3: 80% reduction is supply by large suppliers
DU Scenario 1: Random increase in demand in different months of the year
DU Scenario 2: Sudden random increase in demand (70% to 100%) for four months
DU Scenario 3: Steady long-term increase in demand (from 10% to 120%) over the year
DU Scenario 4: Steady decrease/increase in demand (from 15% to 90%) for different products

We modeled both short-term demand uncertainty, which includes day-to-day variations, and long-term demand uncertainties, which includes seasonal demand variations occurring over longer periods of time, using four different scenarios. The first two scenarios capture the short-term random variations in demand, and the other two scenarios capture the steady long-term changes in demand. The first scenario is a random increase in demand (5% to 70%) in different months of the year for all three products markets (demand of paper in the domestic and the US market, and textile in the Asian market). The second scenario is no demand increase for eight months of the year, but for the rest of four months, there is sudden random increase in demand

(70% to 100%) for all three products markets. The third scenario is a steady long-term increase in demand (from 10% to 120%) over the year for all three products markets. The fourth scenario is a steady decrease in demand (from 15% to 90%) for one product (paper in the domestic and the US market) and a steady increase in demand (from 15% to 90%) for the other product (textile in the Asian market). Under each of the four scenarios, the model produces infeasible solutions, when customer satisfaction level is set at 90% (as in BAU scenario) for all three types of customers (domestic and the US customers for paper, and Asian customers for textile). The model produces feasible solutions only, when the customer satisfaction level for all three types of customers is reduced to 75% in scenario 1 and 2, 55% in scenario 3 and 60% in scenario 4 (Figure 4-3). Therefore, the customer satisfaction level is less impacted under short-term demand uncertainty as compared to long-term demand variation.

4.6.3 Impact of supply and demand uncertainty on overall supply chain costs

There is an increase in the overall supply chain cost when extreme uncertainty in supply is introduced by reduction in wood fibre supply by the suppliers, as compared to the BAU scenario. However, the cost of the pulp mill (nodal agent) receiving unit reduces, as the mill is now procuring wood fibre from fewer suppliers (Table 4-2). The high percentage increase in shortage cost is due to the fact that with the reduction in wood fibre supply by the medium and large suppliers only 75% and 70% of customer demand is met, respectively. This results in high shortage cost due to the fact that the pulp mill receiving unit is unable to meet the demand of the production unit for pulp production. The restriction in supply also increases the shortage cost (102.2% for medium suppliers and 49.6% for large suppliers supply restrictions) of the pulp mill supply unit, as it is not able to meet the demand of the paper and textile mills for production of paper and rayon fibre. The supply uncerainty also increases the downstream costs of the supply chain. However, a direct comparison of the downstream costs with BAU scenario (with customer satisfaction of 90%) is not possible, as the model is not able to achieve the customer satisfaction level of 90% under reduction in wood fibre supply either by medium or large suppliers.

Table 4-2: Change in supply chain costs of the pulp mill receiving unit under supply uncertainty

Supply chain costs	Change in supply chain cost under restriction in supply by suppliers	
	Medium	Large
Ordering	-15.5%	-13.2%
Transportation	-25.7%	-26.3%
Holding	-21.5%	-8.0%
Handling	-22.6%	-12.9%
Shortage	+591.0%	+132.7%

There is no major change in the overall cost of the supply chain as compared to the BAU scenario under all scenarios of demand uncertainty, coupled with wood fibre supply uncertainty, for all three products. However, with increase in demand uncertainty, the supply chain agents are not able to meet the customer demand and the customer satisfaction level reduces from 90% in the BAU scenario. This reduction in customer satisfaction has a major impact on the shortage cost of all agents, especially in the downstream side of the supply chain. For example, the average shortage cost of the downstream paper and textile mills increased from 76.2% to 324.9% under different demand uncertainty scenarios. The average increase in shortage cost of the wholesalers varies from 16.4% to 95.9%, and the average increase in shortage cost of the retailers varies from 283.3% to 953.0% (Table 4-3). In the first two scenarios, the average increase in shortage cost of the receiving unit is higher than the average increase in shortage cost of the supply unit, while it is opposite for the other two scenarios. With random short-term increase in demand, the receiving units are not able to supply pulp to the production unit, whereas with a steady variation in demand, the receiving unit is able to make adjustments in the inventory level.

Table 4-3: Average increase in shortage cost of downstream agents under demand uncertainty

Supply chain costs	Increase in shortage costs of supply chain agents		
	Paper and textile mills	Wholesalers	Retailers
Scenario 1	116.3%	28.9%	444.5%
Scenario 2	122.2%	16.4%	953.0%
Scenario 3	324.9%	20.1%	530.8%
Scenario 4	76.2%	95.9%	283.3%

4.6.4 Role of merchandizing yard

The results of optimized total cost of the supply chain in the business as usual (BAU) scenario were compared with the scenario by including a merchandizing yard between the suppliers and the mills (Figure 4-4). With a merchandizing yard, there is a total annual cost saving of 8.6% in the entire supply chain. However, the nodal agent, pulp mill, has the highest cost saving of 19.2% under the merchandizing yard scenario. The merchandizing yard also helps in reducing the costs in the downstream side (below pulp mill) of the supply chain by 11.1% and in the upstream side (above and including pulp mill) of the supply chain by 12.4%. There is a net annual cost saving of $17.4 million by including a merchandizing yard in the supply chain of a multi-product forest industry. The annual cost of setting up and operation of the merchandizing yard is $47.8 million, and about half ($23.5 million) of this cost is for handling the material in the merchandizing yard and about one-fourth ($12.9 million) of this cost is the holding cost. The handling and holding costs for the merchandizing yard are high, as all suppliers, who harvest forest products (sawlogs, pulplogs, bush chips and hog fuel) from the forest management units, supply these to the merchandizing yard, as opposed to handling and holding these independently at the forest landing. In the downstream side of the supply chain, the paper and textile mills benefit more in cost saving as compared to the wholesalers and retailers in the presence of a merchandizing yard. The handling and holding costs of both the receiving and supply units of mills (pulp mill, paper and textile mills) are generally low, whereas the production and transportation costs are high, as large amounts of materials is flowing in the forest industry supply chain in the presence of a merchandizing yard (Table 4-4). In the present scenario, we only consider one central merchandizing yard, which is located between the suppliers and the mill. However, in the real world, there could be multiple merchandizing yards depending on harvesting locations and the network of roads in the area. A multiple-merchandizing yard scenario would affect the transportation cost, as the distances of the merchandizing yards will vary from the mills.

The merchandizing yard also substantially helps in reducing the inventory levels (both re-order level, *s* and re-order up to level, *S*) of all agents in the supply chain as compared to the BAU scenario, except the retailers, whose inventory level increases by about 2% (Table 4-5). The retailers cannot change their inventory policy under random changes in demand by the customers, and adopt only by changing their orders to the wholesalers. This increases their ordering costs. However, with sustained and assured increase in demand, the retailers can plan to increase the safety stock (For example by expanding the facility or add new buildings and stockyards). The merchandizing yard mostly absorbs the shocks of uncertainty in supply and reduces the annual supply chain costs of all secondary manufacturing mills (paper and textile) in the supply chain. However, a merchandizing yard reduces the number of feasible solutions for minimizing the integrated supply chain cost in the optimization model, because of the restriction that the suppliers have to bring their material to a central location before supplying to the mills. A high customer satisfaction level can also be retained in the presence of a merchandizing yard in the supply chain, as the mills can produce according to the customer demand.

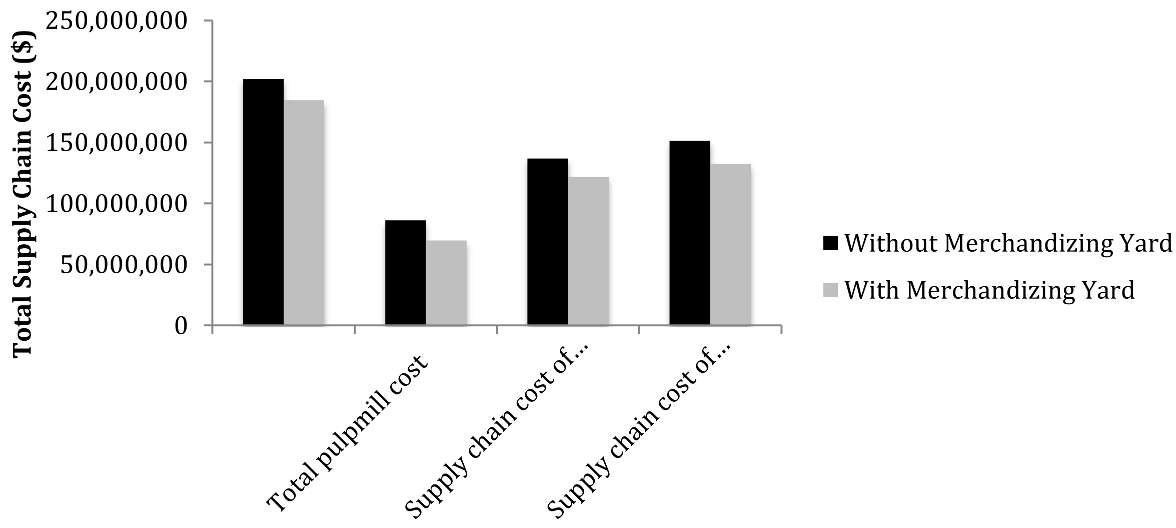

Figure 4-4: Comparison of the results of optimized total cost of the supply chain

Table 4-4: Supply chain costs of pulp mill, domestic paper mills, US paper mills, and Asian textile mills with and without MY

	Pulp mill		Domestic Paper mills		US Paper mills		Asian Textile mills	
	Without MY	With MY	Without MY	With MY	Without MY	With MY	Without MY	With MY
	Receiving Units							
Holding cost ($)	13,782,484	12,885,108	547,596	516,852	2,327,094	2,229,738	881,787	702,954
Handling cost ($)	23,969,902	22,764,885	1,028,087	983,900	4,821,606	4,680,903	1,745,341	1,495,300
Transportation cost ($)	7,117,333	7,047,691	282,678	282,371	1,721,764	1,719,897	558,492	564,742
	Supply Units							
Holding cost ($)	6,273,131	5,782,353	353,472	387,576	1,735,482	1,669,710	644,742	528,318
Handling cost ($)	11,112,434	10,484,414	689,315	737,835	3,602,149	3,506,972	1,285,294	1,123,050
Production cost ($)	3,799,380	3,763,436	294,968	294,648	1,796,623	1,794,675	582,774	589,296
Transportation cost ($)	3,463,639	3,459,884	212,008	211,778	1,291,323	1,289,923	418,869	423,557

Table 4-5: Inventory parameters (s, S) of retailers, wholesalers, paper and textile mills, and pulp mill with and without MY

	Domestic		US		Asian			
	Without MY	With MY	Without MY	With MY	Without MY	With MY	Without MY	With MY
	Retailers							
s (re-order level) (tonne)	999	975	4,767	4,787	1,849	1,821		
S (re-order up to level) (tonne)	6,175	6,200	30,430	30,111	9,022	9,022		
	Wholesalers							
s (re-order level) (tonne)	8,344	8,180	41,237	39,475	12,413	11,275		
S (re-order up to level) (tonne)	19,375	21,008	101,058	99,612	35,996	32,796		
	Paper and Textile mills (RU)						Pulp mill (RU)	
s (re-order level) (tonne)	13,038	12,306	55,407	53,089	20,877	16,737	186,727	171,225
S (re-order up to level) (tonne)	38,085	28,191	134,525	134,508	48,075	43,637	488,449	443,464
	Paper and Textile mills (SU)						Pulp mill (SU)	
s (re-order level) (tonne)	8,416	9,228	41,321	39,755	15,351	12,579	92,714	85,612
S (re-order up to level) (tonne)	19,375	21,178	101,146	101,132	35,999	32,807	220,848	206,566

4.6.5 Sensitivity analysis of the parameters of the merchandizing yard

Although, the establishment and maintenance of a merchandizing yard reduces the shortage cost in the supply chain, it increases the inventory handling, holding and transportation costs, as the merchandizing yard needs to procure and hold more inventory. The results of sensitivity analysis with different cost parameters indicate that the merchandizing yard costs are most sensitive to handling costs (48.1%), followed by holding costs (31.5%), and transportation costs (11.6%). Therefore, the trade-off between the reduction in shortage cost and increase in handling, holding and transportation costs were further analyzed, for different volumes of wood fibre handled by the merchandizing yard (Figure 4-5). Comparing the shortage cost to the other costs, it is observed that as long as the shortage cost is above \$6.80 per m^3, it is viable to keep the merchandizing yard, as below this threshold shortage cost, the handling, holding and transportation for the merchandizing yard becomes too high, and these affect the overall supply chain cost. For uncertainty in supply, introduced by the reduction in supply by the medium and large suppliers, the merchandizing yard reduces the shortage cost by 54.9% and 65.5%, respectively. However, the holding costs only increase by 17.2% and 1.3%, respectively, resulting in saving in the overall supply chain costs. However, the size of the merchandizing yard depends on the volume of wood fibre processed, and the holding time of inventory in the merchandizing yard.

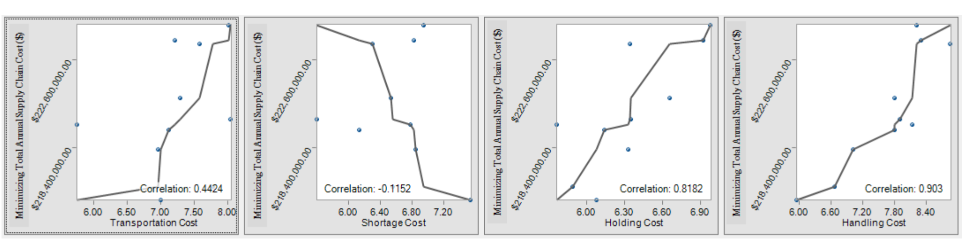

Figure 4-5: Trade-off between shortage and other costs

4.7 Conclusions

The Canadian forest products industry is operating under uncertain supply of wood fibre from the forest management units and uncertain demand of products from the customers. Under these stochastic supply and demand conditions, the forest products supply chain agents are spending a substantial portion of their costs in operational planning decisions (order quantity, inventory planning, and supply quantity). An integrated simulation-based optimization model was developed for the industry that considers the entire supply chain structure and manages all operational planning decisions both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain under supply and demand uncertainty. The supply chain model incorporates two-way flow of information and materials between all the elements of the supply chain across a nodal agent, pulp mill.

Using the model, it is found that the supply uncerainty caused by medium and large wood fibre suppliers has a direct impact on customer satisfaction. When a merchandizing yard is included between the suppliers and the pulp mill, it improves customer satisfaction and results in net annual cost savings in the supply chain. The merchandizing yard not only absorbs supply shocks for the pulp mill and reduces shortage costs, but also reduces the safety stocks on the downstream side. Below a threshold level for the shortage cost, the handling, holding and transportation costs become very high. The customer satisfaction level is also impacted by demand uncertainty. However, the impact is less severe under short-term demand uncertainty as compared to long-term demand variation. The loss in customer satisfaction increases the shortage cost of supply chain agents on the downstream side. The wholesalers can handle some demand uncertainty by increasing their safety stock under steady state long-term demand change scenarios. The retailers cannot make quick changes to their inventory policy under random changes in demand by the customers, and adopt only by changing their orders to the wholesalers. The underlying assumptions do not limit the use of this simulation-based optimization model for any forest products industry supply chain. However, the input parameters need to be adjusted to make the results applicable to specific situations. Future research should focus on integrating this simulation-based optimization model with production planning and scheduling models for the forest products industry, so as to maximize their profits under supply and demand uncertainty. In addition, the simulation-based optimization model should be extended to product markets for secondary industries, such as biorefineries, and should be integrated with forest products trade models.

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CHAPTER 5
Integrating production planning with inventory management decisions in forest industry supply chain under demand and supply uncertainty

Abstract

This paper provides a decision support tool for integrating production planning and inventory management decisions in the forest products industry supply chain under demand and supply uncertainty. A pulp mill is considered as nodal agent in a multi-product, multi-industry forest products supply chain, and an integrated approach is proposed, applying simulation-based optimization method that maximizes the net annual profit of the pulp mill. The supply and demand uncertainty causes a net annual loss of $59.9 million to the pulp mill, as it is only able to run at 10% of its full capacity and achieve 9% customer satisfaction level. The introduction of a merchandizing yard in the supply chain not only absorbs shocks caused due to uncertainty, but also increases the net annual profit of the pulp mill to $26.7 million, ensuring pulp mill running capacity of 70%, and customer satisfaction level of at least 50%. However, the merchandizing yard is viable only if the sales price of pulp is at least $680 per tonne. The integrated supply chain model can be applied to any forest products industry as it considers the entire supply chain structure and manages all business decisions both upstream and downstream in the supply chain.

Keywords: forest products industry, simulation-based optimization, supply uncertainty, demand uncertainty, supply chain management.

5.1 Introduction

The production planning models of forest products industry supply chains do not recognize the demand and supply uncertainty and generate inferior operational management decisions (D’Amours et al. 2008). The Canadian forest industry supply chains are characterized by complex network of suppliers, forest products mills, and distributors, and the inventory stockpiles with each agent affect the overall performance and cost of the entire supply chain. Although, supply chain management tools have been used to optimize harvesting, transportation and production in the forest products industries (D’Amours et al. 2008), very few studies have focused on optimizing inventory levels under demand and supply uncertainties (D’Amours et al. 2008; Shahi and Pulkki

2013).

In the forest products industry, the material flow starts from standing trees in forests, continues through harvesting, bucking, sorting, and transportation into sawmills, pulp and paper mills, where it is converted into products such as lumber, pulp, paper, and dimension parts, and ends with different customers (Bredström et al. 2004; Carlsoon and Rönnqvist 2005). The varied activities of the forest products industry supply chain agents makes the task of integrating the procurement, production, distribution and sales activities very complex, given that these activities are always bounded by tradeoffs between reducing logistics costs and improving customer satisfaction levels (Weintraub and Romero 2006; Carlsson et al. 2008; Shahi and Pulkki 2013).

The tactical planning decisions (e.g. harvesting and supply planning) and operational planning decisions (e.g. production scheduling, inventory planning, transportation planning) in the forest products industry are reliant on demand and supply, which in turn are highly stochastic in nature (Gaudreault et al. 2011; Church 2007; Fahimnia et al. 2013). The supply of biomass from forests is uncertain to a greater extent, because of the involvement of several products or assortments (saw logs, pulp logs, wood chips and hog fuel) and no detailed information of volume for each product is available at the planned harvest areas (Alonso-Ayuso et al. 2003). Whereas, uncertainty in demand is brought about by external factors, such as continuously changing market conditions and customer expectations (Jung et al. 2004). The hierarchical nature of tactical and operational decisions by multiple-agents in the supply chain may result in multiple conflicting and infeasible solutions, necessitating the need for integrated multi-level decision-making (Esmaeilikia et al. 2014; Fahimnia et al. 2013a; Fahimnia et al. 2013b).

Interest in merchandizing yards has increased in response to uncertainty in supply and the need to recover more value from the available resource (Dramm et al. 2002, 2004).

The complex supply chain problem can be solved by integrating optimization models with simulation models, which allow the decision makers to see the performance of the supply chain over time under various scenarios and help them understand the inter-relationships between different model components (Jung et al. 2004). Although, simulation-based optimization models have been used for supply chain management in the manufacturing industries, (Mele et al. 2006; Fu 2002), there is no such models that integrates operational planning with inventory management decision of supply chain agents in the forest products industry.

The purpose of this paper is to develop simulation-based optimization models that integrate production planning and operational management supply chain decisions (order quantity, inventory planning, and supply quantity) under stochastic supply and demand in a multi-product forest industry supply chain with two-way flow of information and materials. The specific objectives are to use the integrated model for: (i) understanding the effects of supply and demand uncertainty on net annual profit of the pulp mill and customer satisfaction levels, and (ii) managing risks associated with supply and demand uncertainty and ensuring capacity-feasible production of the pulp mill.

5.2 Problem Description

The nodal agent (pulp mill) in the forest products supply chain (see Figure 4-1) needs a regular supply of wood fibre (pulp logs) for un-interrupted production of pulp under both stochastic supply and demand conditions. The supply of pulp logs to the pulp mill is done by three categories of suppliers (small, medium and large). The small, medium and large suppliers supply 18%, 36%, and 46% of the annual demand of the pulp mill, respectively. Although, there is a known average annual rate of pulp logs that the suppliers supply to the pulp mill, there is huge variability in monthly supply. In addition to the pulp logs, the suppliers also supply saw logs, bush chips and hog fuel to different mills in the supply chain that produce multiple by-products, which are further used by other mills. Therefore, there is information (demand and order quantity) and material (supply quantity of multiple products) flowing in both (upstream and downstream) directions in the supply chain. Since the demand of products by customers is also stochastic in nature, there is a trade-off between inventory holding costs and shortage costs for the entire supply chain.

5.3 Integrated Supply Chain Model Specification

The integrated supply chain model consists of multiple agents – suppliers of wood fibre from the forest management units, merchandizing yard, primary forest industries (pulp mill, sawmills, and hardwood mills), secondary forest products industries (paper and textile, veneer and panels, lumber and dimensional parts mills), wholesalers, retailers, and customers. The by-products of the secondary forest products industries are either routed back to the pulp mill, or to biorefineries. The model is built in Oracle® software. The supply chain model follows stationary (s, S) inventory policy, which is a minimum/maximum inventory policy, for all agents. The re-order point in this inventory policy is the level s, and the re-order quantity restores the inventory back to the level S. Each agent starts with a beginning inventory level (I_{beg}) and beginning backlog order position (BL_{beg}) for each month. The agent compares its minimum inventory level (s) with the difference between the beginning inventory level and the beginning backlog position, and retains the higher of the two as its initial inventory level (I_{int}) for the month. The next step calculates the initial backlog order position (BL_{int}), which is decided as in equation [5-1]:

$$BL_{int} = \begin{cases} BL_{beg} - I_{beg} + I_{int} & if \quad BL_{beg} \geq I_{beg} - s \\ 0 & if \quad BL_{beg} < I_{beg} - s \end{cases} \qquad [5\text{-}1]$$

As the supply of material (S_{new}) is received from the upstream agent in respect of the previous month's order, the agent updates its new inventory level (I_{new}) for the month as in equation [5-2]:

$$I_{new} = I_{int} + S_{new} \qquad [5\text{-}2]$$

Next the agent checks its demand received (D_{rec}) from the downstream agents, and updates the new demand (D_{new}) by adding the initial backlog order position (BL_{int}) as in equation [5-3]:

$$D_{new} = D_{rec} + BL_{int} \qquad [5\text{-}3]$$

The quantity supplied (Q_{sup}) to the downstream agent is decided by first comparing the new inventory level (I_{new}) with the minimum inventory level (s), and then with the new demand (D_{new}+s) as in equation [5-4] and [5-5].

$$Q_{sup} = \begin{cases} Check(D_{new} + s) & if \quad I_{new} \geq s \\ 0 & if \quad I_{new} < s \end{cases} \qquad [5\text{-}4]$$

$$Q_{sup} = \begin{cases} D_{new} & if \quad I_{new} > D_{new} + s \\ I_{new} - s & if \quad I_{new} \leq D_{new} + s \end{cases} \qquad [5\text{-}5]$$

The model then updates the ending inventory level (I_{end}) and ending backlog order position (BL_{end}) of the supply chain agent as in equation [5-6] and [5-7], respectively.

$$I_{end} = I_{new} - S_{qnt} \qquad [5\text{-}6]$$

$$BL_{end} = D_{new} - S_{qnt} \qquad [5\text{-}7]$$

Finally, an order for supply (O_{sup}) is placed to the upstream agent based on inventory levels (*s, S*) as in equation [5-8]: $O_{\sup} = \begin{cases} 0 & if \quad I_{end} \geq s \\ S - I_{end} & if \quad I_{end} < s \end{cases}$ [5-8]

The total annual ordering cost of the pulp mill receiving unit is given in equation [5-9]. $O_{pulpmill\ (ru)} = \sum_{i=1}^{12} o_{pulpmill\ (ru)}(i)$ [5-9]

Where, $o_{pulpmill\ (ru)}(i)$ is the ordering cost incurred in the i^{th} month by the pulp mill receiving unit. Let $I^{+}(t) = \max\{I\ (t), 0\}$ be the amount of volume physically on hand in the inventory at time *t*, and $I^{-}(t) = \max\{-I\ (t), 0\}$ be the backlog at time *t*, where $I(t)$ is the inventory level at the pulp mill receiving unit at time, *t* (in months), which could be positive, negative, or zero. If the pulp mill receiving unit incurs a holding cost of $ho_{pulpmill(ru)}$ per m^3 per month, a handling cost of $ha_{pulpmill(ru)}$ per m^3 per month held in (positive) inventory, and a shortage cost of $v_{pulpmill(ru)}$ per m^3 per month for the backlogged orders in (negative) inventory, then the total annual holding, handling and shortage cost of pulp logs for the pulp mill receiving unit are:

$HO_{pulpmill\ (ru)} = \sum_{i=1}^{12} ho_{pulpmill\ (ru)}(i) I^{+}$, $HA_{pulpmill(ru)} = \sum_{i=1}^{12} ha_{pulpmill(ru)}(i) I^{+}$,

$V_{pulpmill\ (ru)} = \sum_{i=1}^{12} v_{pulpmill\ (ru)}(i) I^{-}$, respectively.

Finally, the total annual cost for the pulp mill receiving unit, $TC_{pl(ru)}$ is given in equation [5-10]: $TC_{pl(ru)} = O_{pulpmill(ru)} + HO_{pulpmill(ru)} + HA_{pulpmill(ru)} + V_{pulpmill(ru)}$ [5-10]

Using the same logic, the total annual cost for the pulp mill supply unit, $TC_{pl(su)}$ is obtained from the model. The supply unit also incurs a transportation cost for shipping pulp to the downstream mills given by equation [5-11]: $TR_{pulp} = \sum_{i=1}^{12} tr_{pulp}(i) Q_{pulp}$ [5-11]

Where, the pulp mill supplies Q_{pulp} tonnes of pulp per month to the paper and textile mills, and incurs a transportation cost of tr_{pulp} per tonne. The total annual cost for the pulp mill supply unit, $TC_{pl(su)}$ is given by equation [5-12]:

$$TC_{pl(su)} = O_{pulpmill(su)} + HO_{pulpmill(su)} + HA_{pulpmill(su)} + V_{pulpmill(su)} + TR_{pulp} \quad [5\text{-}12]$$

The total annual production cost for the pulp mill is calculated from the total production, Pr_{pulp} tonnes of pulp per month, and production cost of pc_{pulp} per tonne, using the equation [5-13]: $PR_{pulp} = \sum_{i=1}^{12} pr_{pulp}(i) pc_{pulp}$ [5-13]

The costs in equations [10], [12] and [13] are added together to obtain the total annual cost, TC_{pl} for the pulp mill, given in equation [5-14]:

$$TC_{pl} = TC_{pl(ru)} + TC_{pl(su)} + PR_{pulp} \quad [5\text{-}14]$$

The total annual costs of other supply chain agents are calculated in the same manner as explained for the pulp mill, except for supplier, where harvesting costs are also added.

5.3.1 Model Parameters

The total annual demand of paper is 42,000 tonnes in the domestic market, 240,000 tonnes in the US market, and the annual demand of textiles in the Asian market is 72,000 tonnes, with monthly random demand variations. The total annual supply of wood fibre from the forest management units is 1,650,000 m^3, with random monthly supply variations by the suppliers (data obtained in consultation with the pulp mill managers). The demand of paper in the domestic and the US market, and the demand of textiles in the Asian market follow a Poisson distribution with a known monthly average of 3,500 tonnes, 20,000 tonnes, and 6,000 tonnes, respectively. The random monthly supply of pulp logs from each of the suppliers also follows a Poisson distribution with a known monthly average. The cost parameters of the suppliers are shown in Table 4-1. The suppliers harvest trees from the forest management units and convert these into pulp log (54%), saw logs (18%), bush chips (13%), hardwood logs (15%), and hog fuel (13%). It is assumed that the saw mills are of different capacities, and the suppliers supply 10% of their harvested saw logs to saw mill 1, 15% to saw mill 2, 20% to saw mill 3, 25% to saw mill 4, and 30% to saw mill 5. The saw mills convert the saw logs to lumber (50%), saw chips (25%), offcuts (10%), shavings and saw dust (10%), and bark (5%). The hardwood mills convert the hardwood logs to veneer (50%), hardwood chips (25%), offcuts (10%), shavings and sawdust (10%), and bark (5%). The pulp recovery is assumed to be 50% from pulp logs, and 15% from bush and saw chips. In addition, 10% (of total pulp production) black liquor is also produced from the pulp mill. The production cost of pulp in the pulp mill is assumed to be $600 per tonne, if the pulp mill is running at more than 20% of its full production capacity, and $1,000 per tonne otherwise. This is because higher fixed costs at less than 20% running capacity increase the overall production cost. The pulp mill distributes its production to the paper and textile mills, with 11% of pulp production supplied to domestic paper mills, 67% to US paper mills, and rest 22% to Asian textile mills. The average sales price of pulp to the paper and textile mills is assumed to be $1,140 per tonne. The paper and textile mills convert 75% of the pulp received into paper and textiles. The cost parameters of all supply chain agents are shown in Table 4-1. The pulp mill production planning algorithm is shown in Figures 5-1.

5.3.2 Simulation Model

The simulation model starts by generating stochastic monthly demand of paper from the domestic and the US customers, and stochastic monthly demand of textile from the Asian customers. The supply chain agents of each product receive the monthly demand from the customers, and based on their inventory level either supply the desired quantity of product to the customers or place an order to the upstream agent. All the agents in the supply chain maintain their inventory levels using the stationary inventory policy (*s, S*). The supply chain agents are built as autonomous units capable of making decisions and having clearly defined interfaces with other agents in the model (Figure 5-2).

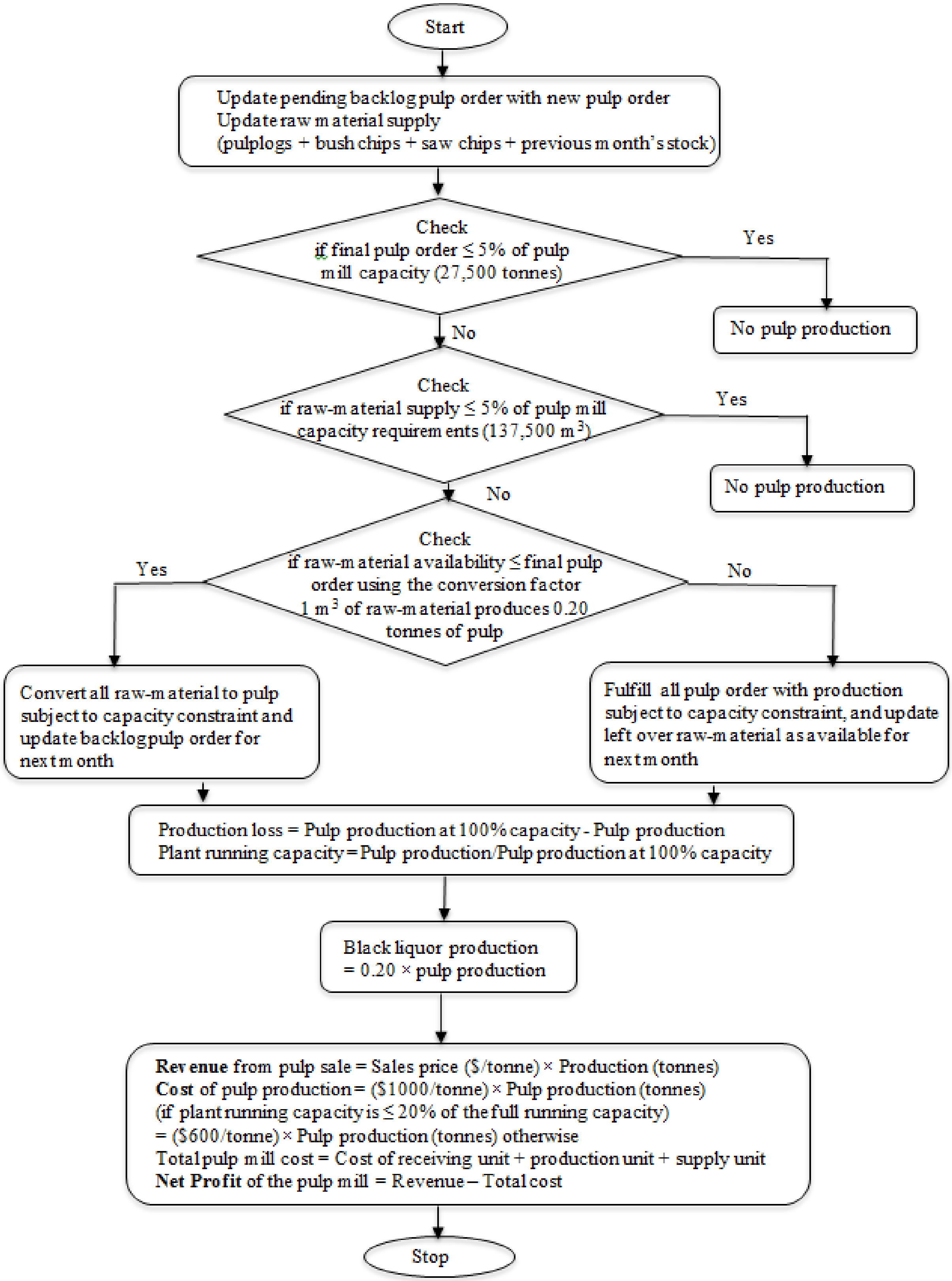

Figure 5-1: Pulp mill production planning algorithm

5.3.3 Optimization Model

The simulation model itself does not prescribe an optimal solution for the integrated production planning and inventory management problem and requires integration with an optimization approach. An OptQuest engine optimization solver that uses meta-heuristic search algorithm guides the search for optimum solutions (Olafsson 2006). Figure 4-10 shows the working of the meta-heuristic algorithm for optimization of integrated supply chain models. The objective function of the optimization model is to maximize the net annual profit (NAP) of the pulp mill. Mathematically, the objective function is given in equation [5-15]:

$$NAP = \sum_{m=1}^{12} P \times Q_m \_(tC_{pl_{(ru)m}} + tC_{pl_{(su)m}} + pR_{pulp_m}) \qquad [5\text{-}15]$$

Where; m =1,…, 12 indicate twelve months of the year. P is the sale price of pulp ($/tonne), Q_m is the total monthly quantity (tonnes) of pulp supplied by the pulp mill, $tC_{pl_{(ru)m}}$ is the total monthly supply chain cost of the pulp mill receiving unit, $tC_{pl_{(su)m}}$ is the total monthly supply chain cost of the pulp mill supply unit, pR_{pulp_m} is the total monthly production cost of the pulp mill, such that a specified customer satisfaction level is achieved. The capacity-feasible requirements in the optimization model is that if the demand of pulp or supply of pulp logs for certain month is less than 5% of full running capacity of the pulp mill, there is no production of pulp in that month. The decision variables for this optimization model are order quantity, inventory parameters (*s, S*), and supply quantity of all supply chain agents. The constraints (*S* is always greater than s for each supply chain agent) are used in the optimization process.

The meta-heuristic algorithm evaluates statistical outputs (net annual profit for the pulp mill and total cost for each agent in the supply chain) from the simulation model, analyzes and integrates these outputs with those obtained from previous simulation runs, and determines a new set of values to evaluate. The meta-heuristic search algorithm uses adaptive memory to remember which solutions worked well before and recombines them into new and better global solutions. The search process continues until meta-heuristic algorithm reaches some termination criteria, in this case a maximum number of simulations (1000 iteration counts). For each simulation, 10 replications are run. Optimization was performed using Intel® *Core™ i7 CPU* with *8 GB RAM*. The overall flow chart of the simulation-based optimization process of the integrated supply chain model is explained in Figure 5-2.

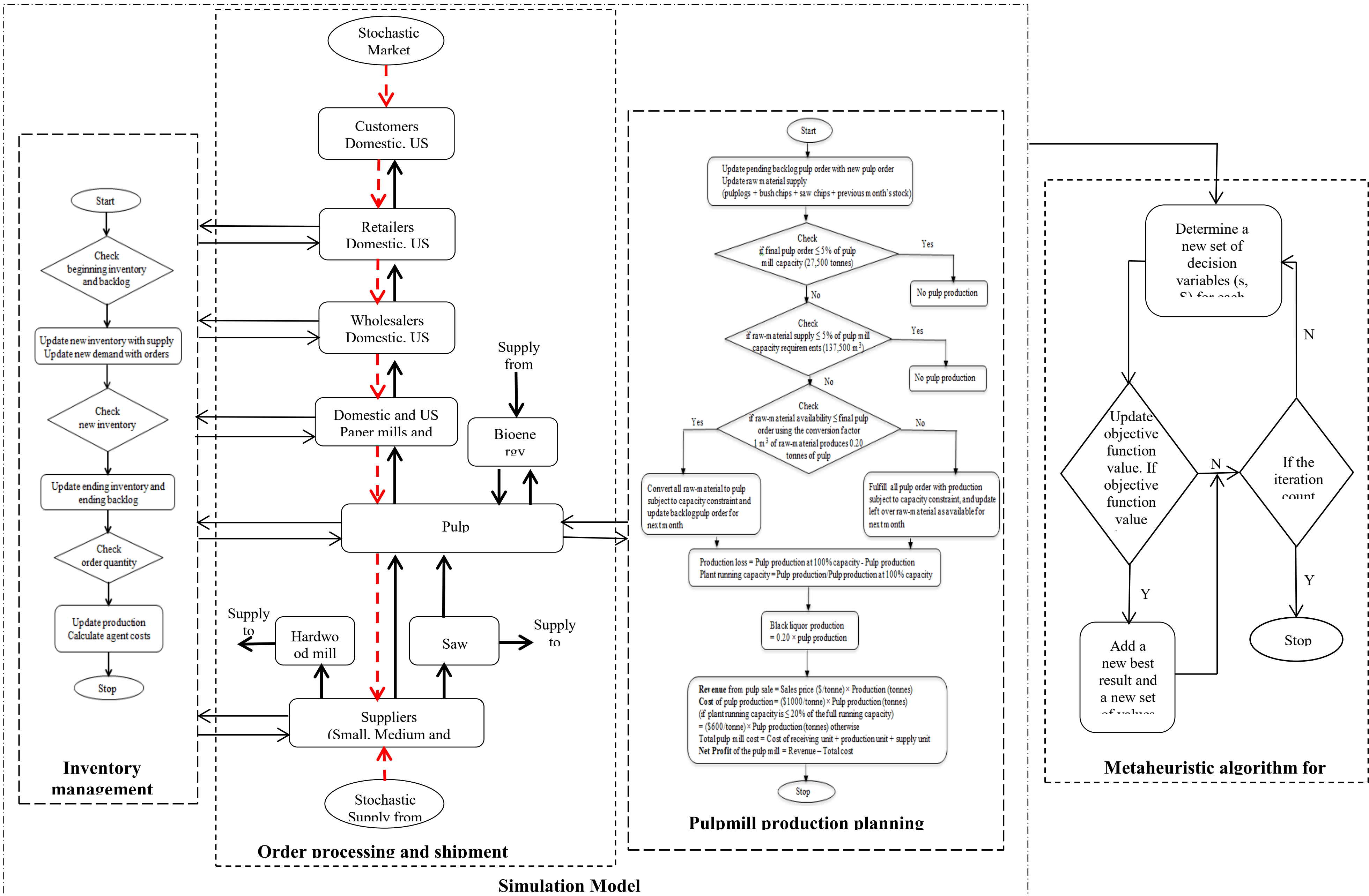

Figure 5-2: Overall flow chart of the simulation-based optimization process. Material flow ⟶ Information flow - ->

5.4 Results and Discussion

5.4.1 Effect of supply and demand uncertainty on net annual profit

The performance chart of 1000 simulations, leading to the optimized solutions by maximizing the net annual profit of the pulp mill is analyzed. Under supply and demand uncertainty, the optimization model converges to a net annual loss of $59.9 million to the pulp mill, with the pulp mill running capacity of only 10% and a customer satisfaction of 9% (Table 5-1). The total annual cost of the supply chain is $196 million (Table 5-1). Therefore, with uncertainty in supply and demand, the pulp mill runs in loss and is not able to provide high satifaction levels to the customers.

The results of optimized net annual profit of the supply chain in the business as usual (BAU) scenario were compared with the scenario by including a merchandizing yard between the suppliers and the mills (Table 5-1). With a merchandizing yard, there is a net annual profit of $26.7 million to the pulp mill, indicating a profit of 144.62% as compared to the BAU without merchandizing yard scenario. In addition, the pulp mill running capacity increases to 70%, and customer satisfaction to at least 50%. Therefore, the rest of the analysis was done by including a merchandizing yard in the model.

Table 5-1: Net annual profit of pulp mill and supply chain costs.

	BAU without Merchandizing Yard	BAU with Merchandizing Yard	%age change
Customer satisfaction (Domestic, US, Asian)	9%	50%, 51%, 55%	
Pulp mill running capacity	10%	70%	
Net profit of the pulp mill	$-59,930,448	$26,738,072	144.62% increase
Total annual pulp mill cost	$65,042,052	$219,093,740	236.85% increase
Total annual downstream level supply chain cost	$111,513,720	$283,608,579	154.33% increase
Total annual upstream level supply chain cost	$149,665,712	$287,992,618	92.42% increase
Total annual cost of the supply chain	$196,137,379	$352,507,456	79.72% increase

5.4.2 Supply uncertainty introduced by small, medium and large suppliers

The change (increase or decrease) in supply by each supplier has an impact on production of pulp (running capacity of the pulp mill) as well as on customer satisfaction levels. The model produces a feasible solution only if the customer satisfaction is set at 45%, and the pulp mill running capacity at 60% under variation in supply by small, medium and large suppliers. It was found that the pulp mill shows a positive net annual profit, provided the supply reduction by small suppliers is not more than 73% of their assured supply (Figure 5-3). Below this level of supply, the pulp mill is not able to meet the existing demand, resulting in an increase in shortage cost, and subsequent net annual loss to the pulp mill. However, the pulp mill cannot allow a reduction in supply by medium suppliers by more than 23% (Figure 5-3), and by large suppliers by more than 27% (Figure 5-3), without affecting its net annual profit. On the other hand, an increase in supply by the suppliers increases the pulp mill running capacity and customer satisfaction levels.

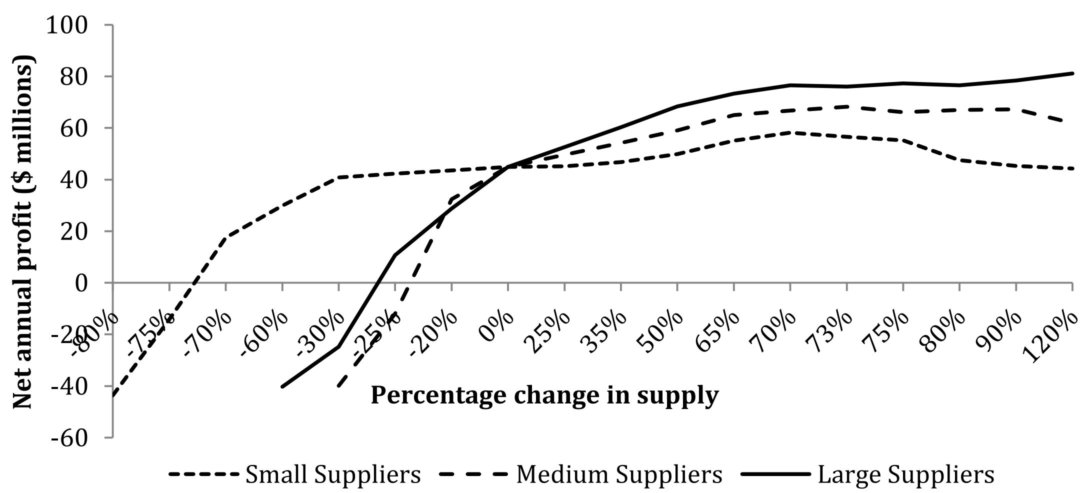

Figure 5-3: Effect of variation in supply by suppliers on net annual profit.

5.4.2.1 Combined effect of supply and demand uncertainty

A small decrease in demand does not substantially affect the net annual profit of the pulp mill, as long as the pulp mill has enough supply to run at 76% of its full capacity. However, with an increase in demand beyond 11% and without an increase in supply, the pulp mill shows a net annual loss. It was also found that with 70%, 20%, 25% reduction in supply by small, medium, and large suppliers, respectively, the pulp mill running capacity is reduced to 61% and customer satisfaction level is reduced to 40%. With 20% reduction in supply by medium suppliers and an increase in demand beyond 30%, or with 25% reduction in supply by large suppliers and an increase in demand beyond 4% results in the pulp mill running in a net annual loss (Figure 5-4). The pulp mill is unable to meet the increased market demand with a reduced supply from medium or large suppliers. This results in increased shortage cost and subsequently net annual loss to the pulp mill. Therefore, policies should be put in place to maintain a regular supply from all suppliers, especially the medium and large suppliers, as reduction in supply by these suppliers has an immediate impact on continuous operation of the pulp mill and its net annual profit.

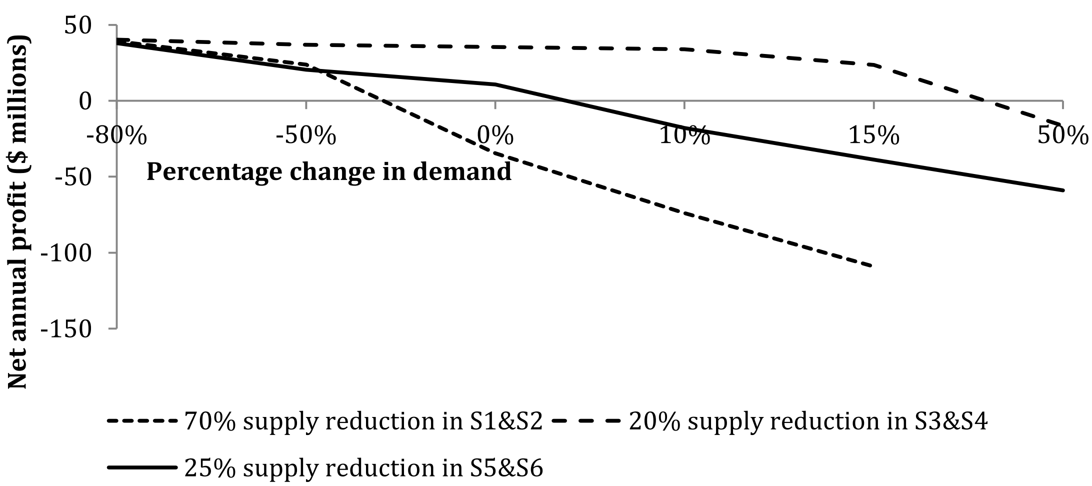

Figure 5-4: Effect of variation in demand and supply on net annual profit.

5.4.2.2 Managing risks associated with supply and demand uncertainty

The merchandizing yard helps in managing risks associated with supply and demand uncertainty by ensuring continuous operation of the pulp mill, resulting in a net annual profit, and an increased customer satisfaction level. By including a merchandizing yard, the increase in total annual cost of the entire supply chain by 79.72% is due to higher production of pulp, and higher operational management costs associated with delivery of forest products to the customers. The shortage costs of downstream side supply chain agents are substantially low (Table 5-2), whereas their handling and transportation costs are high, as they are now handling larger volume of products (Table 5-2). The incorporation of the merchandizing yard also reduces the inventory parameters (*s, S*) of the entire downstream supply chain (Table 5-3). The pulp mill (both pulp logs receiving unit and pulp supply unit) is now required to hold higher inventory to ensure continuous capacity-feasible production (Table 5-3).

The total annual set up and operational cost of the merchandizing yard is $55 million. About half of this cost is used for handling the material in the merchandizing yard and about one-fourth of this cost is the holding cost. The handling and holding costs of both the receiving and supply units of all supply chain agents are generally low, whereas the production and transportation costs are high, as large amounts of materials is flowing the supply chain in the presence of a merchandizing yard (Table 5-4). The merchandizing yard also helps in continuous flow of material along the entire supple chain. There is a substantial increase (633%) in supply of pulp by the pulp mill, with a majority of this increase being taken up by US paper mills. Because of the presence of merchandizing yard, the sawmills and hardwood mills are also able to run at a higher capacity, and supply higher amounts of forest products (lumber, saw chips, offcuts, shavings, and bark) to the markets. In the present scenario, we only consider one central merchandizing yard, which is located between the suppliers and the mill. However, in the real world, there could be multiple merchandizing yards depending on harvesting locations and road network.

Table 5-2: Supply chain costs of retailers and wholesalers.

	Domestic		US		Asian	
	Without MY	With MY	Without MY	With MY	Without MY	With MY
	Retailers					
Holding cost ($)	15,696	14,400	85,842	85,716	33,300	31,734
Shortage cost ($)	409,509	230,281	2,338,265	1,361,832	699,711	377,313
Handling cost ($)	42,673	92,208	236,224	537,015	86,593	182,565
Transportation cost ($)	14,101	79,260	80,675	456,978	24,991	148,871
	Wholesalers					
Holding cost ($)	507,240	92,550	1,379,940	1,225,170	353,130	256,710
Shortage cost ($)	1,327,605	550,348	5,070,765	3,283,038	1,142,226	568,505
Handling cost ($)	822,001	227,824	2,271,354	2,425,764	585,842	563,584
Transportation cost ($)	12,370	94,696	75,347	552,771	24,741	181,507

Table 5-3: Inventory policy parameters of supply chain agents.

	Domestic		US		Asian			
	Without MY	With MY	Without MY	With MY	Without MY	With MY	Without MY	With MY
	Retailers							
s (re-order level) (tonne)	872	800	4,769	4,762	1,850	1,763		
S (re-order up to level) (tonne)	6,200	5,800	30,385	30,000	8,950	8,950		
	Wholesalers							
s (re-order level) (tonne)	16,908	3,085	45,998	40,839	11,771	8,557		
S (re-order up to level) (tonne)	37,593	24,460	91,155	99,266	26,850	26,850		
	Paper and Textile mills (RU)						Pulp mill (RU)	
s (re-order level) (tonne)	27,139	14,868	208,333	55,376	15,849	17,727	61,178	182,836
S (re-order up to level) (tonne)	50,000	32,533	430,500	134,793	35,711	36,485	125,209	443,639
	Paper and Textile mills (SU)						Pulp mill (SU)	
s (re-order level) (tonne)	20,405	3,085	104,166	40,839	11,916	11,351	45,998	91,418
S (re-order up to level) (tonne)	37,593	24,460	215,250	100,764	26,850	26,850	94,134	203,811

Table 5-4: Supply chain costs of pulp mill and secondary mills.

	Pulp mill		Domestic Paper mills		US Paper mills		Asian Textile mills	
	Without MY	With MY	Without MY	With MY	Without MY	With MY	Without MY	With MY
	Receiving Units							
Holding cost ($)	17,228,458	12,092,758	1,139,838	624,456	2,569,476	2,325,792	665,658	744,534
Handling cost ($)	22,947,959	22,431,572	1,645,702	1,019,453	3,776,430	4,098,379	985,664	1,318,367
Transportation cost ($)	1,130,206	7,795,160	19,966	146,479	121,613	892,192	39,932	292,959
	Supply Units							
Holding cost ($)	6,878,468	6,033,588	857,010	129,570	1,931,916	1,715,238	500,472	476,742
Handling cost ($)	8,977,750	9,300,227	1,237,321	282,705	2,839,193	3,032,204	741,003	872,120
Production cost ($)	21,944,514	140,804,958	20,834	152,848	126,900	930,983	41,669	305,696
Transportation cost ($)	247,264	1,794,806	14,975	112,246	91,209	669,144	29,949	219,719

5.4.3 Sensitivity Analysis of the cost parameters

Although, the establishment and operation of a merchandizing yard reduces the shortage cost in the supply chain, it increases the inventory handling, holding and transportation costs, as the merchandizing yard needs to procure and hold more inventory. The results of sensitivity analysis with different cost parameters of the merchandizing yard indicate that the net annual profit of the pulp mill is most sensitive to sales price of the pulp (50.8%, positive correlation), followed by shortage cost (16.5%, positive correlation) and transportation cost (-10.8%, negative correlation). The results of sensitivity analysis reveal that the pulp mill will make a net annual profit only if the sales price of pulp is at least $680 per tonne, the shortage and transportation costs are above $4.80 per m^3 and $9.50 per m^3, respectively (Figure 5-5). The size and location of the merchandizing yard were not analyzed in this study, being outside the scope of this paper.

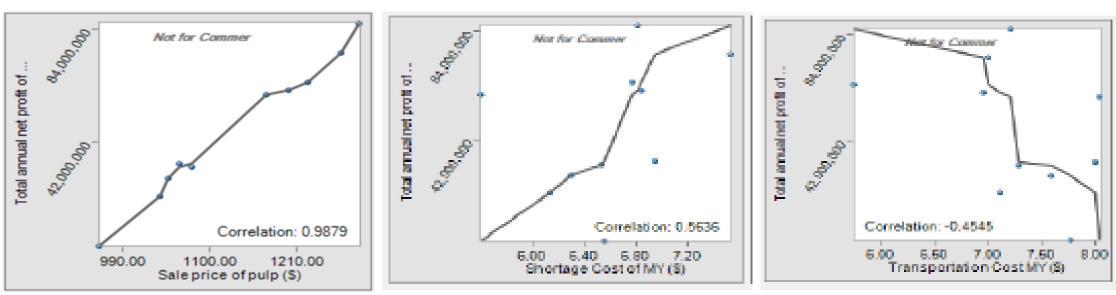

Figure 5-5: Results of sensitivity analysis of net annual profit of the pulp mill.

5.5 Conclusions

The Canadian forest products industry is operating under uncertain supply of wood fibre from the forest management units and uncertain demand of forest products from the customers. Under these stochastic supply and demand conditions, the forest industries are unable to operate at capacity-feasible production, and are spending a substantial portion of their costs in managing their inventory. An integrated simulation-based optimization model was developed for the forest industry that manages all inventory planning decisions, both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain. Using the model, it is found that the supply uncerainty caused by reduction in supply by wood fibre suppliers have a direct impact on both capacity-feasible production and customer satisfaction. Therefore, policies measures need to be developed to ensure un-interrupted supply from suppliers to improve the competitiveness of forest industry in the global markets. When a merchandizing yard is included between the suppliers and the pulp mill, it absorbs supply and demand shocks and ensures continuous production of the pulp mill, as well as improves the customer satisfaction, resulting in net annual profit to the pulp mill. Future research should focus on integrating this simulation-based optimization model with forest products international trade model and including product markets for secondary industries, such as biorefineries.

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CHAPTER 6
General Conclusions

6.1 General Conclusions

The Canadian forest products industry is operating under uncertain supply of wood fibre from the forest management units and uncertain demand of products from the markets. Under these stochastic supply and demand conditions, the forest industries are unable to operate at capacity-feasible production, and are spending a substantial portion of their costs in managing their inventory. This is evident from the large amount of wood fibre inventory held at many forest products industries across Canada. This has impacted both the operational efficiency of the forest mills and their competitiveness in global markets. In this research work, integrated simulation-based optimization models were developed for the forest industry that consider the entire supply chain structure and manage all operational planning decisions both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain under supply and demand stochasticity. The supply chain model incorporates a two-way flow of information and materials between all the elements of the supply chain. The integrated simulation-based optimization model is further extended to ensure capacity-feasible production of the forest mills and desired customer satisfaction levels, and manages all inventory planning decisions, both upstream and downstream in the supply chain.

6.2 Theoretical Contributions

First, the literature related to supply chain models was comprehensively reviewed, and those models were identified, which would best address the needs of the Canadian forest products industry. It was found that the supply chain models used in the forest products industry mostly address either the production planning or inventory management problems. Such supply chain models have been used to optimize isolated harvesting, transportation, production, and distribution in the forest industries. These optimization models focus only on a few operations, do not capture uncertainty in market demand and wood fibre supply, and lack in the two-way flow of information and materials. The second class of supply chain models use a simulation approach that deal with stochastic systems the forest products industry's supply chain. However, these simulation models only capture the system dynamics of large-scale systems in the supply chain network, and do not provide any optimized solutions. Therefore, the need for an integrated simulation-based optimization modeling approach for the Canadian forest products industry supply chain network that considers uncertainty in both demand and supply was identified.

Second, a simulation-based optimization supplier model was developed for a single product (sawlogs), single industry (sawmill) supply chain, which minimizes the overall cost of the supply chain under demand uncertainty. The model was applied to a real sawmill (as a case study) in Northwestern Ontario, engaged in the production of stud grade lumber. The supply chain model incorporates a two-way flow of information and materials between all agents of the supply chain. The supply chain model was used for testing the effectiveness of a merchandizing yard in the supply chain in reducing idle time and cost.

Third, a simulation-based optimization model was developed for a multi-product (pulp, paper, textile, solid softwood and hardwood products, bioenergy and black liqour), multi-industry (pulp mills, sawmills, hardwood mills, paper and textile mills) supply chain, which minimizes the overall cost of the supply chain. The model considers the entire supply chain structure and manages all operational planning decisions (order quantity, inventory planning, and supply quantity) both upstream and downstream in the supply chain, in the presence of continuously changing information across the entire supply chain under supply and demand stochasticity. The supply chain model incorporates a two-way flow of information and materials between all agents of the supply chain across a nodal agent (pulp mill). The model was applied to a real pulp mill (as a case study) in Northwestern Ontario, engaged in the production of pulp for supply to paper and textile mills in domestic, the US and Asian markets.

Finally, the multi-product, multi-industry simulation-based optimization model was extended to integrate production planning of the pulp mill with inventory management decisions of the entire supply chain that maximizes the net annual profit for the pulp mill. The model ensures capacity-feasible production and desired customer satisfaction levels, in the presence of continuously changing information across the entire supply chain under supply and demand stochasticity.

6.3 Implications for Supply Chain Management

1. The simulation-based optimization results for a single product (sawlogs), single industry (sawmill) supply chain model output show that the presence of a merchandizing yard in the supply chain, in fact, increased the wood fibre procurement cost. However, the merchandizing yard absorbs shocks from uncertain demand of the sawmill production unit and reduced idle time in the supply chain. The optimization model output results also show that the procurement cost can be substantially reduced, if optimum inventory policy (*s, S*) is followed for each supply chain agent. The

merchandizing yard was not found to be efficient for a single product (sawlogs) and single forest industry (sawmill) scenario.

2. Using the simulation-based optimization model for multi-product, multi-industry supply chain under both supply and demand uncertainty, it was found that the supply uncerainty caused by a reduction in wood fibre supply by small suppliers does not impact customer satisfaction, whereas the supply uncertainty caused by medium and large wood fibre suppliers has a direct impact on customer satisfaction. When a merchandizing yard was included between the suppliers and the pulp mill, it improves the customer satisfaction and results in net annual cost savings in the supply chain. The merchandizing yard not only absorbs supply shocks for the pulp mill and reduces shortage costs, but also reduces the safety stocks on the downstream side. Beyond a threshold level for the shortage cost, the handling, holding and transportation costs become very high. The customer satisfaction level was also impacted by demand uncertainty. However, the impact is less severe under short-term demand uncertainty as compared to long-term demand variation. The loss in customer satisfaction increases the shortage cost of supply chain agents on the downstream side. The wholesalers can handle some demand uncertainty by increasing their safety stock under steady state long-term demand change scenarios. The retailers cannot make quick changes to their inventory policy under random changes in demand by the customers, and adopt only by changing their orders to the wholesalers.

3. Integrating the production planning and inventory management decisions, the results

of the simulation-based optimization model show that the supply uncerainty caused by reduction in wood fibre supply by small suppliers does not have a major impact on either capacity-feasible production or customer satisfaction, whereas the supply uncertainty caused by medium and large wood fibre suppliers has a direct impact on both capacity-feasible production and customer satisfaction. When a merchandizing yard was included between the suppliers and the pulp mill, it absorbs supply shocks and ensures continuous capacity-feasible production of the pulp mill, as well as improves customer satisfaction, resulting in a net annual profit to the pulp mill. The merchandizing yard not only absorbs supply shocks for the pulp mill and reduces shortage costs, but also reduces the safety stocks on the downstream side. Beyond a threshold level for the shortage cost, the handling, holding and transportation costs become very high. The customer satisfaction level is most severely impacted by the combined impact of demand and supply uncertainty. The pulp mill is unable to operate continuously under demand uncertainty, especially when combined with a reduction in supply by medium and large suppliers. Therefore, policy measures need to be developed to ensure supply from medium and large suppliers to ensure net annual profit and improve the competitiveness of forest industries in global markets.

6.4 Research Limitations and Future Research

The underlying assumptions of the simulation-based optimization models developed in this thesis do not limit the use of these models for any forest products industry supply chain. However, the input parameters need to be adjusted to make the results applicable to specific situations. Some of the limitations of this research study include:

1. The transportation cost is considered as constant in the model. In reality the transportation cost will vary based on the length of road (Highways and forest roads) involved in hauling material from the forest management units to the merchandizing yard.
2. Only one merchandizing yard is considered between the forest management units and the mills. However, the distance and terrain of forest stands from the mills may require multiple merchandizing yards, procuring and processing specific products and species.
3. The exact location of the merchandizing yard between the forest management units and the mills is not analyzed in the model.
4. The pulp logs and saw logs are considered homogenous and uniform. The variation in the characteristics (size and grade) and quality of these logs is not considered in the simulation-based optimization model.
5. The costs of procuring forest material by each supplier are considered same, because of the lack of availability of data. However, small, medium and large suppliers may have different procurement costs.
6. The transportation distance and costs between domestic and international agents (wholesalers, retailers and customers) is considered uniform. The international agents may be using shipping routes for which no data are available.
7. The production planning of only one nodal agent is considered in the model. The production planning of a cluster of industries need to be

integrated together.

8. The economic, political and social conditions, which may vary in domestic and international markets, are not considered in the integrated supply chain model.

Future research should address these limitations and focus on integrating this simulation-based optimization model with forest products international trade models, so as to minimize the impact of global demand fluctuations of forest products on Canadian forest industry operations. Additionally, the simulation-based optimization model should be extended to product markets for secondary industries, such as biorefineries.

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