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Supply Chain Network Optimization of the Canadian Forest Products Industry: A Critical Review

Shashi Shahi, Reino Pulkki

Faculty of Natural Resources Management, Lakehead University, Thunder Bay, Canada.
Email: skshahi@lakeheadu.ca, rpulkki@lakeheadu.ca

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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

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 is 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 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.

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. Meanwhile, it 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 support system with an improved decision 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 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

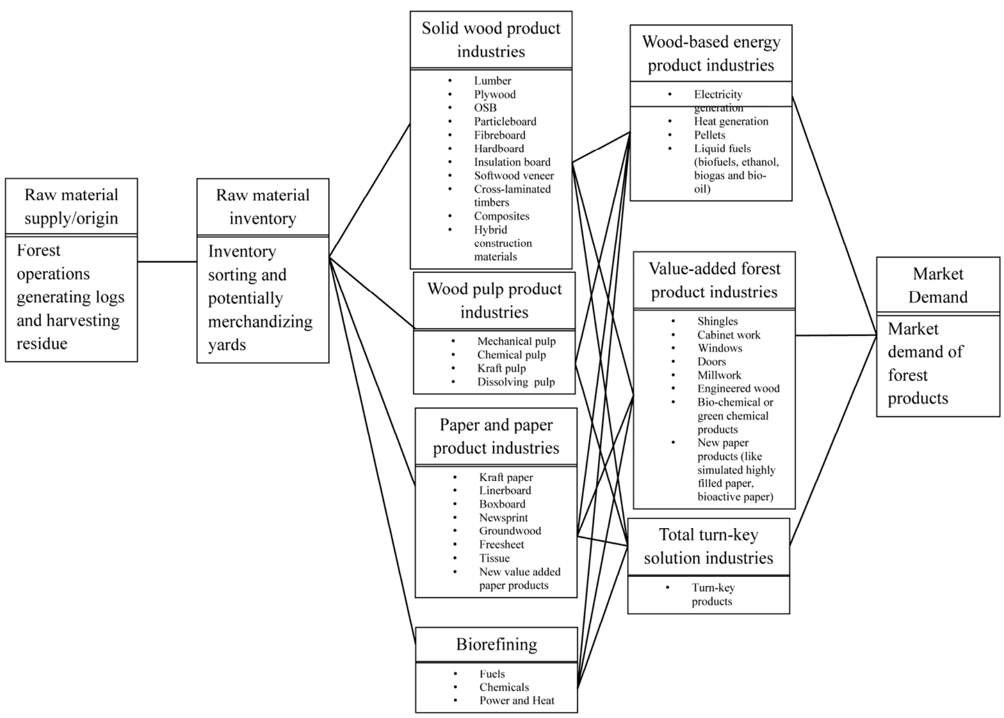

Figure 1. Forest products industries supply chain network.

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 endusers. 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 of 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. 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]. 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]. 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]. 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]. 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]. 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].

2.1. 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]. 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]. 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. 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 incurporating 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 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]. 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 repre-

Table 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 plan-ning 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
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 prob-lems
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
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

sent the supply chains realistically.

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 experimenttation [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].

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]. 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].

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]. 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.

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.

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 objecttives 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** provides a summary of studies on forest product industries supply chain network simulation models.

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

Table 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

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]. 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 3**.

5. Conclusions

The purpose of this review paper was to comprehendsively 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 capture uncertainty in market demand and raw material supply, as well as the lack in the two-way flows of information and materials. The second class of supply chain models uses 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 Ca-

Table 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

nadian 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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