Applications of Discrete-Event Simulation in the Forest Products Sector: A Review

Luke Opacic
Taraneh Sowlati

Abstract

Decisions in the forest products sector have economic, environmental, and social impacts, and involve multiple stakeholders. The complexities and variations in the sector, such as equipment interactions and seasonalities, make discrete-event simulation an attractive decision-support tool. This article reviews the relevant literature to highlight the extensive applications and benefits of discrete-event simulation in forestry. Discrete-event simulation allows one to perform ''what-if'' scenarios and assess the impact of changes on processes, overall throughput, and productivity. It has been used to compare harvesting systems, evaluate the impacts of machine interactions in the forest and in mills, conduct bottleneck analyses, determine the feasibility of machine replacements, assess log transportation methods, and analyze biofuel supply chains. No studies considered the combined interactions of workers and machines, which could be considered in the future. Future work could also consider multiple objectives, the combination of optimization and simulation, the combination of different simulation methods, and the use of simulation for training and performance evaluation.

Thirty-one percent of the world's land surface, equivalent to 4 billion hectares, is covered by forests (Adams 2012). Forests are considered to be the world's largest repository of terrestrial biodiversity (Food and Agriculture Organization of the United Nations [FAO] 2014), and they affect our daily lives considerably (World Wildlife Fund [WWF] 2016). They provide economic benefits for communities and habitats for diverse animal species (WWF 2016). They also reduce global warming by sequestering carbon dioxide during photosynthesis (Pan et al. 2011, WWF 2016). Therefore, it is important to make sure that forests are used in a sustainable manner (Whiteman 2014, Kangas et al. 2015). This requires proper decision making related to forestry while taking into account the competing and often conflicting interests of various stakeholders such as governments, industry, environmental groups, etc.

Decisions made in the sector have economic, environmental, and social impacts (Diaz-Balteiro and Romero 2008, Cambero and Sowlati 2014). For example, where and when to harvest, how to transport logs to mills, and what types of products to produce have economic consequences as well as impacts on the environment and society. Environmental impacts include soil erosion, greenhouse gas emissions, energy use, and biodiversity conservation (Kangas and Kangas 2004, Diaz-Balteiro and Romero 2008, Cambero and Sowlati 2014). Social impacts include recreational activities, level of employment, or indigenous populations (Kangas and Kangas 2004, Diaz-Balteiro and Romero 2008, Cambero and Sowlati 2014). The preferences of stakeholders can be conflicting—positive impacts of a decision on one stakeholder may have negative impacts on another. For example, a government's desire to reduce greenhouse gas emissions may have negative impacts on the private companies trying to maximize their profit because the effects of reducing greenhouse gases could increase the companies' costs. Another complexity in decision making in the forest products sector results from having divergent processes: producing multiple products from trees (D'Amours et al. 2008). Moreover, dependency within different sectors makes the decision making more complicated. For example, one forest supply chain could include mixed species forest management, different harvesting techniques that convert the trees into logs or chips, and various companies depending on each other or competing for the same products—sawmills to create boards or lumber,

The authors are, respectively, Graduate Student and Professor, Industrial Engineering Research Group, Dept. of Wood Sci., Univ. of British Columbia, Vancouver, British Columbia, Canada (luke.opacic@shaw.ca, taraneh.sowlati@ubc.ca [corresponding author]).
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pulp mills to make rolls of paper, and biofuel facilities to generate energy (D'Amours et al. 2008, Mobini et al. 2011). Because of the many challenges facing the forest products sector for the next few decades, many companies must make tough decisions to maintain their competitive advantage (Shahi and Pulkki 2013). The behaviour of an actual or anticipated human or physical system (Power and Sharda 2007) and the balance of social, political, and cultural issues due to forces such as globalization (Ananda 2007) are also possible sources of complexities and uncertainty. The risks and uncertainties that exist in the forest sector make these decisions much more complex, and limit the use of some managerial approaches such as deterministic modeling. Simulation is an appropriate approach to these problems as the impacts of changes must be estimated (are not yet known), in addition to estimations of uncertainties such as weather, transportation times, and machine breakdowns.

Discrete-event simulation is a modeling technique designed to mimic real-world systems where various states of the system (such as queues) change at random points in time because of the occurrence of discrete events (Sadoun 2000, Power 2002, Banks et al. 2005, Hillier and Lieberman 2015, Kaizer et al. 2015). It is the most popular type of simulation (the others being agent based, system dynamics, and Monte Carlo) (Jahangirian et al. 2010), particularly for studies on process flow. The use of discrete-event simulation modeling allows the consideration of uncertain/stochastic variables without the need for a large model that takes up considerable resources or has a very high cost (Myers and Richards 2003, Banks et al. 2005, Hillier and Lieberman 2015). In the forest products sector, the simulation modeling was used to analyze systems with uncertainties and interactions between system components. Most of the studies in the forest products sector that used discrete-event simulation have assessed different facility layouts, harvesting systems, or supply chains. The main uncertainties in these models have been forest and tree attributes, processing times, machine failure and repair rates and durations, machine interactions, demand, and transportation distances.

Because of the increased usefulness of discrete-event simulation as a decision-making tool in other industries such as health care (Swain 2015a), automotive, electronics, and aerospace, the challenges facing the forest products sector (Shahi and Pulkki 2013), and the limited number of existing review papers (Awudu and Zhang 2012, Shahi and Pulkki 2013, Rahman et al. 2014a, Segura et al. 2014) covering discrete-event simulation in forestry, this article reviews the relevant literature (from 1990 to 2015) in the forest products sector to highlight the applications of discrete-event simulation, gain a better understanding of the benefits and usefulness of it as a modeling technique in the sector, and identify future directions for research.

Discrete-Event Simulation Modeling

Simulation can be defined as a method of imitating or mimicking a real-world process or system (Sadoun 2000, Power 2002, Banks et al. 2005, Hillier and Lieberman 2015, Kaizer et al. 2015). Although there are several types of simulation, this article focuses on discrete-event simulation. Discrete-event simulation is a suitable modeling approach when the state of the system changes at random points in time as a result of various ''discrete events'' such as the arrival and departure of customers (Hillier and Lieberman 2015). It consists of entities (such as pieces of wood) that move between different stages of the system (such as machine centers) over time. It involves networks of queues and servers (Sadoun 2000, Greasley 2009, Tako and Robinson 2009, Maidstone 2012), scheduling and sequencing of events (Fishman 2001), and interactions between entities and processes (Skandari 2015c). It is said to be discrete because the state of the system changes only at specific points in time instead of continually (Sadoun 2000, Fishman 2001, Nance and Sargent 2002, Greasley 2009, Tako and Robinson 2009). Discrete-event simulation allows for the analysis of stochastic systems that are impossible or difficult to analyze or solve analytically (Banks et al. 2005, Borshchev 2013, Hillier and Lieberman 2015). It is a modeling technique that allows for the conversion of system relationships into estimates of system performance (Fishman 2001).

Discrete-event simulation has many advantages. It is used primarily to avoid the disruption of the real system (Sadoun 2000) and to evaluate possible system alternatives to address a problem (Power and Sharda 2007, Maidstone 2012, Negahban and Smith 2014), or to make decisions such as capacity planning, purchasing decisions, strategic planning, training, and technology planning (Allen 2011). It allows for ''what-if'' questions to be analyzed when designing new systems or improving existing ones (Sadoun 2000, Power 2002, Banks et al. 2005, Hillier and Lieberman 2015). The alternatives can be simulated as scenarios, and system performance statistics can be obtained from each scenario for comparison (Maidstone 2012, Skandari 2015a). Performance statistics could include throughput, utilization of resources, queue times and lengths at work stations, required staffing levels, social or environmental performance, and the determination of bottlenecks (Sadoun 2000, Banks et al. 2005). The interactions between the variables in a system and their effects on various parameters can be studied (Banks et al. 2005). Bottleneck analysis can be conducted to determine where the model entities are being delayed, or which resources are being over- or underutilized (Banks et al. 2005). Animation features in modern simulation software allow developers to visually communicate the model to the users (Banks et al. 2005, Borshchev 2013), including speeding up or slowing down time to better visualize changes that may occur very frequently or very infrequently (Banks et al. 2005). In addition, the ability to simulate long periods of time in just a few seconds or hours is a very beneficial aspect of discrete-event simulation (Sadoun 2000).

Computerized simulation methods have evolved over the last 50 to 60 years from programming languages to software packages that demonstrate the behaviors of the system visually (Nance 1996, Nance and Sargent 2002, Swain 2013). Much of this evolution is attributed to the available computer power, specifically related to memory and speed (Smith 2003), and therefore the use of simulation modeling progressed from being limited to a few research centers to being almost ubiquitous (Jacobson et al. 2006, Swain 2015a). Simulation has become an extremely useful tool (Swain 2015a), with more than 55 packages currently available on the market (Swain 2015b), all of which are capable of discrete-event simulation.

Although discrete-event simulation has many advantages, there are several disadvantages with this approach. The models cannot be developed or used by unskilled personnel

(Banks et al. 2005) unless proper user interfaces are developed. They can be costly and time-consuming to develop, may require more resources than are available, and require a lot of data that may not be available (Banks et al. 2005). In addition, it can be difficult to determine whether observations are due to system interrelationships or due to the randomness of the variables in the model (Banks et al. 2005). Also, like any other modeling method, simulation models require several assumptions and simplifications to be made, so they do not represent the system 100 percent (Box 1979). However, many models can be considered useful if developed in the right way (Box 1979) with appropriate input data. To ensure the models are useful, they must be verified and validated, which can be a time-consuming (but valuable) process. Verification is the process of ensuring that the actual programming and representation of the model function as expected. For example, checking that an entity proceeds to a different location when a queue is full, or checking that a specific event occurs when the appropriate conditions are true, would be verification of the model. Validation is the process of ensuring that the model represents reality in a way that is considered acceptable to the developers and users of the model. For example, a model is considered valid if it contains all parameters that are relevant to the problem and the functional relationships between the parameters are valid (Miller and Schmidt 1984). One way of determining this would be to get outputs from the model and compare them with outputs from the real system under the same conditions. If the outputs are indistinguishable, the model would be considered valid (Skandari 2015b). It is important to note that all models must have the right mix between accuracy and utility (Miller and Schmidt 1984). However, no matter the amount of accuracy or utility, poor input data will result in incorrect (and thus ''invalid'') output data, which can be referred to as the ''garbage in, garbage out'' analogy (Miller and Schmidt 1984).

A flow chart summarizing the main steps of conducting a simulation study is shown in Figure 1. All discrete-event simulation studies first require knowledge of the system being studied. This is generally accomplished by observation or discussion with experts about the system. During this phase, the parts of the system must be determined—the inputs, processes, relationships, and outputs. The inputs can be collected for example through time studies or obtained from literature and system experts. Regardless, all the input data must be analyzed for its randomness and fit to an appropriate probability distribution. Next, the model is constructed and is verified and validated. Finally, the desired outputs would be determined (e.g., throughput or energy use) and analyzed with respect to the real system to support decision making.

Discrete-Event Simulation Modeling in the Forest Products Sector

Discrete-event simulation has been used in the forest products sector since at least 1972, when Johnson et al. (1972) studied timber-harvesting systems. The studies here are grouped into those that (1) compared forest management techniques and harvesting systems, (2) assessed different facility layouts and configurations, (3) assessed transportation and supply-chain strategies and techniques, (4) determined facility locations, and (5) performed feasibility and cost assessment. Some studies had some overlap between these categories, but they were placed in the category that best matches the main purpose of the article. Table 1 summarizes all the studies and includes their various uncertain parameters.

Comparison of forest management techniques and harvesting systems

Early simulation models in the forest sector were developed to determine the best equipment mix for whole-tree chipping operations (Johnson and Biller 1974). Although these models did assess the interactions of different machines, they did not include a discussion on validation, and they only had three replications of each of 12 scenarios. Many studies before the mid-1990s involved the analysis of either single machines or were deterministic, numerical simulation (Wang et al. 1998, Wang and Greene 1999). It was not until Baumgras et al. (1993), who assessed the differences between two logging crews and different wood utilization alternatives, that most studies included significant validation sections and assessed machine interactions in more detail. It was claimed that validation was not discussed in detail in previous studies mostly because of the high cost of collecting data to perform it adequately (Baumgras et al. 1993).

Three felling methods (chainsaw, feller-buncher, and harvester) and two extraction methods (grapple skidder and forwarder) were compared in a simulation study done by Wang et al. (1998). The study assessed the performance of clear-cuts, shelterwood cuts, and single-tree cuts in both an uneven-age natural stand and an even-age planted stand. The authors analyzed the effects of interactions between stand conditions, harvesting prescriptions, and harvesting equipment on the productivity and site impacts of harvesting. It was determined that the feller-buncher–grapple-skidder combination was the best overall in terms of system productivity. It was also determined that simulation was a useful method for evaluation of complex factors affecting timber-harvesting decisions because it allowed complete control of the equipment. However, the time required to make such manual inputs was a considerable disadvantage.

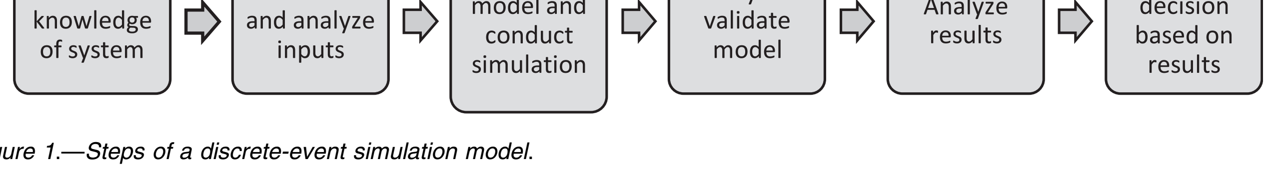

Figure 1.—Steps of a discrete-event simulation model.

Table 1.—Summary of discrete-event simulation studies in the forest products sector.

Purpose of simulation	Application area	Region(s)	Reference(s)	Important uncertainties
Comparison of forest management techniques and harvesting systems	Forest operations	Canada	Myers and Richards 2003	Standing and purchased log inventory, harvesting costs, stumpage rates, transportation costs
		Denmark	Talbot and Suadicani 2005	Seasonalities, stand size, travel distances, delays, road conditions
		Finland	Väätäinen et al. 2006	Harvesters' driving distances, loading and unloading times, interruptions/ breakdowns, log attributes
		South Africa	Hogg 2009, Hogg et al. 2010	Work element times, travel speed, stems per bunch, load sizes
		Sweden	Chiorescu and Gronlund 2001, Ersson et al. 2013	Terrain conditions, stump and root attributes, seedlings per machine reload, working area per machine, log attributes
		United States	Johnson and Biller 1974, Baumgras et al. 1993, Wang et al. 1998, Wang and Greene 1999, Oswalt 2008	Merchantable trees per acre/volume, average tree volume, skid distance, production rate, different logging attributes, equipment type, working times, delays, diameter at breast height, mortality rates, tree attributes, failures and repairs
Assessment of facility layout or configuration changes	Sawmills	Canada	Aune 1973, 1974; Clément et al. 2005; Thoews 2008; Thoews et al. 2008	Log arrivals between stations, cutting patterns, delays, machine failures and repairs, processing times, log attributes
		Chile	Baesler et al. 2004	Log diameter, log attributes (affecting process flow), saw speed/revolutions per minute, processing times
		Italy	Grigolato et al 2011	Failures and repairs, processing times, delays, log loading and positioning times
		United States	Randhawa et al. 1993, 1994; Zhang 1993; Lin et al. 1995; Dogan et al. 1997; Randhawa and Kuo 1997; Reeb 2003; Pinon 2005; Salichon 2005	Processing times, failures and repairs, log supply, log quality, product demand, setup times, cutting parameters
	Furniture manufacturing	United States	Gupta and Arasakesari 1991, Kline et al. 1992, Wiedenbeck and Araman 1995, Kyle and Ludka 2000, Thomas and Buehlmann 2002	Processing times, failures and repairs, log supply, log-quality attributes (wane), product demand, setup times, cutting parameters, raw material attributes
Evaluation of transportation, logistics, and supply chains	Sawmills	Canada	Beaudoin et al. 2013	Yard layout, trailer types, truck unloading times, truck interarrival times
		Lithuania	Puodžiūnas and Fjeld 2008	Consumption volumes, log diameter, load sizes
	Forest operations	Finland	Asikainen 2001, 2010; Karttunen et al. 2012; Windisch et al. 2015	Strand size, strand density, harvesting conditions, machine productivities, loading/unloading times, machine productivity, transportation distance, processing times, transportation distances, failures and repairs
		Finland and Germany	Windisch et al. 2013	Processing times for each activity
		Finland and Sweden	Asikainen 1998	Chip truck operating times, machine productivity, delays (proportion and length), truck type
	Bioenergy	Canada	Mobini et al. 2013, 2014	Biomass moisture and energy contents, transportation distances, failures and repairs
		The Netherlands	De Mol et al. 1997	Biomass availability, energy consumption, transportation distances, type of biomass
Comparison of various facility–preprocessing locations	Bioenergy	United States	Zhang et al. 2012	Amount of biomass, energy content, processing times, machine efficiency, travel distances, moisture content
		Italy	Spinelli et al. 2014	Processing times, delays, failures and repairs
	Forest operations	Sweden	Eriksson 2014	Machine performance, hourly costs

Table 1.—Continued.

Purpose of simulation	Application area	Region(s)	Reference(s)	Important uncertainties
Feasibility and cost assessment	Bioenergy	Canada	Mahmoudi et al. 2009, Mobini et al. 2011	Biomass moisture and energy contents, transportation distances, failures and repairs
	Sawmills	United States	Rappold 2006, Rappold et al. 2009	Failures and repairs, processing times

The importance of the interactions between chipper productivity, extraction distance, haulage distance, bin size, and system interference on the efficiency of a single-machine harvester and a harvester–forwarder combination was investigated by Talbot and Suadicani (2005). The focus was to compare economic and environmental feasibility of the systems in Denmark forests. It was found that for a 15-m^3 wood chip bin size, there was a 95 percent probability that the cost of a single-machine harvester system was between €0.18 m^{-3} and €0.41 m^{-3}, which was more expensive than the two-machine system under typical Danish conditions.

Myers and Richards (2003) developed a discrete-event simulation model to assess whether savings in total cost, inventory handling, and storage costs at the mill could be realized with the use of two different technologies, or a combination of them: (1) a central tire inflation–equipped hauling fleet, (2) a cable-based harvest system, or (3) a combination of both. Variability in operating seasons, supply and demand, operating costs, stumpage, and other interactions were considered. The model was shown to be suitable to evaluate the performance of the supply chain in terms of the operating costs, inventory cost, inventory levels, and machine utilization.

The productivities of one- and two-armed tree planting machines, considering uncertain terrain and Nordic clear-cut conditions, were analyzed by Ersson et al. (2013). Different terrain configurations with varying obstacles combined with the different machine styles were considered, and validation was conducted by sensitivity analysis. Two planting heads per arm rather than two arms per base better increased the productivity on Nordic clear-cuts.

Väätäinen et al. (2006) determined the productivity and cost changes of five different cut-to-length logging concepts (a Ponsse Wisent dual concept, three Valmet combi concepts, and a harvester–forwarder chain concept). Machine interactions and characteristics and transportation distances were considered, but the influence of different logging site characteristics was not. One of the concepts, using the harvester–forwarder combination, was the best for logging sites less than 100 m^3 and for long translocation distances, whereas the Valmet combi concepts were more suitable for a smaller removal per hectare.

Studies by Hogg (2009) and Hogg et al. (2010) were conducted to determine the utility of simulation software for analyzing different forest-harvesting techniques and their effects on productivity and cost. They analyzed three systems: System 1 (the base case) and System 2 consisted of the same machinery, but differed in terms of the operating procedures and policies; System 3 changed both equipment type and operating procedures and policies. It was determined that Arena 9 software could be used for forest operations problems, but it required a high level of user expertise to understand the complexities of the system, as well as some other limitations in the changing of background logic.

The impacts of the short-wood strategy (where crosscutting of logs is done in the forest) combined with different harvesting tools on the final lengths of sawn timber were studied by Chiorescu and Gronlund (2001). The study investigated the impacts of different harvesting techniques on the productivity of the supply chain, particularly the sawmill. Although it considered many machine interactions, grading criteria were fixed and could have been more flexible for both logs and final boards. This appears to be one of the only studies that evaluated how harvesting directly affects a sawmill.

A simulation system to investigate the impact of mixed species management of hardwood plantations on the proportion of clear (wood without knots) cherrybark oak was conducted by Oswalt (2008). The model incorporated different combinations of plantation types (dense and sparse), and different combinations of treatments to the trees. Tree characteristics, such as mortality rate, diameter, volume, and crown size, were uncertain parameters considered. When initial stand density was similar, the mixed-species approach was found to produce greater amounts of clear wood. The model was found to be a valuable method for the evaluation of hardwood plantations.

Assessment of facility layout or configuration changes

There are studies in both primary and secondary wood manufacturing that used discrete-event simulation to assess the different facility layouts or configurations. To the best of our knowledge, discrete-event simulation studies at primary wood manufacturing mills other than sawmills, such as veneer or chipping mills, have not been conducted. Some studies were conducted in furniture rough mills where raw wood or lumber is broken down into the parts required for the furniture being manufactured in other facilities (Kline et al. 1992, Wiedenbeck and Araman 1995, Thomas and Buehlmann 2002), whereas others were conducted in the furniture manufacturing facilities themselves (Gupta and Arasakesari 1991, Kyle and Ludka 2000). To the best of our knowledge, there are no published studies conducted on the manufacturing processes of various engineered wood products, or the manufacturing of products such as kitchen cabinets. This is likely because possible studies would be conducted privately and confidentially by the individual companies and would not be the subjects of published material.

Many early simulation studies in sawmilling focused on log breakdown patterns (Reynolds and Gatchell 1969), whereas Aune (1973) assessed wood manufacturing processes. The study analyzed how changes in the log characteristics and interactions between machine centers affected the total productivity. The productivity was found to be highly sensitive to changes in the characteristics of the logs and machines. The findings of Aune (1973, 1974) led to the development of future models studying facility layouts and configurations, particularly for sawmills.

Kline et al. (1992) conducted a study at an eastern US furniture rough mill to evaluate throughput, operation expenses, inventory levels, and delays due to bottlenecks. The bottleneck of the process was determined to be the ripsaw. The article by Gupta and Arasakesari (1991) assessed the effects of the addition of a third packaging line, a change in the availability of the edge banders, and changes in batch sizes being processed, compared with the existing system, on the capacity and in-process inventory of a facility in Zeeland, Michigan. The interactions of all machinery, including the breakdowns and downtime, were considered. The development of a model to evaluate a proposed layout of a dining room tabletop plant was discussed in Kyle and Ludka (2000). The evaluation was based on the effects of the proposed layout on staffing levels in each department, batch sizes, buffer sizes, and the flow between multiple departments. Specific results were not provided, but it was stated that the study provided great value to the partner company. Moreover, the impacts on staffing levels could be considered as a connection to the social implications of simulation modeling.

Four articles described the development of object-oriented softwood sawmill simulation models (Randhawa et al. 1993, 1994; Zhang 1993; Randhawa and Kuo 1997). One model, called the softwood sawmill simulator (S3), was developed by Randhawa et al. (1993, 1994) and Zhang (1993). Reports were obtained from the model to determine the utilization of machine centers, and the model was deemed to be valid because of its close approximation to the real system. The article by Randhawa and Kuo (1997) developed a methodology to make decisions in sawmills on the basis of multiple performance measures. The performance measures were scaled on the basis of their time and value, and then were weighed on the basis of their importance to the decision maker, which created a scenario score. The score was then used in the evaluation of the scenarios in a sawmill. The article concluded that the evaluation of multiple criteria required trade-offs involving the weights of each criterion.

Some studies analyzed the impacts of changes to the system design of sawmills, including machine replacement and facility layout. Lin et al. (1995) investigated the impacts of different machine layouts by analyzing different combinations of log-sawing methods (live sawing and five-part sawing) and board-cutting methods (crosscut-first and rip-first cutting). The interactions between machines, the effects of Grade 2 and Grade 3 logs, and the effects of different cutting patterns were all analyzed. Dogan et al. (1997) analyzed the effects of changing the forklift availability for sorting operations in a hardwood sawmill and the effects of separating logs in the yard by grade. In the study by Reeb (2003), sawmill management was interested in determining the impact of increasing the number of graders from two to three on two shifts on the volume and value of lumber produced. The study looked at the interactions of workers, interactions between the length of lumber and line speed, the effects of short lumber, and the relationship between the line speed and the downtime.

Different machine configurations, log diameter distributions, speeds of the circular saw, and decrease in log positioning time were analyzed by Baesler et al. (2004) at a Chilean sawmill. This study used experimental design to assess all possible combinations of the uncertain parameters, which for many studies would be very time-consuming. A case study at a sawmill in British Columbia, Canada, was analyzed by Thoews (2008) and Thoews et al. (2008). Mill management was interested in finding improvements in the throughput. The analysis of the whole system found that the length trimmer was the system bottleneck for both small-log and large-log lines in a softwood sawmill. However, improvements at the trimmer shifted the bottleneck to the edger on the small-log line. Despite this, mill management decided to make improvements at the trimmer. Without the simulation model, management would not have been able to make an informed decision without possible negative effects on the overall throughput. Another study looking to find and improve bottlenecks was conducted by Grigolato et al. (2011) at an Italian sawmill. Its primary purpose was to investigate the effects of log diameter variability on the facility. Once the cut-saw was found to be the bottleneck, a faster replacement machine was analyzed to determine its effect on the bottleneck and overall throughput. Because of the work from the 1980s and 1990s proving the utility of discrete-event simulation for assessing forest products sector processes, many of the studies during the 2000s and early 2010s were similar, and were based more on case studies rather than attempting to build on the bank of knowledge.

In the mid-2000s, there were large quantities of hardwood trees being left standing because they were too short or too thin (Clément et al. 2005). However, short and small-diameter logs are not economically viable (Clément et al. 2005). In Canada, there is more and more industrial demand for hardwoods, which is making the supply of economically viable logs more scarce, increasing the desire to process logs shorter than 8 feet long (Clément et al. 2005) and less than 7 inches in diameter (Pinon 2005, Salichon 2005). Short and small-diameter logs cause problems in traditional hardwood sawmilling; therefore many companies choose not to use them (Clément et al. 2005, Pinon 2005). Clément et al. (2005) analyzed the effects of short logs on the total yield of a conventional log sawmill (base case) versus a short-log sawmill, combined with the effects of two different cutting techniques: (1) crosscutting first and (2) rip-cutting first. An important result obtained from this study was that the use of the correct cutting pattern could result in satisfactory yield for No. 1–grade boards. Pinon (2005) conducted a study to determine the efficient utilization of small-diameter logs at a sawmill in Oregon. Ultimately, the goal was to determine the best mix of log sizes that would result in the highest throughput, while increasing the amount of the small-diameter logs being processed. Changes to equipment were also analyzed, which found that the use of a three- or four-deck sort (compared with the existing two-deck sort) considerably minimized the decrease in throughput. A follow-up study by Salichon (2005) determined that downtimes had a significant influence on the throughput when processing logs with varying diameters. This study, however, determined that an increase in the speed of the end-dogging log feeding system had little effect on the throughput unless more small-diameter logs were processed, at which point it had a big effect. Also, an increase in the speed of both the gang edger and the end-dogging log feeding system resulted in a significant increase in production, but it was limited by the following machine centers that could not process the higher material flow. Because of the expected increase in small-diameter logs in the future, the authors found that changes to the machine centers should be investigated to offset the lost production.

Because of decrease in average size of logs, furniture rough mills also need to change their procedures to better utilize shorter lumber. Wiedenbeck and Araman (1995) analyzed the effects of the lumber length on the equipment utilization and volume of the parts produced. The study considered crosscut first and rip-cut first as the scenarios, similar to studies in sawmills looking to assess the effects of short logs (e.g., Clément et al. 2005, Pinon 2005, Salichon 2005). The replacement of the moulder and the ripsaw with a fixed-arbor machine would increase the productivity in a rip-cut-first mill. One article in particular, by Thomas and Buehlmann (2002), assessed how a specific model (ROMI-RIP) was validated with data from an actual state-of-the-art rough mill, which was not common with the other articles.

Evaluation of transportation, logistics, and supply chains

Several discrete-event simulation studies were conducted to analyze different transportation methods of wood chips and logs to the mills that process them. Asikainen (1998) analyzed the interactions of four chipping system–trucking type combinations: (1) chipping onto the ground, loaded into a truck with a draw-bar trailer using a wheeled loader; (2) chipping directly into a truck with a draw-bar trailer; (3) chipping directly into an interchangeable container truck; and (4) chipping directly into a truck with a semitrailer; the number of trucks also varied. It was determined that there was no significant difference between the truck with the draw-bar trailer or the semitrailer, but the unit cost of transportation varied considerably depending on the distance and number of trucks.

Five different barge transportation systems for carrying out logging on an island and transporting the logs to the mainland were studied by Asikainen (2001). The existing system involved forwarding onto a buffer raft, loading by the barge's loader, and then transporting by barge to the mainland. The scenarios changed the number of barges and their locations. It was found that at transport distances less than 100 km, the single-powered barge system was the cheapest option. The barge system with three barges and a pusher boat was the most efficient option for distances greater than 100 km.

Asikainen (2010) conducted a study to determine the optimal number of trucks to transport chips from a roadside landing to a district heating plant. The transportation distances varied from 20 to 120 km, and the number of trucks varied from one to four. It was found that two trucks would be the most cost-competitive option for distances less than 40 km, a third truck should be added for distances over 40 km, and a fourth truck should be added for travel over 100 km. The results were very similar to those obtained by De Mol et al. (1997) and Karttunen et al. (2012), where it was concluded that road transportation was a good option for short distances and water transportation was appropriate for longer distances. Karttunen et al. (2012) also determined that the most economical waterway transportation options used fixed barges with loading and unloading of barges being conducted with a wheeled loader and a belt conveyor.

Log-yard truck operations were analyzed using discrete-event simulation by Beaudoin et al. (2013). The authors considered three different allocation strategies for three log-loader models to serve four different types of trailer, which would arrive at the mill by two different entrances. There were some restrictions in the operations because not every loader was able to unload every trailer. The purpose of the simulation model was to determine the unloading policy to follow when allocating the loaders. The study assessed three alternative policies: (1) first in, first out; (2) empty the queue first; and (3) longest queue first. The assessment of different policies was a key driver of simulation modeling—testing various what-if scenarios for operating policies. The authors recommended that additional experiments be conducted before modifying the existing system to validate alternative strategies that did not penalize certain trailer types. Another study assessed the effects of different delivery schedules, number of loaders, and the proportions of domestic and import raw material sourcing on roundwood handling at a Lithuanian sawmill (Puodžiūnas and Fjeld 2008). It was found that the removal of unfavorable sources of roundwood increased the productivity of the sorter and decreased the truck waiting times.

A limited number of studies assessed the supply chains of wood-pellet facilities using discrete-event simulation (Mobini et al. 2013, 2014). Changes to the delivered cost of wood pellets when subjected to uncertainties, such as interactions between processes and changes to the operations of the supply chain, were investigated by Mobini et al. (2013). It was found that the addition of bark to the mix of biomass used for the fuel production reduced the cost, but the energy consumption and CO_2 emissions increased. Torrefaction, a method to improve wood-pellet properties, was assessed by Mobini et al. (2014). It was determined that torrefied pellets were preferred to regular pellets for long-distance delivery because of their increase in delivered energy.

Two studies assessed the differences between two biofuel supply chains in Finland and Germany (Windisch et al. 2013, 2015). The work-time expenditures for organizational and managerial tasks, based on the interactions of the stakeholders within the supply chains, were analyzed. It was found that the results were company specific and cannot be generalized, but the methodology was shown to have potential for future analysis of supply chains in forest business (Windisch et al. 2013, 2015).

Comparison of various facility–preprocessing locations

A limited number of studies assessed different facility locations, mainly on the basis of demand fulfillment or their overall performance. Zhang et al. (2012) conducted a study to determine the best location of a biofuel facility in Michigan. The authors considered the cost of delivered feedstock, energy consumption, and greenhouse gas emissions. Nine potential locations were simulated with capacities varying from 30 to 50 million gallons of biofuel per year. It was concluded that the smallest plant size provided the best performance measures. This conclusion may be surprising to some people expecting that economies of scale would rule all decisions. However, this finding shows how simulation is very beneficial in making these kinds of complex decisions since the ''obvious'' answer of getting a bigger plant was the wrong answer in this case.

Selection of the type of biomass comminution and the location of conducting the techniques were analyzed by Spinelli et al. (2014) and Eriksson (2014). Spinelli et al. (2014) compared two different comminution locations: (1) forwarding logs to a roadside landing and chipping there, or (2) chip the wood at the pad in the forest and forward the chips to the landing. It was determined that the comminution should be conducted at the forest pad and two forest-to-landing shuttles was the best overall option. Eriksson (2014) studied the same problem with two different locations: (1) comminution with a mobile chipper at the roadside landing, or (2) comminution with a large unit at the energy plant. In this study, the most productive option was comminution at the roadside landing and independent transport with a self-loading chip truck and trailer. However, the transport of uncomminuted raw material was cost competitive for short distances. Therefore, both Eriksson (2014) and Spinelli et al. (2014) concluded that comminution should be conducted closer to the biomass source, which differs from the results obtained by De Mol et al. (1997), which claimed that it should be done at the energy plant. The different results could be owing to the different types of biomass, government regulations, advances in comminution equipment, or different model assumptions.

Feasibility and cost assessment

Some studies evaluated the feasibility and viability of supply-chain operations at bioenergy plants (Mahmoudi et al. 2009, Mobini et al. 2011), mainly on the basis of the overall cost of the system. Mahmoudi et al. (2009) initially simulated 1-year supply and logistics of roadside residues from conventional harvesting to a potential 300-MW power plant. They included the effects of seasonal fluctuations in logging operations and delays due to weather. It was determined that if only roadside residues were considered, there would not be enough biomass to meet the annual demand of the power plant. It was suggested to include other harvesting systems, which would increase the amount of available biomass, or decrease the power plant capacity to reduce the demand. Mobini et al. (2011) extended the previous model by Mahmoudi et al. (2009) to simulate 20 years of operations, incorporating three harvesting systems and the effects of the mountain pine beetle infestation on the biomass availability. It was determined that biomass demand of the power plant would not be fulfilled in some of the years.

Rappold (2006) and Rappold et al. (2009) conducted a study to estimate the cost of raw materials for hardwood lumber products at two hardwood sawmills (one high output, one medium output). Three different costing approaches were evaluated to determine the most precise method for allocating costs: the activity-based costing method, the volume costing method, and the lumber yield costing method. We believe these are the only studies that assessed lumber costing methods using discrete-event simulation.

Conclusions

Discrete-event simulation has been used in the forest products sector to compare harvesting systems, evaluate the impacts of machine interactions in the forest and in mills, conduct bottleneck analyses, determine the feasibility of machine replacements, assess log transportation methods, and analyze biofuel supply chains. It allows incorporation of uncertain or stochastic variables in the model that could not be represented in other modeling types such as deterministic models (Myers and Richards 2003, Banks et al. 2005, Hillier and Lieberman 2015). Common uncertainties in these models include supply and demand of products and raw materials, and processing times.

Discrete-event simulation has been used extensively to study processes in sawmills and furniture rough mills, but has not been used for assessing processes in engineered wood products facilities (such as those that make plywood, parallel-strand lumber, particleboard, medium-density fiberboard, or oriented-strand board), or in millwork facilities (such as those that make commercial or residential cabinets).

Most of the previous studies considered economic indicators; however it is not always feasible to use only one objective to make decisions. Only a few articles included environmental considerations (greenhouse gas emissions) in their studies (Mobini et al. 2011, 2013, 2014; Zhang et al. 2012). Environmental concerns could be assessed using simulation and life-cycle assessment to determine the impact of various scenarios.

In addition, future research in the forest products sector could include the combination of different types of simulation and other modeling approaches, such as simulation–optimization. Some studies have already begun using simulation–optimization techniques to combine the advantages of simulation and optimization together (Baesler et al. 2002, Rahman et al. 2014b). The main benefit of this combination is to obtain an optimal solution by searching thousands of possible alternatives, while still considering uncertainties and complexities in the model (Skandari 2015c).

The development of industry-specific software is another area for future work. The increase in software development would lead to an increase in the use of models by industry (Smith 2003, Jahangirian et al. 2010, Negahban and Smith 2014).

Finally, the interactions between workers and machines should be considered in simulation models, similar to patient–machine studies conducted in health-care studies (e.g., Jun et al. 1999, Brailsford and Hilton 2001, Jacobson et al. 2006, Hamrock et al. 2013). Because many workers in the forest products sector are cross-trained (Macdonald 2013) and are able to operate multiple pieces of equipment, there is value in studying the interactions between the workers and the machines they operate and how their assignments could be adjusted to improve productivity. There is also significant potential to use simulation for training and performance evaluation. For example, a ''flight simulator''–style training program could be created for operations such as panel processing or sawmill operation in which the new employees could make adjustments to a virtual system to see how their decisions affect system performance without incurring the cost and potential damage to the real system. As in a flight simulation, we would rather have pilots crash the virtual plane than the real one, something that also applies to many manufacturing processes.

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