Risk Assessment of the Timber Supply Chain in Southern Ontario using Agent-Based Simulation

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Contents

Abstract

The bioenergy sector has been experiencing significant growth in the last two decades. That said, the industry faces many challenges, mainly focused around the understanding of feedstock supply risk. Developers and investors cannot properly price risk without raw material supply chain risk understanding, making the development of the bio-energy industry slower than it would otherwise be. Currently biofuel, or wood pellet, production in Ontario requires wood chips supplied by existing sawmills. The supply of wood chips in turn depends on the supply of timber. A model was developed here simulating the timber supply chain in Southern Ontario. The objective of the simulation was to show the applicability of computer simulation methods in determining the most resilient areas from a perspective of a developer looking to build a new biofuel plant. The simulation presented here, developed in AnyLogic 7.3.5, is considered a base simulation. That is, it can be improved upon to simulate different disturbances, or add/change experiment assumptions. The simulation is therefore a first version of a useful tool that has a potential to improve the understanding of risk among biofuel developers and investors.

Introduction

The bioenergy sector has been experiencing significant growth in the last two decades (Krigstin et al. 2016). Although energy production from biomass has been a part of human civilization since the advent of fire, only recently new technological advancements allowed for wider implementation of bioenergy. However, production of energy from organic sources tends to be more expensive than fossil fuel based sources of energy. These higher costs are mainly associated with higher costs of biomass feedstock per energy unit, resulting in less energy produced per dollar (McKendry 2002).

That said, biomass costs are not intrinsically higher, and in fact can have negative value. The high cost of biomass is due to high transportation and processing costs, i.e. costs associated with the supply chain. A supply chain is defined as

> "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" (Mentzer et al. 2001).

Developers of bioenergy projects need to understand risks associated with biomass supply chains prior to making investment decisions. Furthermore, these developers require robust biomass supply-chain management plans to ensure the continuity of business energy production.

There are various types of bioenergy feedstocks, i.e. raw materials that get converted into biofuels. They range from agricultural residues to whole trees. Currently, one of the most widely used and economical feedstocks are wood chips, residuals from lumber production. These wood chips have been traditionally used for pulp and paper production. With the plummeting demand for pulp and paper and increased demand for wood pellets, broadly categorized as biofuels, wood chips are increasingly recognized as best suitable feedstocks for biofuel production (Krigstin et al. 2016).

One of the main challenges faced by bioenergy developers is an understanding of feedstock supply risk. Since wood chip production is dependent on lumber production, the understanding of wood chip supply risk stems from the understanding of sawmill ability to maintain production levels. That in turn, and among other things, depends on a sawmill's ability to secure timber supply. Therefore, by understanding sawmills' risk of running out of timber inventory, developers can better understand wood chip supply security, allowing them to be more confident in bioenergy investments.

Timber supply chains are complex and their robustness depends on a number of factors interacting together (Vahid 2011). Because timber is harvested on geographically distributed forests, the supply chains are susceptible to various disturbances, such as natural events (e.g. floods, fires), infrastructural risks (road closure), or political events (changing regulations). Supply chain complexities, especially when undergoing a disturbance, are difficult to comprehend using traditional methods, such as spreadsheet modeling or linear programming. However, a relatively new method of agent-based simulation, already widely applied in other industries (for example: Baker et al. 1999, Karageorgos et al. 2003, Cowling et al. 2004), allows for more realistic modeling of timber supply chains and variables that affect them.

This research attempts to quantify risk of wood chip supply through simulating the entire timber supply chain and potential disturbances to it. To do so, an agent-based model was designed using AnyLogic 7.3.5, a fairly new software suite allowing for simulations of complex systems, including supply chains. The objective of this project is to show the applicability of computer simulation methods in determining the least resilient areas in the Southern Ontario timber supply chain from a perspective of a developer looking to build a new biofuel plant.

This paper starts with an introduction to the biofuel sector, followed by an overview of timber supply chains, which feed raw materials into biofuel manufacturing facilities. The paper then provides an overview of the forest sector supply chain in Ontario, Canada. These introductions to the industry are followed by an overview of supply chain risk theory, and then by a review of relevant modeling approaches, with an emphasis on agent-based modeling. The remaining sections deal with simulation methodology, design, scenario, and results. These are followed by a discussion and recommendations for further improvement.

1.0 Background Research

1.1 Biofuel Sector Overview

Demand in Europe has been driving wood pellet production in North America since the mid 2000's (Arsenault 2014). In Canada, due to its healthy forest products sector the provinces of British Columbia and Alberta have been leading wood pellet production and export. However, increase in European demand is currently being challenged by wood pellet demand increase in Asia. Due to geography, some Western Canadian exports have shifted from Europe to Asia (WRI 2013). This situation creates an opportunity for other Canadian regions to develop wood pellet capacity (Krigstin et al. 2016).

Ontario could take advantage of this opportunity. The Ontario forest products sector has experienced significant downturn in the past decade (Krigstin et al. 2012). Forest sector jobs were lost at an average rate of 11% per year from 2001-2006, while employment levels in other areas increased. The volume harvested by the forest industry has decreased significantly as well:

from 73% of what was available in 2004, to 42% in 2008 (OMNRF 2012). One of the major reasons for such situation is the lack of innovation and diversification in the sector (Hansen et al. 2007). The growing wood pellet market could provide an opportunity.

Wood pellets are made from sawmill residues: wood chips, sawdust and shavings. Sawmill residues are traditionally regarded as disposable wastes of the sawmilling process (Williston 1988). With the development of the wood pellet sector, however, sawmill residues have started to play a more productive role in North America economies. Although other markets for sawmill residue exist, including mulch, hog fuel, animal bedding and pulp, these markets tend to be scattered and unstable, lowering the perceived value of the material. Moreover, other than the pulp and paper market, which in itself is in decline (Opeongo Forestry Service 2009) other markets for sawmill residue are small and highly seasonal (Krigstin et al. 2012). A development of the wood pellet industry in Ontario would provide significant benefits to the Ontario forest sector, creating a market for sawmill residues and therefore strengthening the entire forest products industry by making it more resilient to economic fluctuations (Krigstin et al. 2016).

The wood pellet industry development is most active in the Southeastern United States, where production capacity tripled from 2012 to 2013 (WRI 2013). In 2014, 10 million metric tons of wood pellets were produced in the region, with 2.7 million tonnes under development (Aguilar et al. 2015). Canada currently has 55 operating pellet mills with a combined productive capacity of 5.6 million tonnes per year (Wood Pellet Association of Canada 2015). 12% of this capacity is produced in Ontario (Krigstin et al. 2016) with five operating mills (Canadian Biomass 2015).

Krigstin et al. (2016) suggest that current trends in wood pellet use indicate that pellets from Ontario would be in demand in Europe and possibly the US, if only production capacity is developed. Liew (2016) suggests that one of the reasons why it is much more difficult to develop wood pellet manufacturing capacity in Canada than in the US Southeast is the lack of understanding of sawmill residue supply risk. If such risk were better understood, investors would be more confident in the wood pellet industry, financing more developments.

1.2 Overview of Timber Supply Chains

Timber supply chains, like all other supply chains, have inherent risks associated with them. Since the forest sector depends on raw wood supply, these supply chains risks translate into operational risks for the entire forest industry. Understanding these risks, what factors influence them most, would provide for better mitigation strategies (Chauhan et al. 2009).

The main objective of the timber supply chain is to provide timber for different uses by the forest products sector. Providing suitable supply of timber requires dealing with issues ranging from strategic forest management, such as harvesting activities, to operational tasks related to harvesting and transportation. Forest supply chain planning typically involves planning at different temporal horizons. For example, in well managed forests harvesting activities are planned based on multi-decade planning horizon, and incorporate not only economic needs, but also societal values put on forests. For that reason, timber supply chain planning tends to differ from country to country (D'Amours et al. 2008).

Generally, forest products supply chains are complex. Complexity of a supply chain is defined to be the sum of two components: the total number of nodes and the total number of forward, backward, and within-tier materials flows (Craighead, et al. 2007). Although private companies are the main actors in these supply chains, the networks are significantly influenced by government agencies, non-governmental organizations, environmental groups, and community organizations. Macro-economic variables, such as business cycles, international trade trends, and currency fluctuations also have an important influence on forest products supply chains (Vahid 2011). Additionally, these supply chains are susceptible to meteorological and other natural events, such as floods, forest fires, and insect outbreaks (D'Amours et al. 2008). The forest products supply chain in Ontario is no different.

1.3 Timber Supply Chain Planning

1.3.1 Strategic Planning

Strategic planning in forestry is typically long-term, extending over multiple decades. For example, one timber harvesting rotation can take more than 80 years (D'Amours et al. 2008). In terms of mills utilizing timber, a life-cycle of a mill is at least 30 years, with many pulp and paper mills operating for more than a century (Wood2Energy.org 2016). For these reasons, strategic planning regarding mill construction or acquisition, investments in equipment and transportation, road construction etc. require long-term approach.

The type of forest land tenure may also play an important role in strategic decision making. Timber can come from public (Crown) or private lands, or both. Depending on where wood comes from, different procurement strategies need to be considered. This is the case in Ontario specifically, where the government dictates how much wood is available to which mill (OMNRF 2016).

Despite the fact that strategic planning is very important for timber supply chains, little research pertains specifically to it. The scarcity of research in timber supply chain strategic planning indicates the need for knowledge creation in this domain. It also shows the lack of integration between long-term forest management and supply chain planning. Working on these shortcomings would be beneficial to the forest industry and its decision-making processes (D'Amours et al. 2008). According to Ronnqvist (2003), strategic planning problems are well served by time intensive modeling approaches, including Mixed Integer Programming (MIP), stochastic modeling, and agent-based methods.

1.3.2 Tactical Planning

Tactical planning serves as a link between the long-term comprehensive strategic planning and the short-term detailed operational planning. As such, tactical planning should ensure that the subsequent operational planning is drafted according to the directives established by the strategic plan (D'Amours et al. 2008).

In terms of its application, "tactical planning normally addresses the allocation rules that define which unit or group of units are responsible for executing the different supply chain activities or what resources or group of resources will be used. It also sets the rules in terms of production/distribution lead times, lot sizing and inventory policies" (D'Amours et al. 2008).

One of the main reasons for importance of tactical planning is the seasonality of timber supply chains. Seasonality has great influence on the outbound flow timber from the forests. Seasonality is important to consider mainly due to the shifting weather conditions throughout the year, which can make it difficult if not impossible to transport timber on forest roads in, for example, wet spring periods. On the other hand, a large proportion of timber is harvested in winter months when frozen ground allows for log forwarding without damaging the forest floor (D'Amours et al. 2008). Note that this research considers strategic planning only, therefore tactical issues, such as seasonality of timber supply, are not programmed into the simulation.

1.3.3 Operational Planning

Operational planning is planning that precedes and determines daily, real-world operations. Therefore, operational planning must adequately reflect the detailed reality in which operations take place, typically in terms of days or even hours. For example, activities such as a detailed log supply planning and hauler selection and routing are at the operational planning stage.

1.4 Understanding forest sector supply chain in Ontario

In Ontario, the availability of timber is determined by the Ontario Ministry of Natural Resources and Forestry (OMNRF). This is due to the fact that the vast majority of forests in Ontario are owned by the Crown, that is, are publically owned. The OMNRF serves as a management agency of Crown forests, and therefore oversees the planning of timber harvests. Consequently, the OMNRF maintains a dataset with forest inventory information, called the Forest Resource Inventory (FRI). This dataset is later used to prescribe future harvests by modeling forest growth and structure, thereby ensuring that the harvests result in healthy forests. The models' outputs are later used in the preparation of Forest Management Plants (Krigstin et al. 2016).

The Crown forest in Ontario is divided into Forest Management Units (FMUs). In total, there are 41 FMUs in the province. To limit the scope to the most active region in the province – Southern Ontario, only 11 of the 41 FMUs are analyzed in this project.

Each FMU is managed by an agency composed of local stakeholders, in most cases companies who have rights to harvest on that specific unit. These agencies are responsible for preparing Forest Management Plans (FMPs), which typically lay down detailed plan for harvesting operations over a 20-year period. The FMPs are updated every ten years, with more frequent updates if necessary (OMNRF 2016).

The OMNRF controls timber allotments to optimally utilize the forest resources to maximize economic, social and environmental aspects of the forest resources. To ensure optimal use of forest resources, OMNRF allocates specific quantities of timber to be cut by mills in Ontario through a mechanism called Timber Supply Agreement, or alternatively called 'commitment'. These commitments are based on Forest Management Plans, and are therefore assigned for a 20-year period, with a review process every five years (Wallace 1992).

In addition to long-term timber allocation, OMNRF can allocate temporary timber licences when such are needed to maintain continuity of supply to a particular mill. The mechanism is called an Interim Management Plan and is conducted on an annual basis, until the additional allotments are included in the main plan (Wallace 1992).

2.0 Overview of Theory of Supply Chain Risk

A supply chain is defined as "a network of organizations that are involved, through upstream and downstream linkages, in different processes and activities that produce value to consumers" (Christopher & Holweg 2011). From modeling perspective, a supply chain can be defined as "a network of autonomous or semiautonomous business entities collectively responsible for procurement, manufacturing and distribution activities associated with one or more families of related products" (Swaminathan et al. 1998).

Risk is most commonly (for example, Christopher and Peck 2004) defined by the following simplified equation:

$$\textit{Risk} = \textit{Likelihood of Occurrence} \times \textit{Consequences of Disturbance.}$$

There are three broad strategies when dealing with risk: 1) inventory management – build up safety stock; 2) sourcing – developing contingency strategies for specific suppliers or supply chain links; 3) acceptance – doing nothing as costs of mitigation outweigh benefits (Manners-Bell 2014).

In general, the higher the complexity of supply chains the higher risk becomes, due to factors such as the globalization of supply chains, increased volatility and variability of demand and supply, increased outsourcing, etc. (Chen et al. 2013); although complexity can also promote resiliency through build-up of network density (Falasca et al. 2008). The risk in supply chains usually originates from uncertainty and volatility of the business environment. Also, disruptive events, such as natural disasters, have a significant effect on supply chains (Chen et al., 2013).

Four main concepts in supply chain risk assessment include 1) vulnerability, 2) robustness, 3) disturbances, 4) resilience.

2.1 Vulnerability

Supply chain vulnerability was likely first conceptualized by Svensson (2000). The researcher defined supply chain vulnerability as “the existence of random disturbances that lead to deviations in the supply chain of components and materials from normal, expected or planned schedules or activities, all of which cause negative effects or consequences for the involved manufacturer and its sub-contractors” (p.732). In line with this definition, Vlajic et al. (2012)

identify vulnerability sources as “characteristics of the supply chain or its environment that lead to the occurrence of unexpected events and as such, they are direct or indirect causes of disturbances” (p.179).

2.2 Robustness

In supply chain management theory, robustness and vulnerability are perceived as opposite. The concept of robustness describes a supply chain as a system which has an ability to resist disruptions, retaining the system structure intact. Based on this concept, Vlajic et al. (2012) further refine the definition of supply chain robustness as “the degree to which a supply chain shows an acceptable performance in (each of) its Key Performance Indicators (KPIs) during and after an unexpected event that caused disturbances in one or more logistics processes” (p.188). In other words, “a supply chain is robust with respect to a KPI if the value of that KPI, adequately measured over an observation period, is sustained in a predefined desired range [the Robustness Range], even in the presence of disturbances.”

This definition indicates that supply chain robustness can be quantified. This characteristic allows researchers to model supply chain robustness. For example, supply chain robustness is often modeled by stochastic programming, such as the Monte Carlo methods.

2.3 Disturbances

Svensson (2000) defines supply chain disturbance as “a deviation that causes negative consequences for the firm involved in the supply chain” (p.735). Vlajic et al. (2012) are more specific: “supply chain disturbance [is] a minor or major deviation, or failure of one or more logistics processes triggered by unexpected events in the supply chain or its environment resulting in poor performance of the process itself, company and potentially along the supply chain in a given time period" (p.179). Vlajic et al. further write that supply chain disturbances can be characterized by a number of elements, including: a) frequency of occurrence, b) possibility of detection, c) impact on supply chain performance, and d) disturbance cause and size.

Disturbances are significant because of impacts they have on supply chain robustness. Disturbance becomes larger if a supply chain is not flexible and responsive to that disturbance. In other words, disturbances grow in significance if a supply chain cannot adapt to a new situation. Disturbances can range from local, affecting just one linkage in the chain, or system wide, affecting the entire supply chain. For instance, harvest failure would be a system wide disturbance (Svensson 2000; Vlajic et al. 2012).

Damage due to a disturbance can be limited through agility, or rapidity of response. A supply chain is agile when each member of the supply chain is agile (Manners-Bell, 2004). Agility has two elements: supply chain visibility and supply chain velocity (Christopher and Peck, 2004). Supply chain visibility refers to a clear understanding of demand and supply. Supply chain velocity refers to the time lapsed between order from a supplier and delivery, and the supply chain's ability to accelerate deliveries after a disturbance, i.e. "how quickly can product delivery be speeded up to respond to a particular event in the supply chain" (Manners-Bell, 2004).

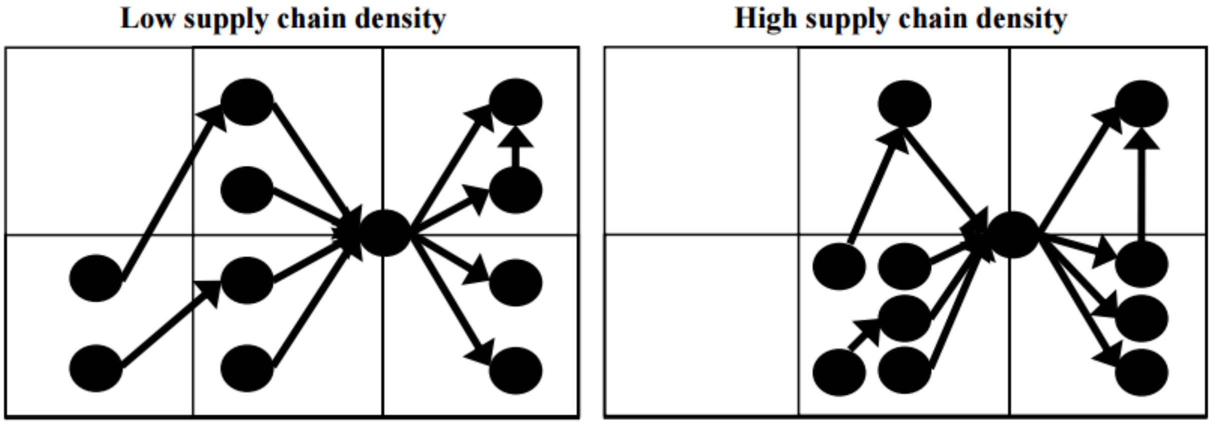
2.4 Resilience

The first concise definition of supply chain resilience (SCRES) can be found in Christopher & Peck (2004), who define it as "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed.” Further theorization about resilience is based on Falasca et al. (2008).

The concept of resilience can be regarded as an extension of the concept of resistance traditionally used in disaster management field. Resistance is used as a measure to determine performance of structures, infrastructure, and other elements in reducing losses from a disaster. As such, disaster resistance emphasizes the importance of pre-disaster mitigation. However, the concept of resilience builds upon this notion and includes improvements in the flexibility and performance of a system both during and after a disturbance. Consequently, Falasca et at. (2008) define supply chain resilience as “the ability of a supply chain system to reduce the probabilities of a disruption, to reduce the consequences of those disruptions once they occur, and to reduce the time to recover normal performance” (p. 596).

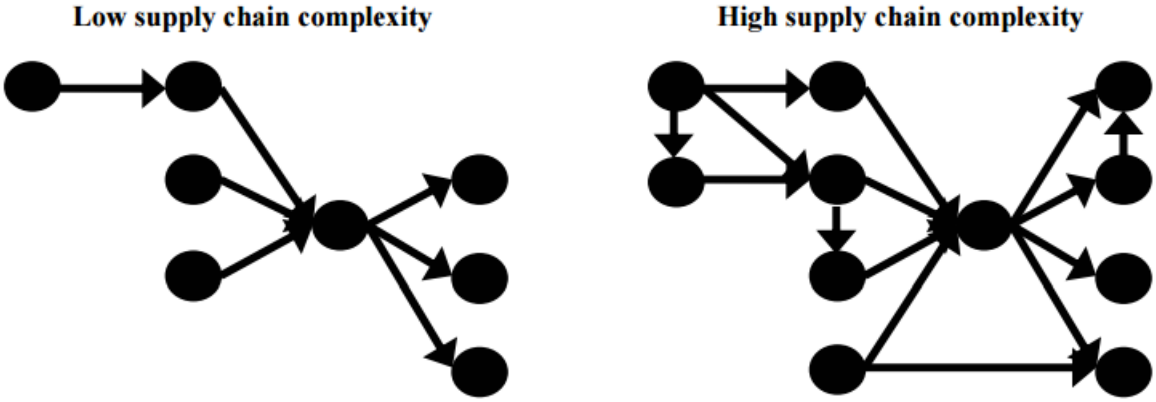
Based on this definition, Falasca et al. develop a model which quantifies supply-chain resilience. There are three determinants of resilience within a supply chain. The first determinant is supply chain density, which is defined by the quantity and geographical spacing of nodes within a supply chain. A supply chain is denser if a large number of nodes are clustered closely together. Therefore, in the case of the timber supply chain in Ontario, if there are clusters of mills together, these regions could suffer significantly if a nearby disturbance occurs.

Figure 1: Different degrees of supply chain density. Adapted from Falasca et al. (2008).



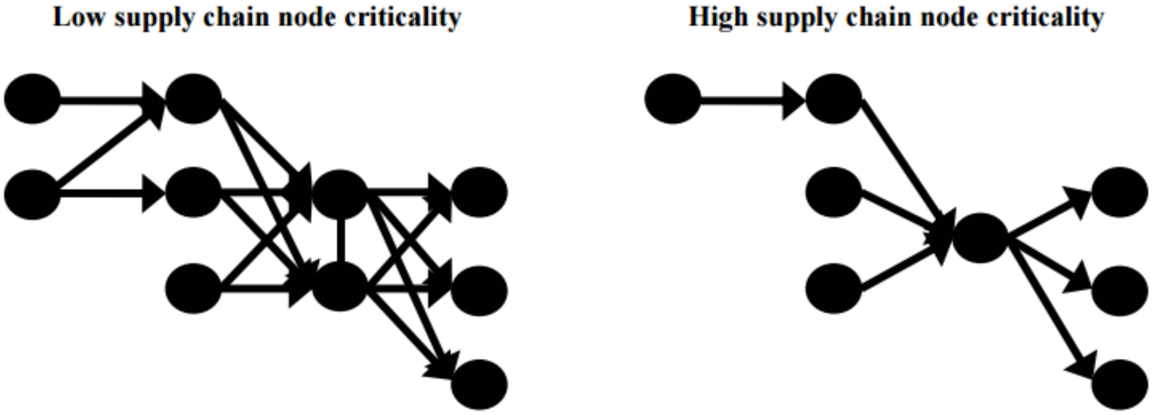
Secondly, the number of nodes and connections between them are directly related to supply chain resilience. However, as pointed out by Craighead et al. (2007), it could differ whether this relationship is positive or negative. For example, because a lower complexity supply chain by definition has less nodes or less interconnections, a disturbance would have a relatively lower impact on it. That said, if each node is crucial to a supply chain and it is taken out, without sufficient complexity of interconnections the supply chain is likely to be less resilient. This is likely to be the case in the Southern Ontario timber supply chain.

Figure 2: Different degrees of supply chain complexity. Adapted from Falasca et al. (2008).



The third determinant of supply chain resilience is somewhat related to the previous one: node criticality. Node criticality is defined as “the relative importance of a given node or set of nodes within a supply chain” (Craighead et al. 2007). In the Southern Ontario timber supply chain node criticality is based on production by Forest Management Units and the consumption levels by sawmills.

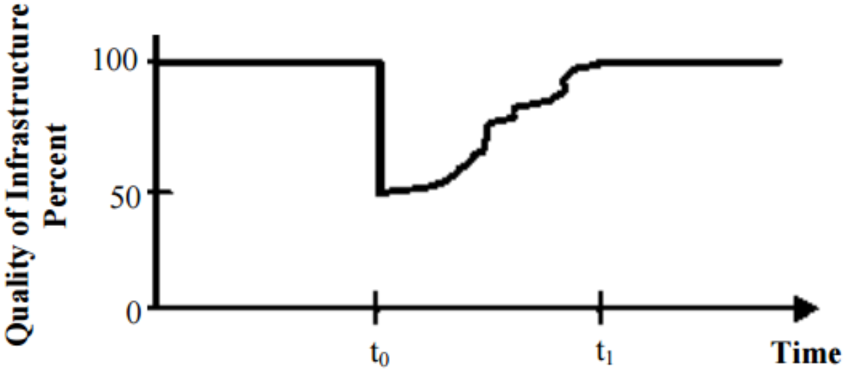
Figure 3: Different degrees of supply chain node criticality. Adapted from Falasca et al. (2008).



2.5 The Resilience Triangle

Tierney and Bruneau (2007) discussed the concept of the resilience triangle (sometimes also referred to as resilience curve). The resilience triangle is used to conceptually show the loss of system functionality due to disruptions and the subsequent restoration and recovery. The resilience triangle shows this recovery over time. As further described by Falasca et al. (2008), “the resilience triangle provides a simple, high-level means of representing the performance loss of a supply-chain system, together with the time to recovery.

Figure 4: The Resilience Triangle. Adapted from Tierney and Bruneau (2007).



3.0 Review of relevant modeling approaches.

3.0.1 Centralized vs. Decentralized Models

Supply chain models are also classified into centralized and decentralized categories, depending on the flow of decision-making process present in a supply chain (Vahid 2011). As the name suggests, centralized models incorporate one controlling entity that makes decisions for the entire supply chain. Due to the centralized nature of these models, they exhibit a higher level of control and collaboration among supply chain members, resulting in often more efficient decision making (Stadler 2005). The tendency in the literature was traditionally towards centralized models (Vahid 2011).

That said, often it is not realistic to assume that decisions are made in a centralized fashion. This is especially the case if the supply chain members do not belong to the same organization, as is the case in the forest products industry in Ontario. To better model the reality in such cases, decentralized models are more suited. In a decentralized model each organization (or supply chain controlled by one organization) is modeled separately based on earlier established goals. However, all organizations interact in the same environment, affecting each other. The decentralized modeling approach is significantly more realistic than the centralized one, especially in large supply chains (Stadler 2005).

3.0.2 Optimization vs. Simulation Approaches

The final approach of classifying supply chain models is based on the modeling approach and solution method. Considering this scheme, supply chain models can be classified into optimization and simulation models (Vahid 2011). Optimization models are used to find optimal answers to well defined problems. For instance, an optimal location for a distribution center based on constraints such as distance to ports or retail stores (Shapiro 2001). Optimization models tend to be centralized (Vahid 2011).

Simulation models comprise another type of supply chain modeling approach. They include approaches such as discrete-event simulation, system dynamics and agent-based modeling. Instead of defining specific constraints and goals of a model to best optimize an output, simulation models simply mimic the behaviours of the real world by allowing the variables, or agents, to interact in an often unpredictable manner. For this reason, simulation modeling approaches are best suited for decentralized supply chains (Chen et al. 2013).

3.1 Agent-Based Modelling Overview

Agent-based modeling is a particular type of simulation modeling. It originates from the study of complex systems and cellular automata. Agent-based modeling is “today recognized as among the most promising paradigms for detailed investigations and reliable problem-solving of complex real-world supply chains” (Chen et al. 2013). Although there is no one established definition of agent-based modeling, Sanchez & Lucas (2002) attempt to define it by “a simulation system comprising agents, objects, or entities that behave in an autonomous way.” In other words, agent-based modeling employs programmed entities which are independent of each other, and which interact in the same programmed environment. Due to this inherent independence of interacting agents, the entities’ behaviours often result in unpredictable patterns and outcomes. It is because of these unpredictable outcomes that simulations are useful – they allow decision makers to see supply chain patterns and results that may be difficult to guess. These results may even be counterintuitive.

Although the patterns and outcomes of agent-based simulations may be complex, the behaviours programmed into agents tend to be simple (Chen et al. 2013). That is, agents tend to have simple rules to abide by, and through multiple interactions these simple behaviours result in complex outcomes. Equally importantly, no sophisticated mathematical programming is necessary to build an agent-based model. The models depend more on computer power as opposed to complex mathematical statements. Agents’ behaviours are based on certain assumptions; it is the interactions of these behaviours that render complex and interesting results (Santa-Eulalia et al. 20111).

Another important aspect of agent-based modeling is its reliance on discrete-event simulation mechanisms. A discrete-event simulation means that time is simulated in the model, therefore allowing for not only simulating of what happens in a certain system, but also putting that information into time-referenced context. Consequently, it is possible to introduce various events into the system, such as natural disasters or unforeseen economic cycles. Therefore, agent-based simulation models are very suitable for analyzing risk, and developing mitigation strategies through testing different scenarios (Kleijnen 2004).

3.2 Agent-Based Simulation in the Forest and Biomass Sectors

Gallis (1996) simulated a forest biomass supply chain in Greece, and it was based on a simulation language called SLAMSYSTEM. The simulation was designed to examine the effects of interest rate, loss of value due to fibre deterioration, inventory times, and operational systems on cost of wood fibre, and as a function of time. Among other results, the simulation indicated that the most important factor affecting cost in all scenarios was the inventory time of biomass. Consequently, the model supports the claim that proper inventory management is crucial to mitigating risks in wood biomass supply chains.

Ebadian et al. (2014) propose a modeling approach which integrates the tactical and operational planning levels in the biomass supply chain. The approach integrates the optimization and simulation methods. The model aims at designing a supply chain to fulfill the daily biomass demand year-round for a commercial-scale cellulosic ethanol plant and to reduce biomass delivery costs. The optimization model prescribes the design of the supply area in a way that the annual biomass demand is met at a minimum delivery cost for a five-year planning horizon. Once a supply area is established, the simulation methods are used to schedule deliveries of the biomass across entire supply chain. If the daily demand cannot be met, the outputs of the simulation model are used to adjust the design in the optimization model to assure the fulfillment of the daily demand. The authors claim that "the application of the integrated model to a proposed […] plant shows the efficiency of the integrated approach to design the supply are in a way that the daily biomass demand is met at the minimum delivery cost possible" (p.171).

In terms of the forestry industry, discrete-event, and later agent-based simulation has most prominently been used to model sawmill operations (Vahid 2011). Randhawa et al. (1994) review early discrete-event models in the sawmilling industry. However, only some of these studies included simulations and analyses of entire supply chains. Perhaps the most relevant study was conducted by Beaudoin et al. (2007), who develop a stochastic model simulating wood procurement in Canadian context. The researchers applied Monte Carlo methods to simulate stochasticity, effectively arriving at a method to measure risk inherent in wood fibre procurement.

4.0 Simulation Methodology

4.1 Rationale to Solve the Objective

The objective of this paper is to determine the most resilient areas in the Southern Ontario timber supply chain from a perspective of a developer looking to build a potential new biofuel plant consuming sawmill residues, such as a pellet mill or a cellulosic ethanol plant. Sawmill residue production is directly proportional to the quantity of timber processed by sawmills. On average, approximately 50% of timber weight is converted into sawmill residue, mainly wood chips (Krigstin et al. 2012). Due to this direct relationship between quantity of timber processed and quantity of sawmill residue produced, all things being equal, it is possible to determine sawmill residue supply risk through estimating timber supply risk. In other words, assuming economic variables (such as demand for Ontarian lumber) remain constant, one can derive a risk profile for sawmill residue supply by estimating the risk profile of timber supply. Such rationale is applied in this analysis.

4.1.1 Study Area

The simulation focuses on Southern Ontario, Canada. In particular, there are 11 Forest Management Units under investigation here (Map 1). These Forest Management Units have been chosen because traditionally Southern Ontario was the epicentre of the Ontarian forest industry, and currently has lots of potential for the wood pellet industry (Krigstin et al. 2016).

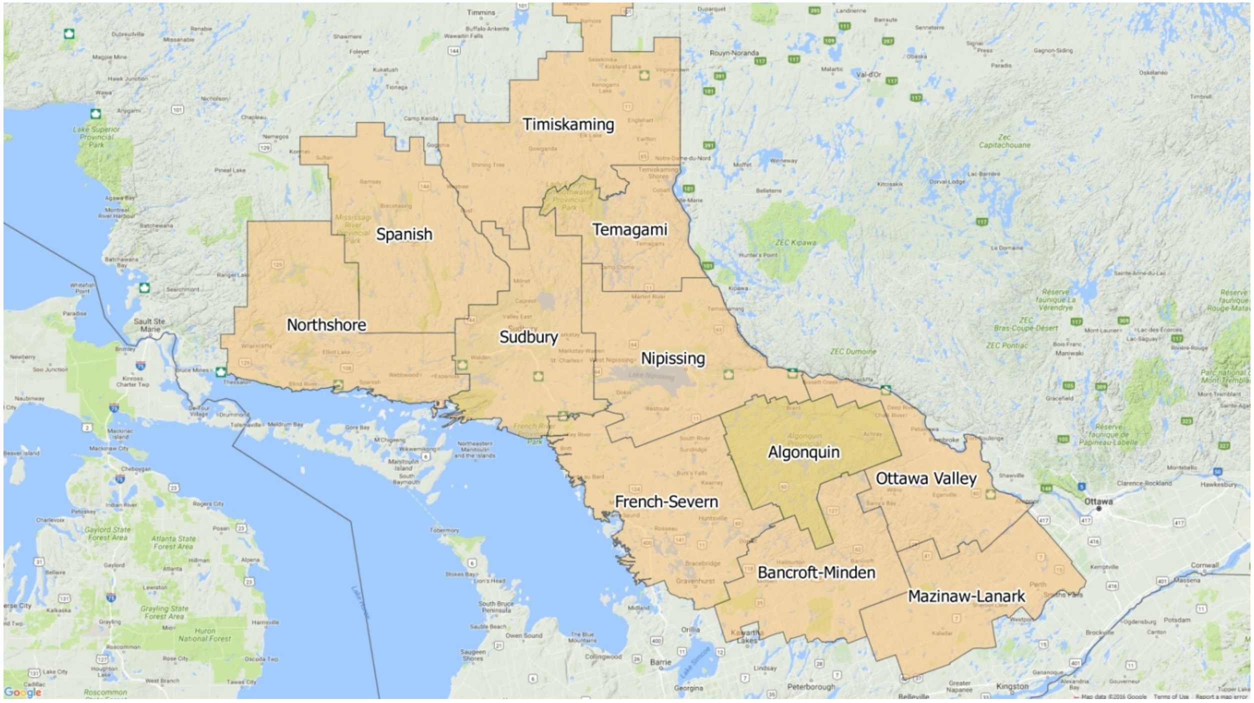
Table 1 indicates Forest Management Units analyzed in this simulation, together with corresponding quantities committed to sawmills. Map 2 shows all sawmills to which wood fibre from within the study area is committed to.

Table 1: Forest Management Units analyzed in the simulation.

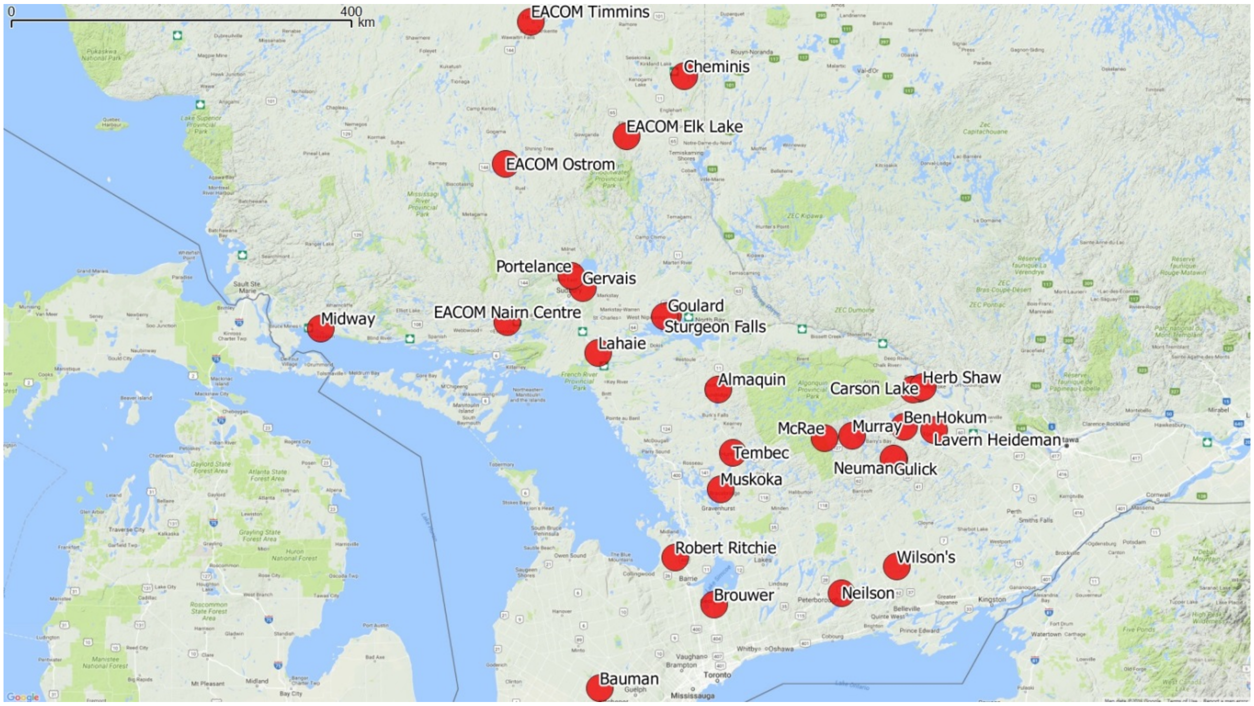
Forest Management Unit	**Commitments (cubic meters / year)**
Algonquin	937,735
Bancroft-Minden	108,050
French-Severn	192,700
Nipissing	400,900
Northshore	367,500
Ottawa Valley	120,800
Spanish	1,014,300
Timiskaming	907,300
Temagami	94,000
Mazinaw-Lanark	73,400
Sudbury	358,900

Source: Ontario Ministry of Natural Resources (2016)

Map 1: Forest Management Units in the Study Region.



Map 2: Sawmills in the Study Area.



4.2 Supply Chain Definitions

4.2.1 Raw Material - Timber

The simulation developed as part of this project models flow of timber in Central and Southern Ontario. The term timber describes wood fibre in the form of a log. Another common term for timber is roundwood. Timber is the first stage of wood processing. It is created following tree harvesting activities, i.e. tree felling and delimbing.

Timber is typically divided into two broad categories: pulpwood and sawtimber. The names for these categories are based on their destinations: pulpwood is traditionally turned into pulp (for paper), and sawtimber has been traditionally purchased by sawmills. In general, pulpwood is timber that is either too small or of too poor quality to become sawtimber. Additionally, timber that currently has no markets could become pulpwood. For instance, sawmills may have no demand for certain species (such as poplar in Ontario), making them of little value, and therefore rendering even large timber of this species pulpwood (OMNRF 2016).

Despite the forestry industry's division of timber into pulpwood and sawtimber, in the simulation developed here all timber streams are considered as one.

4.2.2 Sawmills

There are four types of mills consuming timber in Southern Ontario: sawmills, OSB mills, pulp mills, and pellet mills. The categories are based on the product each mill produces. In this project only sawmills are considered.

A sawmill is a facility which intakes timber, in the form of sawtimber, and cuts the timber into various pieces and shapes, producing a product referred to as lumber. Around 50% of the weight of raw timber is converted into lumber, the rest are residuals, in the form of bark, wood chips, shavings, and sawdust. These residuals have been traditionally used either internally as fuel for sawmill kilns, or as feedstock for pulp and pellet mills (Krigstin et al. 2012).

Each sawmill specializes in a specific product. For this reason, each sawmill procures logs according to its quality, size, and species needs. These differences are not reflected in this model; all timber procured by sawmills is considered timber. There are 29 sawmills in this simulation, and their locations are as follows: South River, Wallenstein, Killaloe Station, Keswick, Pembroke (three mills), Larder Lake, Elk Lake, Nairn Center, Ostrom, Timmins, Bancroft, Falconbridge, Sturgeon Falls (two mills), Palmer Rapids (two mills), Alban, Eganville, Whitney, Thessalon, Madawaska, Bracebridge, Norwood, Hanmer, Elmvale, Huntsville, Madoc; all sawmills are located in Ontario.

4.2.3 Log Truck

In this model, there is one moving agent in the form of a log truck. This agent picks up timber from a forest and delivers it to a sawmill. Log trucks in Ontario tend to be owned or directly contracted by sawmills (Liew 2016), therefore the sawmills control risks associated with truck performance. Trucking could be one of the most limiting factors of production, therefore can pose a major risk to the continuity of the supply chain (Barrett 2001).

4.3 Model Structure – Agent Overview

In this model there are three types of agents categorized into two categories: stationary and dynamic. Stationary agents have one specific geographic location. Dynamic agents move, following established routes between stationary agents. There are two types of stationary agents: Forests and Sawmills. The dynamic agent is represented by a Truck. The Truck agent delivers timber from the Forest agent to the Sawmill agent.

4.3.1 Agent 1: Forest Agent

Forest agents are polygons whose coordinates are defined by the Ontario Ministry of Natural Resources and Forestry. These boundaries are called Forest Management Units (FMUs) and have been discussed earlier. Forests are agents from which Timber flow originates. In other words, the supply chain starts off in Forest agents. Each Forest agent features a predetermined quantity of Timber available for consumption each year. These quantities are defined by OMNRF, and although they may slightly change over time, for the purposes of this model they are kept constant. It is important to note however that the quantities designated by OMNRF indicate maximum Timber available, meaning that Sawmill agents can consume less Timber than designated.

Forest agents interact with Truck agents. A Truck agent arrives at a Forest agent, loads 32 metric tons of Timber and leaves the Forest agent. The 32 metric ton quantity is then subtracted from the annual Timber availability predetermined for the Sawmill agent procuring Timber from the Forest agent.

It is assumed that an unlimited number of timber Trucks can be picking up Timber from Forest agent at any given time. In total, there are 11 Forests in the simulation.

Summarizing, in terms of Timber flow, there are two stages that occur at Forest agent:

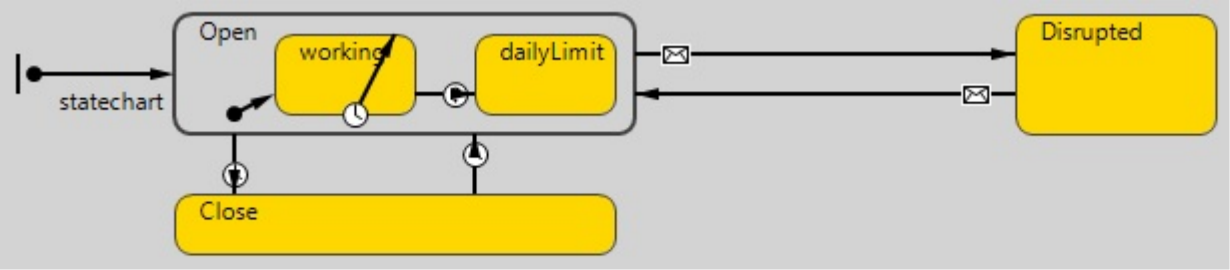
Stage 0: Availability of Timber from Forest agent to each particular Sawmill agent.

Stage 1: Truck agent from a particular Sawmill arrives. The Truck loads 32 metric tons of Timber material. It takes 30 minutes (Swartz 2012) to load the Truck agent with Timber. The Truck leaves the Forest.

Stage 2: Availability of Timber from the Forest agent to the Sawmill agent from which the Truck arrived has decreased by 32 metric tons.

A statechart (Figure 5) is a depiction of states and transitions of an agent. The Forest agent is open for 12 hours, and closed for 12 hours. When open, the Forest agent produces Timber for Truck agents to pick up. When closed, Trucks cannot pick up Timber from Forests. Additionally, Forest agents can undergo a disruption. A disruption is triggered by model user. Once triggered, a disruption closes down a Forest, not allowing any Trucks to pick up Timber from that particular Forest.

Figure 5: Statechart for the Forest agent.



4.3.2 Agent 2: Sawmill

The Sawmill agent is a stationary agent represented by a point. The Sawmill agent procures Timber from a Forest Zone agent. Locations and names of Sawmills were acquired from Ontario Ministry of Natural Resources and Forestry (2016). Because the OMNRF data may sometimes be outdated, the operational status of each sawmill was verified directly by phone. In total, there are 29 Sawmill agents in the simulation.

Sawmill agent interacts with the Truck agent. The Truck agent arrives with 32 metric tons of Timber. It unloads the Timber for 25 minutes (Liew 2016). The 32 metric tons of Timber are then added to Timber inventory at the Sawmill agent.

Keeping a healthy Timber inventory at Sawmill agent is the main mitigation strategy a Sawmill can implement to ensure constant supply of wood fiber. It is assumed that a Sawmill agent operates 12 hours per day (8am – 8pm), seven days a week.

Stage 0: Initial inventory of Timber.

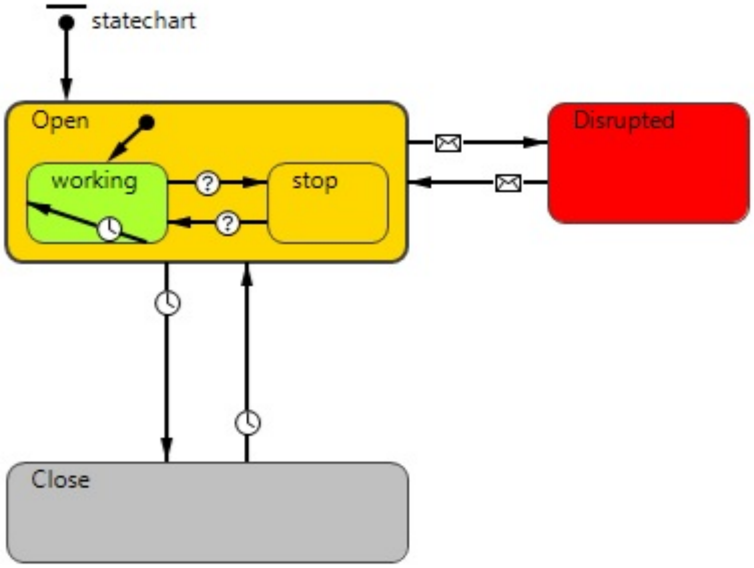
Stage 1: Truck agent arrives with 32 metric tons of Timber material and unloads for 25 minutes. Timber inventory increases by 32 metric tons.

Stage2: Timber is consumed at a rate equal to the total annual capacity of a Sawmill divided by 360 days * 12 hours per day.

Note that Timber inventory cannot have a negative value, i.e. weight less than 0.

The statechart for the Sawmill agent (Figure 6) indicates a sawmill's operational hours. A Sawmill agent is open for 12 hours and closed for 12 hours. When open, the Sawmill agent processes Timber (into lumber), sends trucks to Forest agents to pick-up Timber, and accepts Timber from those Truck agents that arrived. When closed, all these operations stop.

Figure 6: Statechart for the Sawmill agent.

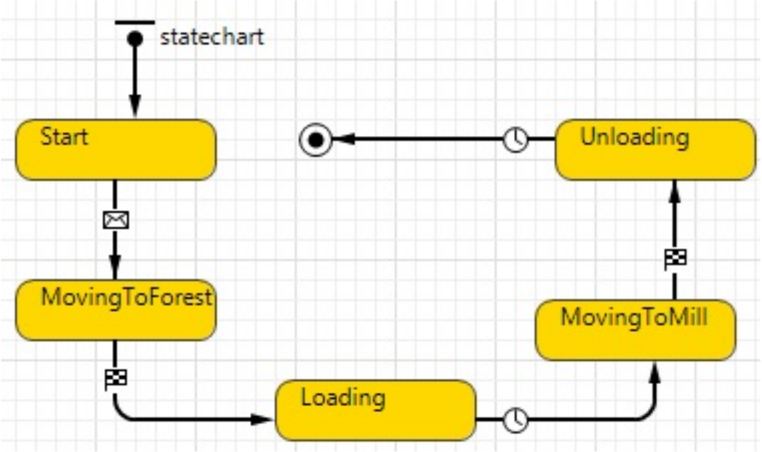


4.3.3 Agent 3: Truck

Truck is a dynamic agent. It interacts with and moves between Forest and Sawmill agents. Forest sends a signal to Truck that Timber is ready for pick-up. A Truck leaves a

Sawmill, travelling along a road according to the speed limit on that road. It arrives at a Forest Zone and waits 30 minutes to be loaded with 32 metric tons of Timber material. Once loaded, the Truck agent leaves the Forest and travels back to the Sawmill it came from. When it reaches the Sawmill, it unloads Timber into the Sawmill's inventory; the unloading takes 25 minutes. As seen in Figure 7, the Truck agent's statechart follows the above description.

Figure 7: Statechart for the Truck agent.



4.3 Timber Allocation

The Ontario Ministry of Natural Resources and Forestry is very specific with the quantity of timber allocated from each Forest Management Unit to each sawmill. These allocations are referred to as *commitments*. By law, each FMU requires a Forest Management Plan, developed every 20-years with 5-year updates. These Forest Management Plans specify the commitments, that is, the quantities of timber each sawmill can procure from a particular forest (OMNRF 2016). Therefore, to acquire data on annual timber allocation from each forest to each mill, all 11 forest management plans were reviewed. Table 2 shows a matrix of timber commitments acquired from forest management plans and used in this simulation. Units are in cubic meters per year, which, on average, is equal to metric tons per year (Liew 2016).

Table 2: Timber Commitments Matrix

	Timiskaming	Spanish	Temagami	Northshore	Mazinaw-Lanark	Nipissing	Ottawa Valley	Algonquin	French-Severn	Bancroft-Minden	Sudbury
Almaquin Forest Products	9500	0	0	0	0	0	0	0	0	0	0
Bauman Sawmill	1000	0	0	0	0	0	0	0	0	0	0
Ben Hokum & Son	0	0	0	0	3000	19000	47400	24000	1000	4000	0
Brouwer Wood	0	0	0	0	0	0	0	0	1000	0	0
Carson Lake Lumber	0	0	0	0	0	0	0	30600	0	0	0
Cheminis Lumber	45800	0	0	0	0	21500	0	0	0	0	0
Dament & Charles Lumber Manufacturing	0	0	0	0	3200	2000	3400	41000	0	0	0
EACOM Timber (Elk Lake)	477000	24000	0	0	0	0	0	0	0	0	0
EACOM Timber (Nairn Centre)	0	199000	94000	0	0	32000	0	0	0	0	143000
EACOM Timber (Ostrom)	0	230000	0	0	0	0	0	0	0	0	0
EACOM Timber (Timmins)	0	268000	0	0	0	0	0	0	0	0	0
Gervais Forest Products	0	5000	0	0	0	0	0	0	0	0	20000
Goulard Lumber	0	0	0	0	0	61500	0	0	8200	0	21800
Gulick Forest Products	0	0	0	0	1300	0	4200	4300	0	0	0
Herb Shaw & Sons	0	0	0	0	0	3000	5200	17785	0	0	0
Lahaie Lumber	0	0	0	0	0	0	0	0	2000	0	21900
Lavern Heideman & Sons	0	0	0	0	20900	1000	13000	30000	0	0	0
McRae Mills	0	0	0	0	0	0	0	106700	0	22600	0
Midway Lumber Mills	0	3000	0	77700	0	0	0	0	0	0	0
Murray Brothers Lumber	0	0	0	0	0	0	29100	80600	0	32400	0
Muskoka Timber Mills	0	0	0	0	0	0	0	0	104100	0	9000
Neilson Lumber	0	0	0	0	0	0	0	0	0	3600	0
Neuman Lumber	0	0	0	0	3200	0	6200	0	0	3600	0
Portelance Lumber	0	0	0	0	0	3400	0	0	2400	0	900
Robert Ritchie Forest Products	0	0	0	0	0	0	0	0	1000	0	0
Sturgeon Falls Brush & Manufacturing	0	0	0	0	0	500	0	0	0	0	0
Tembec	0	0	0	0	0	0	0	25750	40000	3200	0
Wilson's Forest Products	0	0	0	0	300	0	0	0	0	750	0

Source: Ontario Ministry of Natural Resources and Forestry (2016)

4.4 Disturbances

For the simplicity sake, only one type of disturbance is modeled in this simulation: a political disturbance. The political disturbance was specifically chosen because such disturbance would cause a removal of one entire Forest Management Unit (or Forest agent) from the simulation. This means that each of the 11 Forests can be taken out easily, and a comparative analysis between impacts of each Forest's absence on the Timber inventories can be measured within the timeframe of this project.

Perhaps more importantly, a political disturbance is a real threat to the biofuel industry in Southern Ontario. As a public resource, forests tend to be subjected to wide debates over their exploitation. Over the past few decades many Environmental Non-Governmental Organizations (ENGOs) had made forests their centres of attention. Greenpeace is one of such ENGOs which has had significantly negative impact on the ability of the forest supply chain to maintain its wood flow.

Resolute Forest Products is a Canadian company operating a number of pulp and paper facilities across the country, including five in Ontario (Resolute Forest Products 2016). Over many years of operations, the company has embraced sustainability policies as an answer to customers' expectations, mainly driven by wider environmental awareness among the public. One of the most important sustainability initiatives Resolute had embraced is the Germany-based Forest Stewardship Council (FSC) certification scheme. FSC is currently recognized as a 'gold standard' in the forestry industry world-wide.

A few years ago FSC retracted Resolute's certification, citing lack of needed consent from the First Nations and additional concern with Resolute's approach to woodland caribou, which is officially designated as a threatened species. The FSC retracted certification on approximately 10 million hectares of forest in Ontario and Quebec. Greenpeace used this opportunity to defame Resolute by convincing Resolute's customers to stop using paper from the company. The campaign worked and after some struggle Resolute was forced to close down its mill in Iroquois Falls, ON (Yakabuski 2015). This case shows that the ability to harvest timber from Ontario forests can be influenced by politically or ideologically motivated actions, such as a defamation campaign by an ENGOs. Because each Forest agent represents a separate jurisdiction in the real world, it is likely that if a political disturbance occurs, it would affect the entire Forest Management Unit (i.e. Forest agent).

This is just one example of a disturbance that could be modeled by the simulation. Other disturbances, such as forest fires, floods, road blockades etc. can be easily modeled, as long as their estimated spatial extent is known.

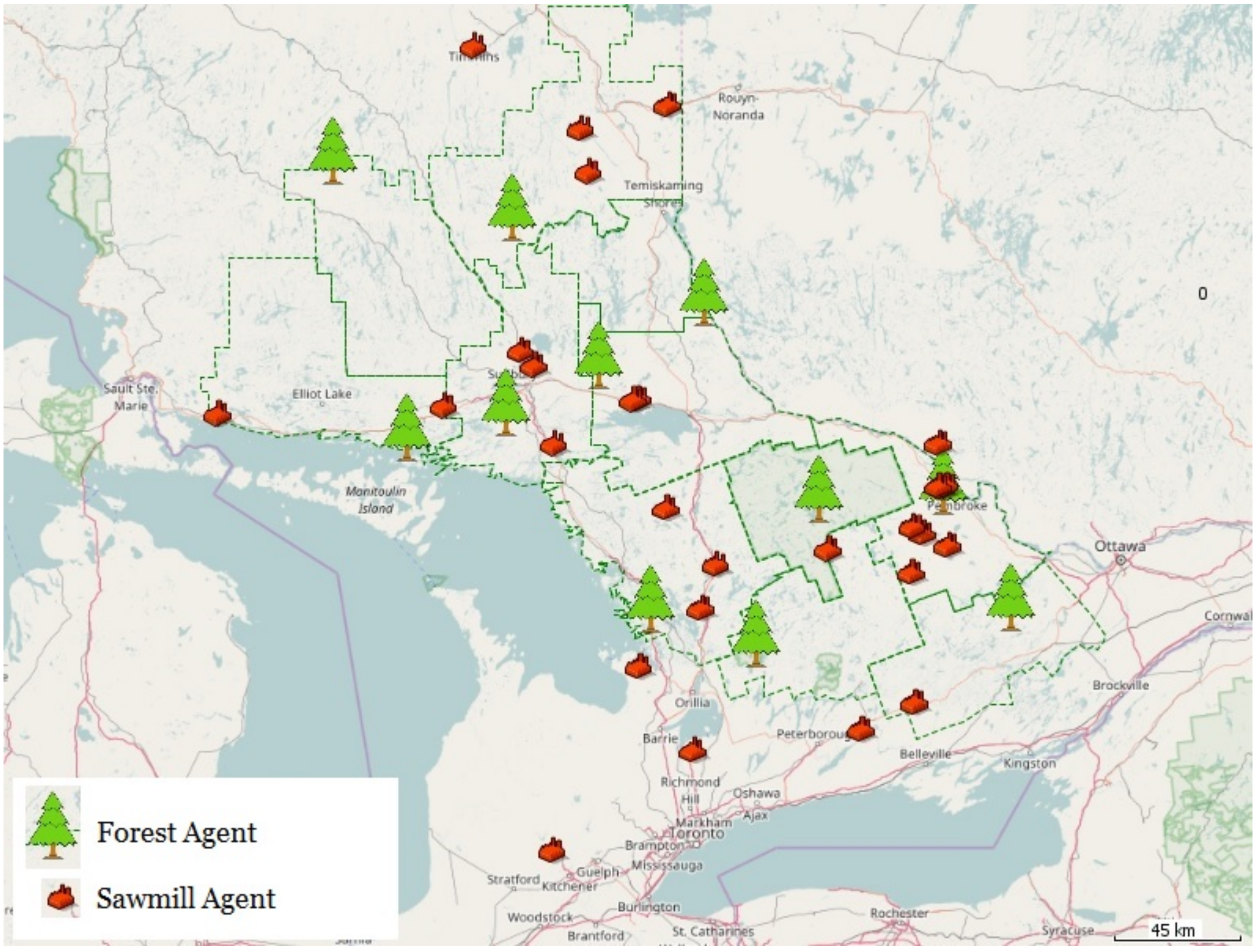
4.5 Simulation Set Up

The simulation was set up in AnyLogic 7.3.5, which allows for spatial representation of a supply chain. Each Forest Management Unit is represented by a polygon, for which shapefiles were acquired from the Ontario Ministry of Natural Resources and Forestry (OMNRF). The point from which Timber is picked-up by Trucks is determined by the nearest city to the center of the forest. These locations are depicted in Table 3 below and by tree icons in Figure 8. That said, the modeled in programmed in a way that the user can define exact locations from which timber needs to be picked up. For example, with additional work and access to files describing harvesting plans in the Forest Management Plans (OMNRF 2016), it is possible to simulate actual harvesting activities as planned by forest companies.

Table 3: Cities which act as timber pick up locations in the simulation.

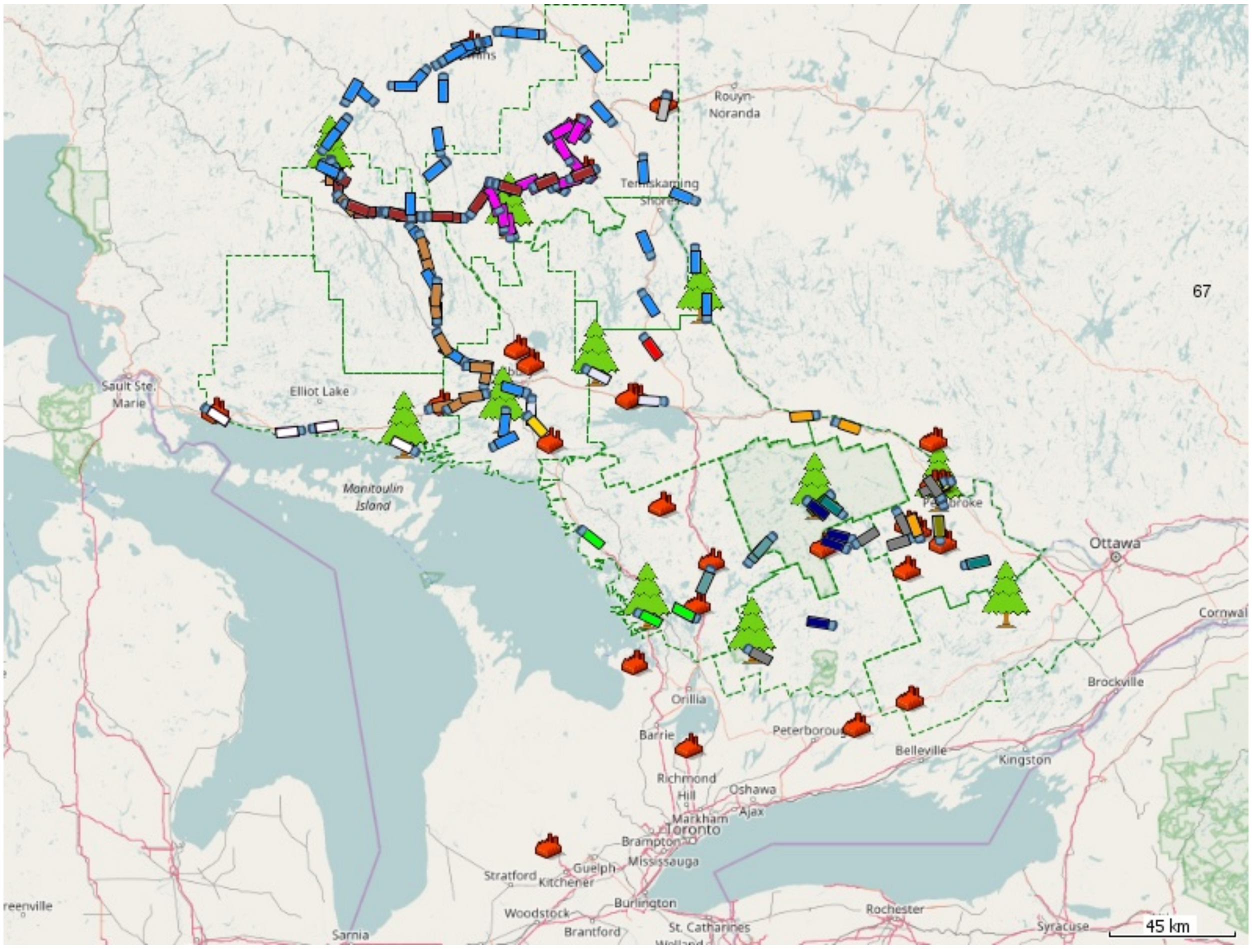
Forest	**City**
Timiskaming	Elk Lake
Spanish	Jerome
Temagami	Temagami North
Northshore	Elliot Lake
Mazinaw-Lanark	Kaladar
Nipissing	Tomiko
Ottawa Valley	Eganville
Algonquin	Algonquin Provincial Park
French-Severn	Spence
Bancroft-Minden	Minden
Sudbury	White Pine Chutes

Figure 8: Sawmills and Forests rendered in GIS environment.



Sawmills are depicted by red factory icons (seen in Figure 8). Locations are based on actual sawmill addresses researched online. The operational status of each sawmill was verified by phone. Trucks are depicted by small truck icons of different colours, which move as they go between Forests and Sawmills. Trucks follow actual roads and associated speed limits, which are programmed into the AnyLogic GIS (Geographic Information System) environment.

Figure 9: Running simulation in AnyLogic 7.3.5 in GIS environment.



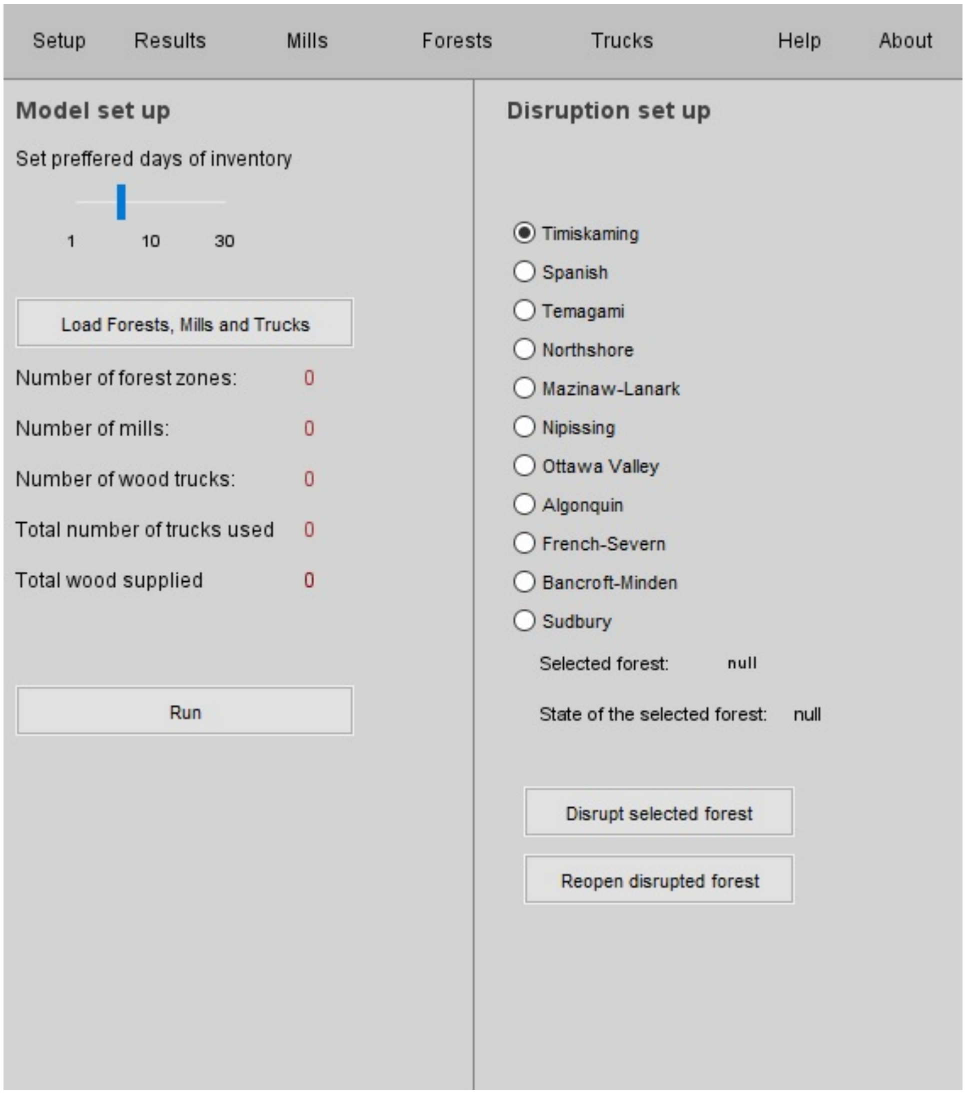
Source: AnyLogic 7.3.5

In addition to the GIS-based graphical representation of the timber supply chain, there is a model set-up dashboard (Figure 9). The dashboard allows the user to control inputs into the model. Firstly, it allows the user to specify the number of days of inventory the model should simulate. The number of inventory days determines how large timber inventory should be.

The user first loads all agents into the model, and then runs the model. While the simulation is running, the user can disrupt one or more Forest agent, by selecting a forest and clicking on the 'disrupt selected forest' button. Once a forest is disrupted, it appears red on the simulation map.

In addition to inputs, the dashboard features two output graphs. The first graph indicates the total number of trucks loaded since the start of simulation, the second graph outputs the total quantity of timber supplied.

Figure 10: Main simulation dashboard with model and disruption set up options, as well as total output graphs.



Number of forest zones: 0
Number of mills: 0
Number of wood trucks: 0
Total number of trucks used 0
Total wood supplied 0

● Timiskaming
○ Spanish
○ Temagami
○ Northshore
○ Mazinaw-Lanark
○ Nipissing
○ Ottawa Valley
○ Algonquin
○ French-Severn
○ Bancroft-Minden
○ Sudbury

Selected forest: null
State of the selected forest: null

Each agent has a separate dashboard that showcases simulation output at each point of time. The dashboard for the Sawmill agent (Figure 11) incorporates all variables associated with the agent, such as current stock or the number of Trucks sent, as well as a statechart and the inventory line graph. The statechart indicates whether a Sawmill is currently open or closed. The line graph represents timber inventory over time, with the quantity (in metric tons) on the vertical axis and the time (in hours) on the horizontal axis.

Figure 11: Simulation dashboard for Sawmill agent.

Mill's name: Almaquin Forest Products

Amount of wood used 5,816.038

Number of truckes arrived to this Mill 180

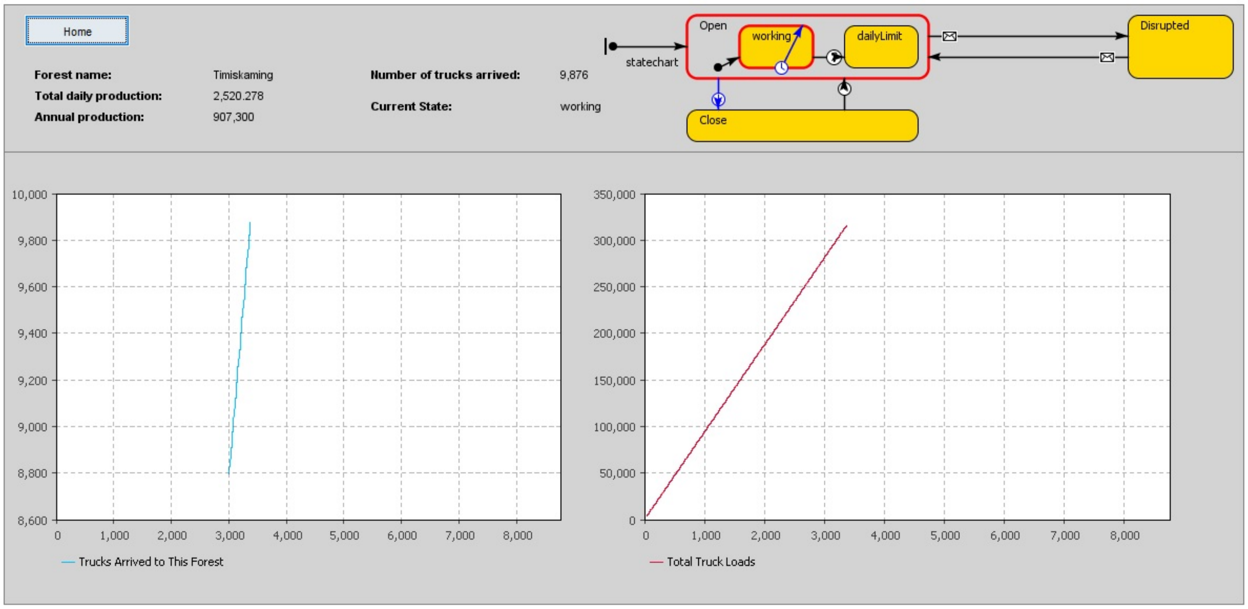
Amount of wood received 5,760

Current stock value: 207.851

Current State: working

Similarly to the Sawmill agent, the Forest agent dashboard incorporate a number of important variables, such as current stock and the number of Trucks arrived, as well as a statechart and output line graphs. The statechart indicates whether a Forest agent is operational, closed overnight, or is undergoing a disruption. The first line graph outputs the quantity (in metric tons) of timber that has been consumed from the Forest agent. The second line graph outputs the number of trucks that have arrived to this Forest agent. Note that both graphs indicate cumulative quantities, meaning that unless there is a disruption the line should follow an upward trend.

Figure 12: Simulation dashboard for the Forest agent.



Forest name: Timiskaming
Total daily production: 2,520.278
Annual production: 907,300
Number of trucks arrived: 9,876
Current State: working

5.0 Experiment & Results

5.1 Experiment

The simulation designed for the purpose of this study is flexible, allowing for an indefinite number of set ups, in terms of variables and assumptions. The simulation therefore functions like a software package, where inputs, timeframes, assumptions etc. can be changed at any moment. Consequently, the model can render an infinite number of results, depending on how it is run.

To show capabilities of this model a specific scenario (experiment) was chosen. Firstly, the timber supply chain operates with no disruption for two weeks (336 hours). Secondly, one Forest is disturbed at 337th hour for a period of two weeks, stopping the Forest's production. At 672nd hour, the Forest is reopened, the production level goes back to normal, and remains so until hour 1000. This scenario was run for three starting inventory levels: 10, 20, and 30 days. With 11 Forest disturbances to test, the simulation was run a total of 33 times.

5.2 Objectives

Based on the scenario above, the objective of these simulations is to answer the following:

1. What is the minimum Sawmill inventory level to keep the supply chain resilient to Forest disturbances?
2. How resilient is the timber supply chain to Forest disturbances, at each inventory level?
3. Which Forests are most significant to the supply chain, i.e. which forests, when disturbed, cause most negative reaction in the supply chain?
4. What is the risk a specific sawmill will close down during the two week Forest disruption, at each inventory level?
5. What are the most risky areas to site a biofuel plant in, in terms of sawmill closure and wood fibre availability risk, based on the Forest closure scenario?

5.3 Raw Simulation Results

Figures 13 -15 show examples of simulation results for the selected experiment. In all three cases Algonquin Forest was disturbed. The horizontal axis indicates time, in hours. The vertical axis indicates current inventory levels. Inventory levels tend to oscillate because of the difference in time between consumption and deliveries of Timber. A typical Sawmill starts consuming Timber a few hours before the first load of Timber is delivered.

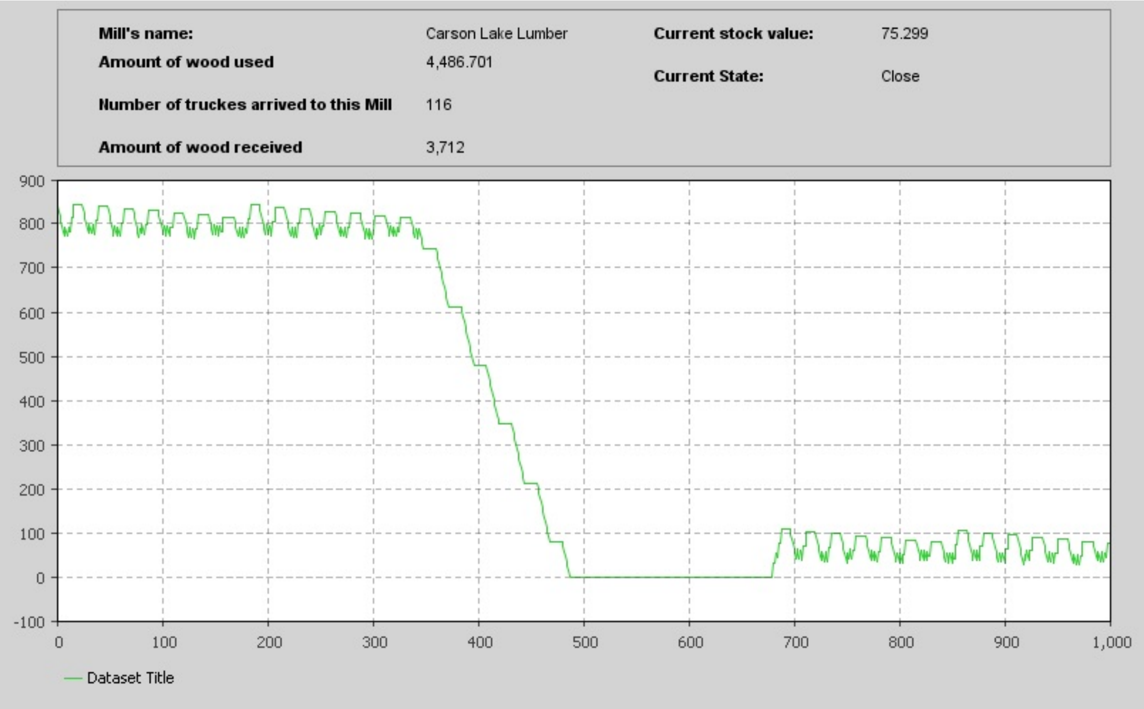
The 'Amount of wood used' indicates the total amount of wood consumed by a Sawmill during the 1000 hour simulation. The 'Amount of wood received' indicates the total amount of wood received by a Sawmill during the 1000 hour simulation. If a Sawmill is a subject to Forest disturbance, the amount of wood received is significantly lower than the amount of wood used, due to the unavailability of wood, therefore resulting in significant drops of inventory levels.

Figure 13 shows an example of a Sawmill that had to shut down completely due to the lack of wood inventory. This means that, at the initial inventory level of 10 days, the Sawmill is not resilient to a potential two-week disturbance to Algonquin Forest. The Sawmill remains shut down for approximately 200 hours, or eight days.

Figure 14 shows an example of a Sawmill that was affected by Algonquin Forest two-week disturbance, but managed to remain operational, therefore proving its resiliency to the disturbance. The inventory levels visibly decrease, however, once the Forest opens the inventory levels still remain at about 500 metric tons. Such resiliency is likely due to the Sawmill's ability to acquire wood from other Forests.

Figure 15 shows an example of a Sawmill that is not affected by Forest disturbance at all. The inventory oscillates between same levels even when a Forest is disturbed. Therefore, this Sawmill does not depend on that particular Forest at all.

Figure 13: An example of a simulation output for a Sawmill that is not resilient to Forest closure. The Mill remains shut down for approximately 200 hours.



Mill's name: Carson Lake Lumber

Amount of wood used 4,486.701

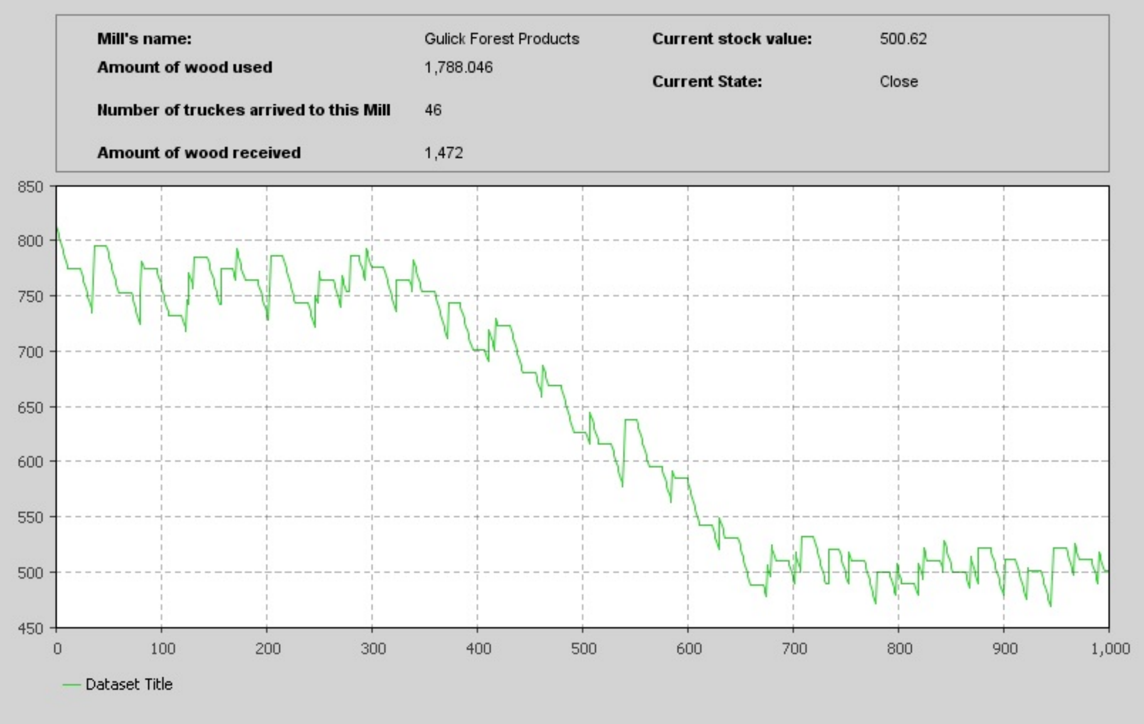
Number of truckes arrived to this Mill 116

Amount of wood received 3,712

Current stock value: 75.299

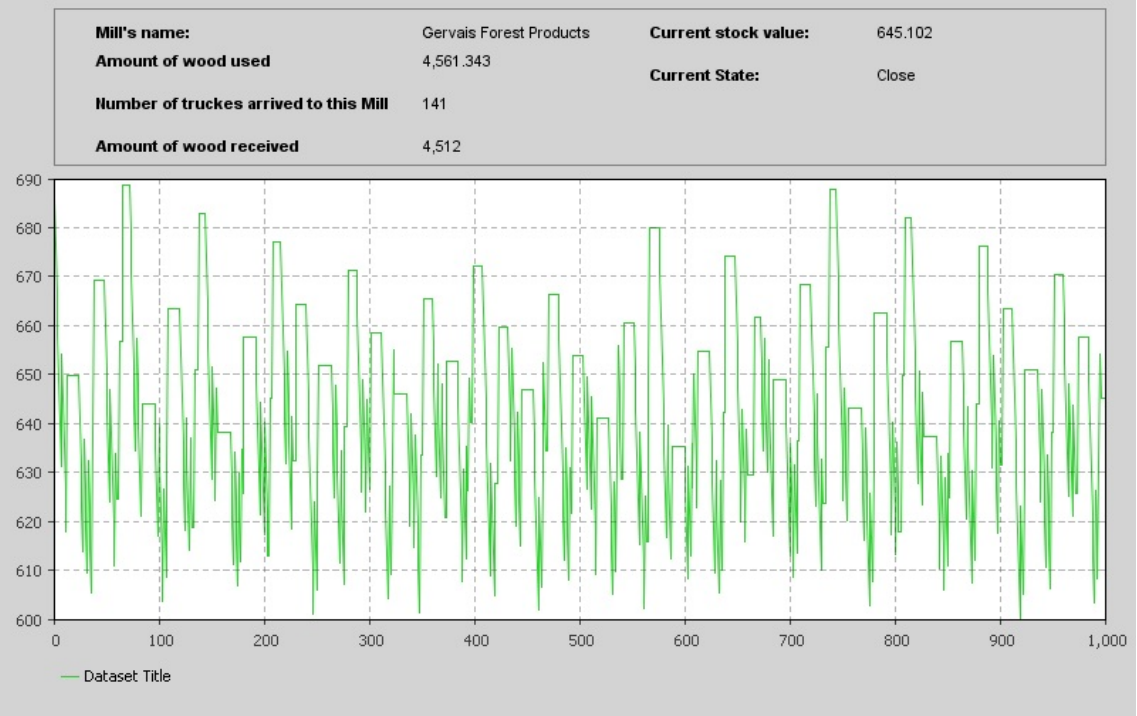
Current State: Close

Figure 14: An example of a simulation output of a Sawmill that is affected by Forest disturbance, but remains resilient to it and does not shut down operations.



Mill's name: Gulick Forest Products
Amount of wood used 1,788.046
Number of truckes arrived to this Mill 46
Amount of wood received 1,472
Current stock value: 500.62
Current State: Close

Figure 15: An example of a Sawmill that is not affected by Forest disturbance.



Mill's name: Gervais Forest Products
Amount of wood used 4,561.343
Number of truckes arrived to this Mill 141
Amount of wood received 4,512
Current stock value: 645.102
Current State: Close

5.4 Supply Chain Resiliency Overview

Table 4 indicates the number of times a Sawmill closed, i.e. the number of times its inventory reaches 0. The table is ordered by the number of times a Sawmill closes. For example, Sturgeon Falls experiences most closures, and Tembec experiences least closures. It is important to note that five Sawmills, starting with inventory for 10 days, shut down operations in almost all instances - 10 or 11 times. This result simply indicates that at the 10 day inventory level, these Sawmills cannot operate, even when all Forests are open. In the real world, therefore, the Sawmills likely import timber from outside the Study Area, or trade timber with other Samwills.

Other than those five Sawmills, the supply chain seems to be robust. Gulick and Portelance Sawmills close twice at the starting inventory levels of 10 days. However, once the starting inventory level increases to 20 days, they do not close at all. The remaining 21 Sawmills close only once. Nine of them close at both 10 and 20 day starting inventory levels. 12 close only at 10 day starting inventory levels.

The conclusion that the timber supply chain in Ontario is robust, from the perspective of this simulation, is further visible in Figures 16 and 17. The figures indicate the total quantity of wood supplied to Sawmills, for each disturbance scenario, and at each starting inventory level. It is apparent from Figure 16 that the two week disturbance during a six week timeframe does not significantly affect the supply chain as a whole. Forests whose disturbance has the most significant effect on the total quantity of wood supplied are Spanish, Timiskaming and Algonquin.

Figure 17 better illustrates the relative importance of each Forest to the supply chain. The vertical axis was shortened to make differences in the quantities of supplied wood better visible. Here we see that, in comparison to other Forests, Spanish and Temagami affect the supply chain the most. However, this effect is only visible at the 10 day starting inventory level. Once the starting inventory level increases to 20 days, the disturbances are barely noticeable. ***It is safe to conclude then that the timber supply chain in Southern Ontario is resilient to two-week forest closures, provided that the inventories are kept at 20 days.***

Table 4: Number of Sawmill shut downs by simulated starting inventory days. Sawmills are ordered by susceptibility to closures due to Forest disturbances.

Mill Name	Inv10	Inv20	Inv30
Sturgeon Falls	11	11	1
Wilson's	11	11	1
Robert Ritchie	11	1	1
Bauman	10	1	1
Brouwer	10	1	1
Gulick	2	0	0
Portelance	2	0	0
Almaquin	1	1	0
Carson Lake	1	1	0
EACOM Elk Lake	1	1	0
EACOM Ostrom	1	1	0
EACOM Timmins	1	1	0
Lahaie	1	1	0
Midway	1	1	0
Muskoka	1	1	0
Neilson	1	1	0
Ben Hokum	1	0	0
Cheminis	1	0	0
Dament & Charles	1	0	0
EACOM Nairn Centre	1	0	0
Gervais	1	0	0
Goulard	1	0	0
Herb Shaw	1	0	0
Lavern Heideman	1	0	0
McRae	1	0	0
Murray	1	0	0
Neuman	1	0	0
Tembec	1	0	0

Figure 16: Quantity of wood delivered to all Sawmills by starting inventory level, and Forest disturbed.

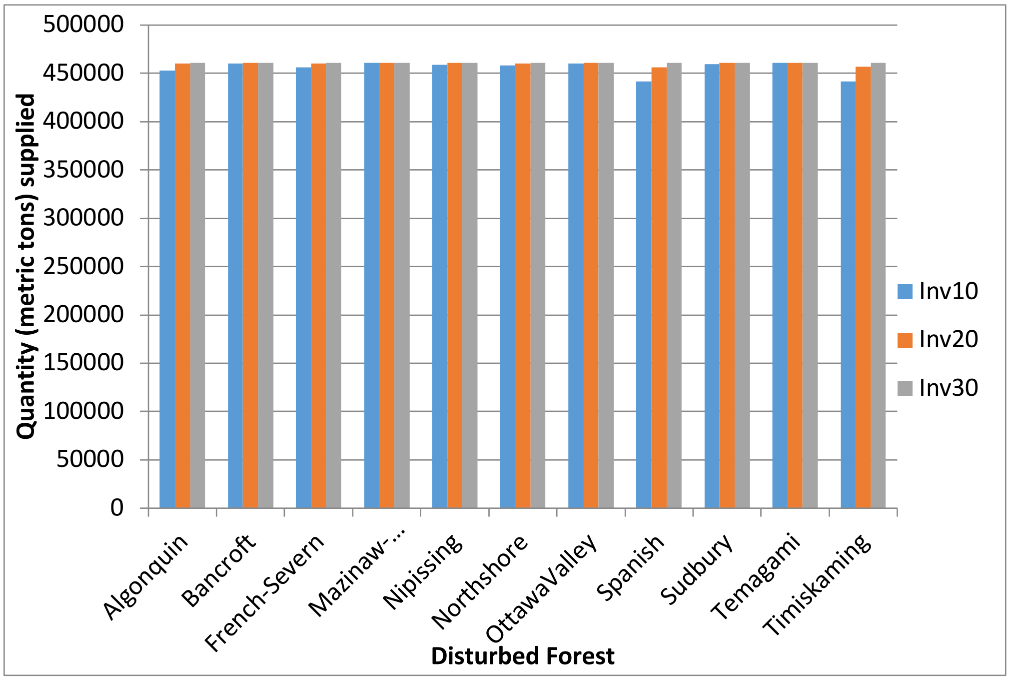
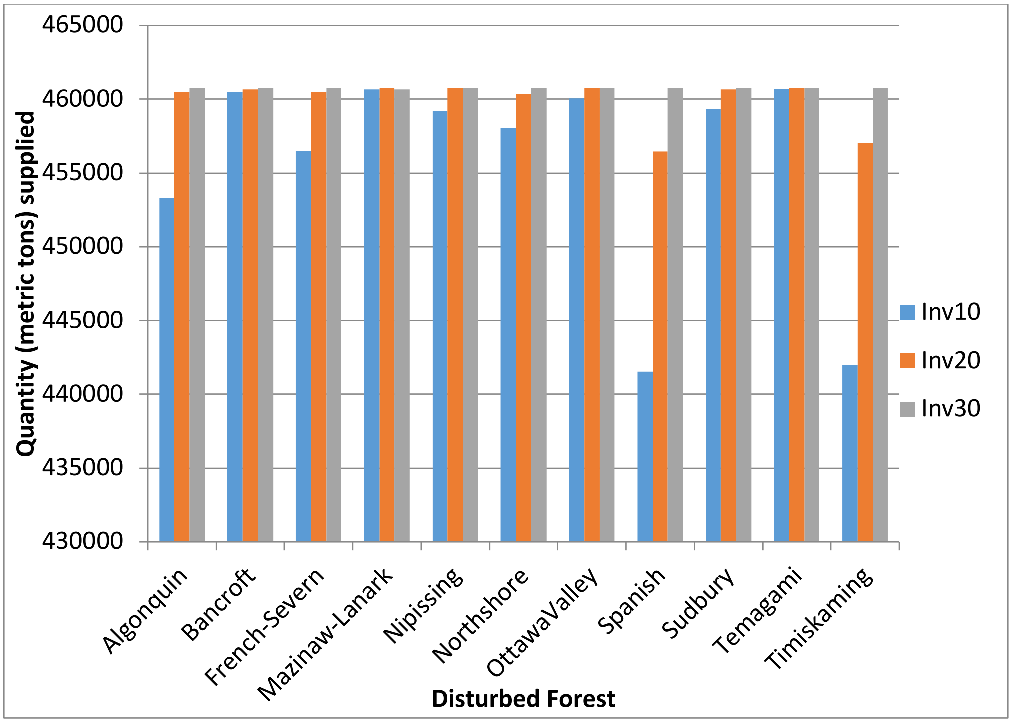


Figure 17: Quantity of wood delivered to all Sawmills by starting inventory level, and Forest disturbed. Vertical axis starts at 430,000 MT to better illustrate differences in the quantity of wood supplied.



5.5 Most Resilient Locations

When siting a new biofuel plant a developer does not look at a supply chain as a whole, but rather at each region separately. It is therefore important to analyze simulation results in a spatially-based environment. In this case, the results were analyzed in a Geographic Information System (GIS) environment using QGIS 2.14.3 Essen (Maps 3 - 8).

Due to the limitations of this simulation (as discussed later), risk of disturbance in wood fibre supply cannot be measured objectively. Therefore, the risk of wood fibre supply loss is presented as *relative* risk here. There are two separate methods the risk is measured using results from the simulation.

1) All quantities of loss of wood supply were aggregated for each Sawmill (for each starting inventory level). The resulting quantity indicates how much wood (in total) would be lost if all Forests were disturbed once.

2) The quantities calculated in (1) are expressed as proportion of the total quantity of wood consumed if no Forests were disturbed. For example, a 0.25 represents a proportion of total consumption that is not supplied to the Sawmill due to disturbances. Just as in (1), the data are aggregated for each Sawmill, representing proportion of wood lost if all Forests were disturbed once.

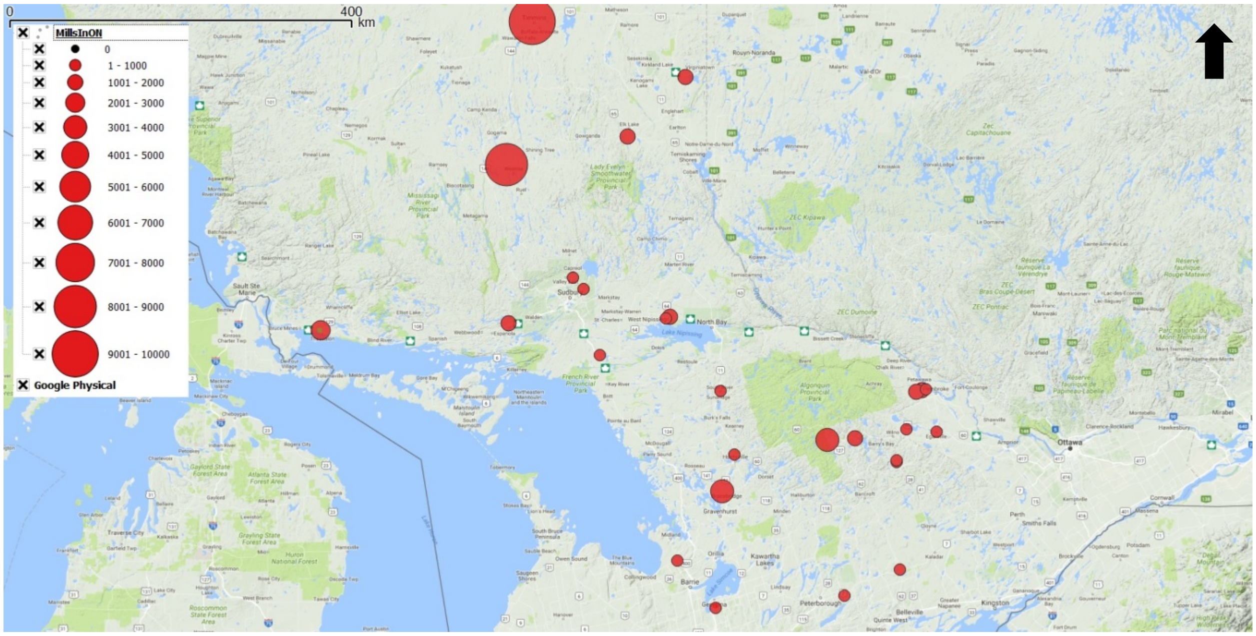
It is important to note that the quantities presented in these maps are meaningless on their own. That is, it is inconceivable that each Forest would close down precisely once, and exactly for two weeks. These metrics are meant to indicate *relative risk* posed in any given region. For instance, a cluster of large red dots in a particular region indicates that Mills in this region may not be resilient to Forest disturbances, and therefore this region poses high risk of loss of wood fibre supply - *in relation to other regions*. One cannot conclude, for instance, that there is a specific probability that a particular Sawmill will lose exactly 10,000 metric tons of fibre supply.

Map 3 indicates each Sawmill's relative risk of wood fibre supply loss, as simulated for 10-day starting inventory levels. The results indicate that the least resilient region in the study area is the northern part of it, with two Sawmills showing a high degree of risk. However, this could be indicative of the fact that in the real world these Sawmills likely draw wood from forests other than the ones analyzed in this study – which would explain why the two Sawmills with highest relative risk are located close to the northern border of the study region. Another explanation for the results is that the two Sawmills showing the highest relative risk, in terms of quantity of wood fibre loss, are large operations for which even slightest disruption of supply translates into large fibre losses.

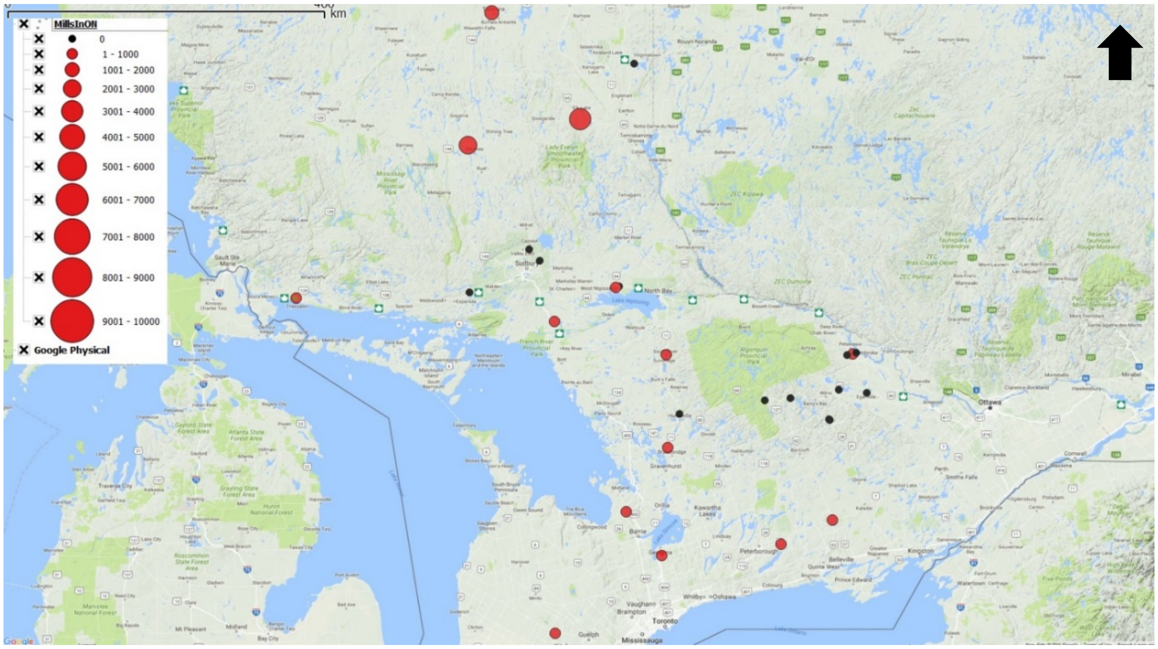
As initially shown in Table 4, and now indicated on Map 3, at 10-day starting inventory levels all Sawmills experience loss of fibre supply. This is in comparison to Sawmills simulated at 20-day starting inventory levels, as shown on Map 4. The area south of Algonquin Forest, represented by a cluster of Sawmills, may seem as relatively non-resilient region if 10-day starting inventories are considered. However, considering 20-day starting inventory output (Map 4), this region appears relatively robust, with 8 out of 10 Sawmills not experiencing any interruption in fibre supply.

Looking at the maps of relative fibre supply loss based on 30-day starting inventory levels (Map 5), it is apparent that the loss of wood fibre to the supply chain is negligible. In other words, if all Sawmills start off with 30-day inventory, a two-week disturbance to any (or all) Forests does not affect the supply of wood fibre. Therefore, maintaining inventory levels at 30 days makes the entire supply chain robust to two-week forest closures.

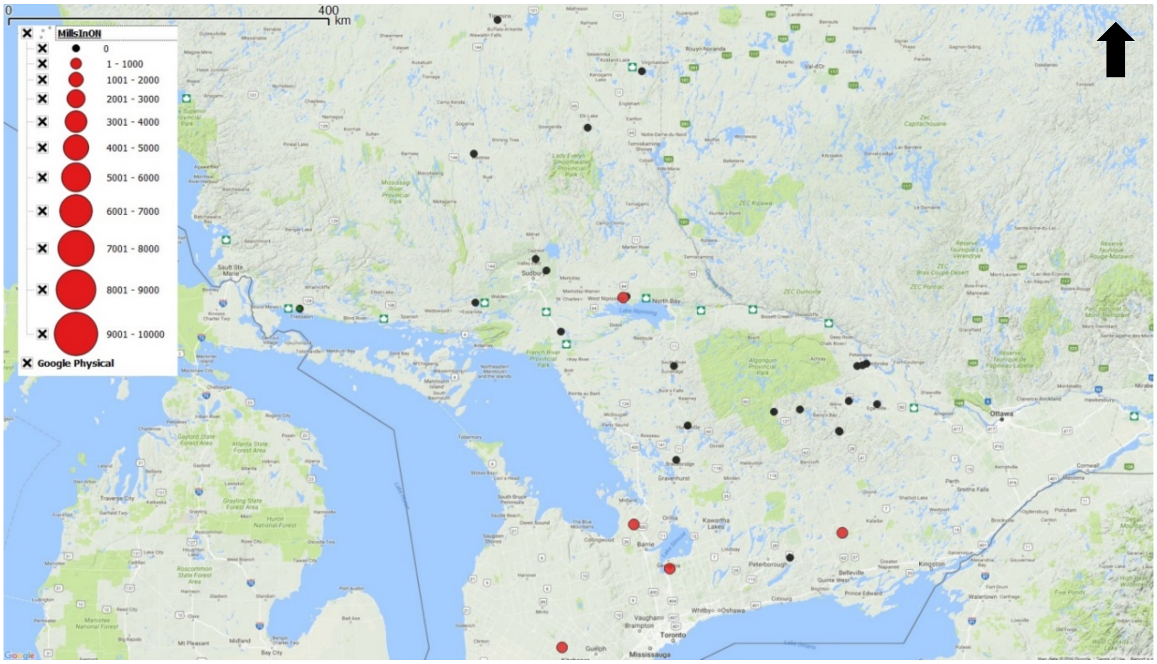
Map 3: First measure of relative risk of wood fibre supply loss, based on the total quantity of wood supply loss after each of the 11 Forests had been disturbed, and results aggregated. Results based on 10-day starting inventory levels.



Map 4: First measure of relative risk of wood fibre supply loss, based on the total quantity of wood supply loss after each of the 11 Forests had been disturbed, and results aggregated. Results based on 20-day starting inventory levels.



Map 5: First measure of the relative risk of wood fibre supply loss, based on the total quantity of wood supply loss after each of the 11 Forests had been disturbed, and results aggregated. Results based on 30-day starting inventory levels.



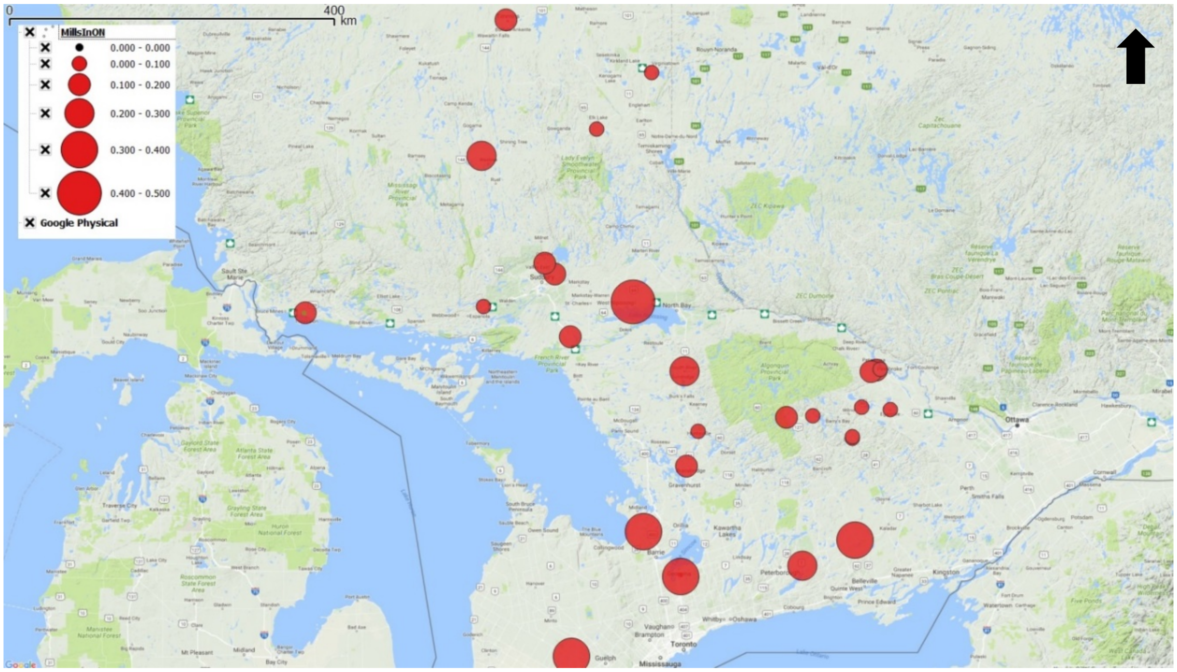
Maps 6 – 8 present a different method of estimating relative risk of fibre supply loss. Instead of measuring quantity of fibre loss, the method measures the proportion the lost fibre makes up in comparison to the total availability of wood if no disturbances occurred. This way of measuring risk is useful to estimate if a disturbance significantly affects Sawmills' operations in relation to their size. For example, it is useful if a biofuel plant expects to procure wood fibre from a small number of large sawmills.

The difference between the two methods of measuring relative risk is best illustrated by the two northern mills represented by the largest red dots in Map 3 (EACOM Timmins and EACOM Ostrom). What seems like an area prone to risk when considering method (1), the area seems resilient while considering method (2). In Map 6 EACOM Timmins and EACOM Ostrom are represented by relatively small dots, measuring that in proportion to their total wood consumption, the two-week disturbance does not affect them significantly.

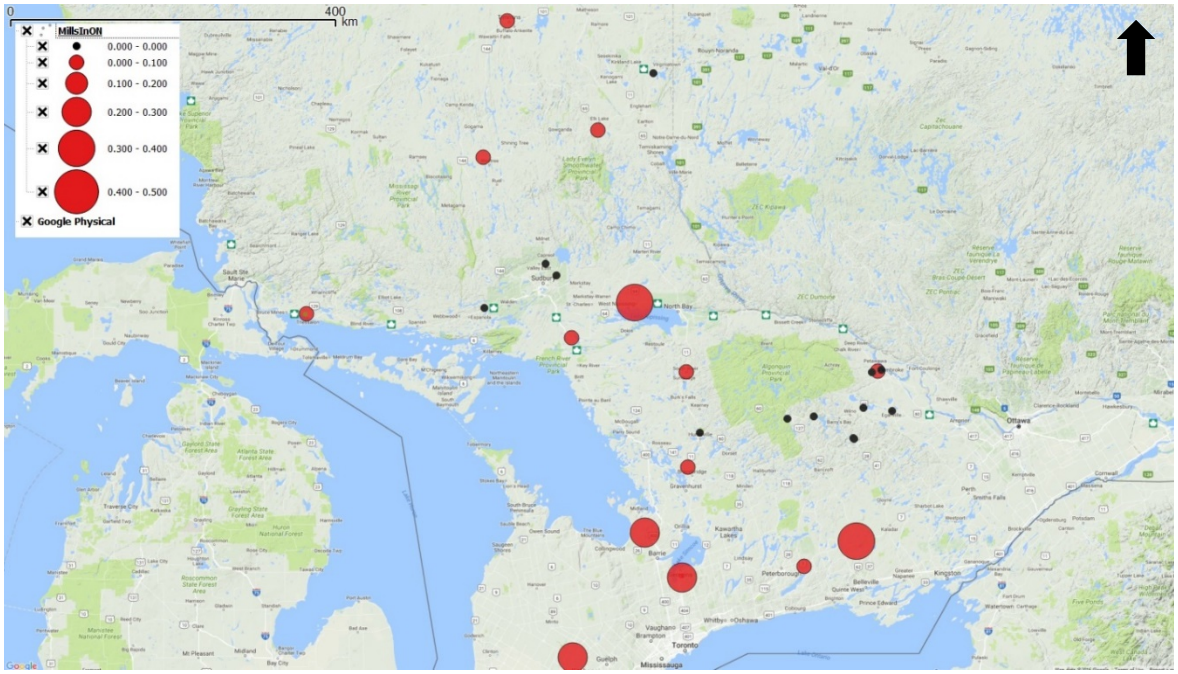
Maps 6-8 further indicate that the least resilient area, as estimated by method (2) is the most southern part of the study region. This is consistent with expectations, as this region is characterized by small Sawmills dependent on one or two Forests, meaning that if a Forest shuts down, a Sawmill with low inventory is likely to shut down too.

One interesting example of a Sawmill which shows high susceptibility to Forest closures is Sturgeon Falls, located approximately in the center of the maps. This Sawmill showed high resiliency when method (1) was applied, but with regards to method (2), it shows low resilience, even at 30-day starting inventory level. This example indicates that measuring risk of wood fibre loss using both metrics could provide insights that cannot be acquired from using just one method.

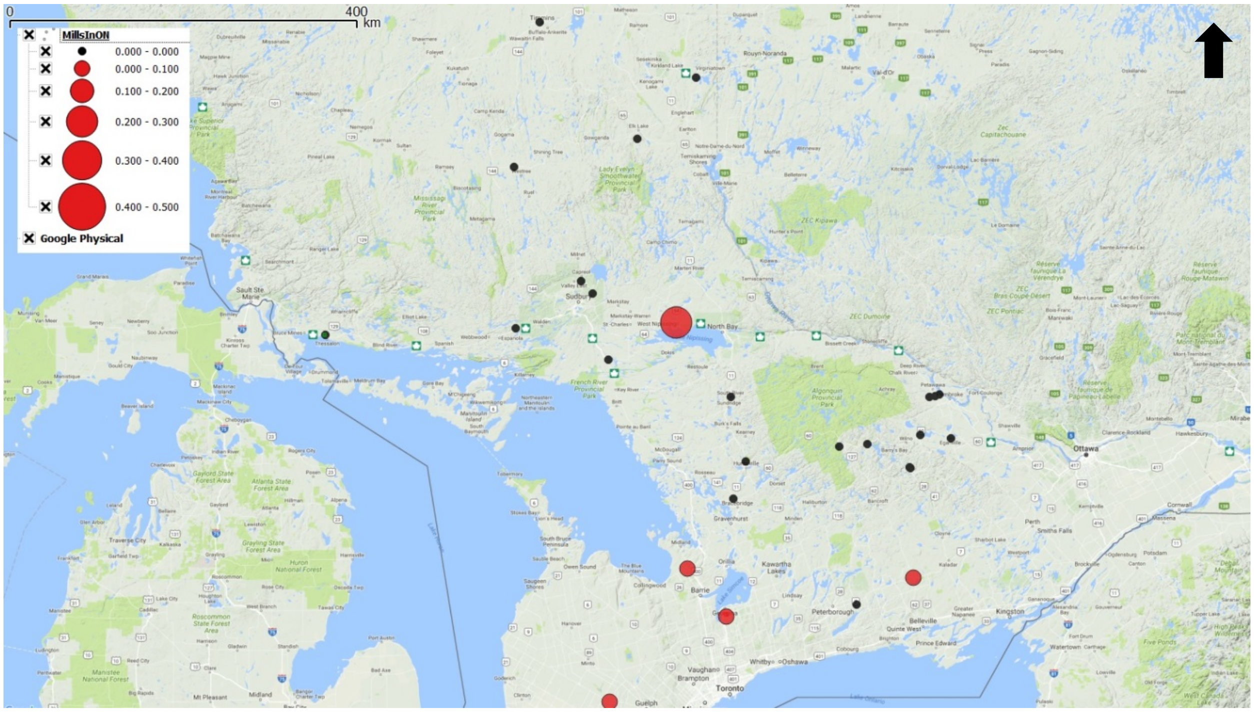
Map 6: Second measure of the relative risk of wood fibre supply loss, based on percent of total wood supply loss due to disturbances (results for all 11 simulations aggregated). Results based on 10-day starting inventory levels.



Map 7: Second measure of the relative risk of wood fibre supply loss, based on percent of total wood supply loss due to disturbances (results for all 11 simulations aggregated). Results based on 20-day starting inventory levels.



Map 8: Second measure of the relative risk of wood fibre supply loss, based on percent of total wood supply loss due to disturbances (results for all 11 simulations aggregated). Results based on 30-day starting inventory levels.



6.0 Discussion

A model was developed here simulating the timber supply chain in Southern Ontario. The objective of the simulation was to show the applicability of computer simulation methods in determining the most resilient areas from a perspective of a developer looking to build a new biofuel plant. In this case, a scenario was tested whereby each Forest Management Unit in the study area is closed (due to a political disturbance) once for a period of two weeks. The results indicated which sawmills, and by extension which areas, are most resilient to the two-week disturbance. Two different methods were applied to measure relative risk of wood fibre loss, one based on the total quantity of wood supply loss, the other based on percent of total wood supply loss. Additionally, each simulation was performed based on three starting timber inventory levels: 10, 20 and 30-day.

Simulation results show that in general the wood supply chain in Southern Ontario is robust. Aggregated results for all simulation runs, and separated by starting inventory levels, show that during the two-week disturbance of any Forest Management Unit, the vast majority of sawmills remain open; those that shut down due to the lack of timber inventory are the very small operations. The total quantity and the percentage of wood loss due to disturbances are further visualized on GIS-rendered maps. The maps specify areas where the supply chain is least resilient to the disturbance by quantifying relative risk, based on the total quantity and the percentage of wood loss. Therefore, the maps serve as indicators of best potential locations for a biofuel plant, from a perspective of risk posed by a theoretical two-week closure of a Forest Management Unit.

This analysis is of course based on the limited scope of assumptions that went into building the simulation. The simulation that was developed here should be regarded as a base for future improvements, as opposed to a finished product. With each additional layer of complexity, each additional variable, the simulation would become more realistic, that is, would resemble the real world in more detail. To judge the simulation's applicability at its current state, and understand what future improvements can be implemented, it is important to understand what aspects of the real world the assumptions omit.

6.1 Lack of Competitors

Perhaps the most significant omission of this simulation is the lack of consideration for competitors for wood chips. Currently in Southern Ontario all wood chips are utilized, mostly serving as feedstock for pulp and paper production and wood pellet manufacturing (Krigstin et al. 2016). Any overproduction of wood chips is easily exportable, as the commodity is in high demand in regions such as Quebec (Liew 2016). Therefore, an understanding of the competitive landscape, and risks associated with it, is crucial to understanding risks associated with wood chip supply in the region. Simulating current demand for wood chips should be a priority in the next step of this simulation development.

6.2 Imprecise Spatial Extent of the Forest Agents

Forest Management Units (FMUs), as defined by the Ontario Ministry of Natural Resources and Forestry, tend to be geographically large. Timber harvesting can take place anywhere across the FMUs. In fact, actual spatial extents over which harvesting activities take place are defined in Forest Management Plans prepared by companies conducting these activities, and are available to the public through OMNRF website. However, due to time constraints present when developing this agent-based model, the geographic location of harvesting activities at any time was assumed to be the main urban area located close to the central point of each Forest polygon. This is one of the major limitations of this model. Having one location for timber pick up for each Forest does not properly reflect the reality, as actual geographic extent where forestry activities occur are carefully planned and take place across a FMU. Consequently, the simulation oversimplifies the actual supply chain, and therefore runs a risk of being an inadequate representation of the situation on the ground. For instance, transportation distance from a Forest to a Sawmill may be significantly affected, changing the transportation time of each load and therefore affecting the rate with which sawmill residue is generated. Future improvements to this model therefore should take into account actual spatial extent on which harvesting activities take place.

6.3 Simplification of Business Relationships

The simulation developed here assumes that there are no previously established contracts or other business relationships in the supply chain. Business relationships can involve mutual agreements between two Sawmills to share timber resources. This is likely to be the case, for example, when two or more Sawmills are owned by the same company. Additionally, in the real-world Sawmills can trade timber among each other. For example, if one sawmill requires more timber than is predetermined from the Forest agent, then it can purchase timber from another sawmill. This dynamic has not been considered in this simulation, because such information is unavailable.

The assumption used here is that wood flow acts accordingly to the supply and demand dynamics of an open system. In reality, however, there are contracts or other dependencies between businesses. However, due to confidentiality of these dependencies, it is almost impossible, and certainly impractical, to consider actual business relationships in the model. That said, lack of consideration of actual business relationships in the supply chain is a limitation to this model.

6.4 No Distinction between Softwood and Hardwood

This study considers timber as one indistinguishable commodity. In reality, species of timber play a significant role in the marketplace because different products are produced from different species. Timber species are typically categorized into two broad categories: softwoods and hardwoods. Generally, softwoods are conifers – or evergreen trees recognized by needles. Hardwoods are broadleaf trees. The names come from wood density. Softwoods tend to be low in density, and therefore ‘soft’; hardwoods are the opposite. The distinction between softwood and hardwood is important to the objective of this model because wood pellets are typically produced as softwood or hardwood, and mixes of the two are hardly marketable (Krigstin et al. 2016). For simplification purposes this distinction between softwoods and hardwoods, although significant, has not been considered in this simulation. Next variations of this model should take differences in species into account.

6.5 Closed System

This simulation is a representation of a closed system. According to the assumptions made in this simulation, there are no imports or exports of timber to and from the system. This is of course a simplification of the reality. In the real world, if a sawmill is in desperate demand for timber, it can often procure wood from outside the system; in this case from other FMUs, the province of Quebec, or even New York State. Imports of timber require more sophisticated modeling as the distance from which a sawmill can procure timber is directly related to the cost of the commodity, which was not modeled here. Future improvements to this simulation may involve opening up the system to timber imports from outside the 11 Forest agents.

6.6 Price Variable

This simulation only considers material flow between different agents. It does not look at the price component. The price component is crucial in understanding where sawmills can source timber from. For instance, if a sawmill can pay more for timber, it could purchase extra timber from another sawmill, which may have access to more timber than necessary. Price, therefore, is an important determinant of a sawmill's ability to procure extra timber. As a matter of fact, financial risks, such as the risk of price increase due to increased harvesting costs because of a weather event, is as important as the general availability of wood (Beaudoin et al. 2007).

Despite the limitations listed above, it is not necessarily required to program all potential variables into the simulation. The goal of each simulation exercise is to test various ideas, and gain insights into how the system reacts to these ideas. In the relatively simple simulation of the timber supply chain in Ontario that was developed here, a relative measure of wood supply resilience for a potential biofuel plant was determined. Such approach could serve developers in better understanding of risks associated with wood supply, and therefore could make investors more confident in the industry. The flexibility of agent-based simulation and its ability to test multiple scenarios to understanding supply chain risk, as presented in this project, could prove of great value to the emerging bio-economy and its investors.

7.0 Conclusions

A model was developed here simulating the timber supply chain in Southern Ontario. The objective of the simulation was to show the applicability of computer simulation methods in determining the most resilient areas from a perspective of a developer looking to build a new biofuel plant. Political disturbance was chosen as an example of how the simulation can be applied to real-world risks. The simulation experiment resulted in a dataset indicating areas with highest and lowest resilience.

The biofuel industry faces many challenges, of which raw material supply risk is one of the most significant. The experiment presented here provides an example of the applicability of using an agent-based simulation in biofuel industry development decision-making process. By simulating the entire supply chain, a decision-maker can understand areas of highest risk of, for example, supplier closure due harvesting disturbance. Understanding risk has a potential to lower risk perception, promoting investment into biofuel industry, and lowering investment debt. With lower investment debt, the likelihood of biofuel plant success increases (Solomon, 2016). The potential of agent-based simulation in the bio-energy industry is therefore significant.

The simulation presented here, developed in AnyLogic 7.3.5, is considered a base simulation. That is, it can be improved upon to simulate different disturbances, or add/change experiment assumptions. The simulation is therefore a first version of a useful tool that has a potential to improve the understanding of risk among biofuel developers and investors.

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