### DEVELOPING SIMULATION MODELS TO IMPROVE THE PRODUCTION PROCESS OF A PARALLAM MILL

by

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### Abstract

Engineered wood products are manufactured by adhering small pieces of wood together with a bonding agent. They have many benefits. They allow the logs to be used more completely and more efficiently. They can increase the structural efficiency of wood frame construction, and natural wood defects can be dispersed in the product, which increases the uniformity of the mechanical and physical properties. Parallam® is one of these engineered wood products. It is manufactured in only two facilities in the world – Delta, British Columbia, Canada, and Buckhannon, West Virginia, United States. Parallam is manufactured from a grade of veneer that is not suitable for other products using Douglas Fir at the Canadian plant, and various species of pine at the American plant. The veneer is cut into strands, which are then adhered into long billets and are cut into the desired sizes. The Canadian plant was experiencing limitations in their total throughput, and was interested in exploring solutions to improve it. Since production operations are complex and subject to a variety of uncertainties and complexities, discrete-event simulation modelling was used to analyze the processes and evaluate potential improvement scenarios.

Two projects were conducted in this research where simulation models were developed to analyze different scenarios for possible alternative plant configurations or policies. The first project analyzed the replacement of a machine, changing the policy of order customization, and the flow of quality assurance pieces. The main finding was that the machine replacement had no positive impact on the throughput and should not be done. In addition, it was determined that a decrease in the amount of customization could increase the throughput by 20%. The second project analyzed the worker-machine interactions within the entire mill and the automation of an outfeed conveyor. The main finding was that the addition of one worker to the packaging station and the automation of the conveyor could result in a 22% increase in throughput. Further research should be conducted to assess the impact of quality assurance pieces through the mill, or to assess the impact of different workers' schedules instead of just their assignments.

### Preface

This research was conducted by the author, Luke Opacic, during his M.Sc. program. Advising support was provided by the research supervisor, Dr. Taraneh Sowlati, and committee members Dr. Greg Smith and Dr. Thomas Tannert. The research included a literature review, data collection and analysis, model development for two projects, output analysis, and recommendations.

A journal article was created from a modified version of Chapter 2 that has been submitted and is under review as of May 2016. Another article was created out of modified versions of Chapter 3 and Chapter 4 that will be submitted shortly after the conclusion of the author's M.Sc. program. The publication list is shown below:

- Opacic, L., & Sowlati, T. (2016). Applications of Discrete-event Simulation in the Forest Products Sector: A Review., submitted April 2016.
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### **Chapter 1 Introduction**

### 1.1 Background

The demand for all wood products in Canada has been increasing over the past several years, particularly for exports to Asian markets (Stewart, 2011), after a significant drop due to the collapse of the United States housing market during the 2008 economic recession (Couture & Macdonald, 2013; Natural Resources Canada, 2016). Due to the decrease in supply of adequate old-growth trees for solid timber, the production of engineered wood products has increased, to get more value out of previously unusable smaller trees (McCafferty, 1990; Guss, 1995; Lam & Prion, 2003). Engineered wood products are created using small pieces of wood adhered together with a bonding agent (Guss, 1995; Lam & Prion, 2003), and can range from structural products, such as parallel strand lumber (Parallam®), laminated veneer lumber (LVL), and glulam, to panel products such as oriented strand board (OSB), plywood, and particleboard (Guss, 1995). They are used in many different applications, including residential, commercial, and agricultural structures (Lam & Prion, 2003). Engineered wood products have many benefits: 1) They allow the logs to be used more completely and more efficiently through the combination of smaller pieces of wood, for example, 2-by-12 laminated veneer lumber could be created from logs that would only otherwise have produced standard 2-by-4 lumber (McCafferty, 1990), and 2) Natural wood defects can be dispersed in the product, which increases the uniformity of the mechanical and physical properties (Lam & Prion, 2003) and can result in an increase in the structural efficiency of wood frame construction which improves building performance and reduces cost (Lam & Prion, 2003).

Parallam® is a patented wood product that is used for structural beams and columns (Postles, 2014; Weyerhaeuser, 2016b, 2016c). It is produced in only two factories in the world –

one in Delta, British Columbia, Canada, and the other in Buckhannon, West Virginia, United States (Silverwood, 2014; Weyerhaeuser, 2016a). It was developed throughout the 1970s and 1980s by MacMillan Bloedel as a high strength wood material (Churchland, 1988; Bland, 1991; Silverwood, 2014) and is produced from a grade of veneer that is not suitable for other products (Churchland, 1988; Postles, 2014; Silverwood, 2014). While any species can be used to produce Parallam, including grasses such as bamboo (Bland, 1991), the Canadian plant uses Douglas Fir (*Pseudotsuga menziesii*) and the American plant uses various species of pine (*Pinus spp.*) (Bland, 1991). About 30-40% of the product created at the Canadian plant stays in the Metro Vancouver area, while much of the remaining product is sold to western United States (particularly California) and Japanese markets (Silverwood, 2014). The production operations of Parallam are subject to a variety of uncertainties, such as the frequency of machine breakdowns and their durations. Moreover, there are dependencies and interactions between different processes that affect the production throughputs. There are also high degrees of complexities in these systems.

Discrete-event simulation modelling is an appropriate approach for analyzing production processes and evaluating potential improvement scenarios. The risks and uncertainties that exist in the production process limits the use of some managerial approaches such as deterministic optimization. The use of discrete-event simulation modelling allows the uncertain/stochastic variables to be represented in the system without the need for a large model that takes up considerable resources or has a very high cost (Banks et al., 2005; Hillier & Lieberman, 2015; Myers & Richards, 2003). Both Myers & Richards (2003) and Beaudoin et al. (2013) identified previous research in the forest products sector that have used simulation to analyze systems with uncertainties such as those related to individual machine function, interaction between logging system components, and interaction between logging phases. In addition, Jahangirian et al. (2010)

determined that discrete-event simulation was the most popular decision support tool in manufacturing and business, particularly for studies on process flow. Forestry simulation models analyzed harvesting techniques (e.g. Talbot & Suadicani, 2005; Väätäinen et al., 2006), process flow in sawmills (e.g. Reeb, 2003; Baesler et al., 2004), process flow in furniture factories (e.g. Wiedenbeck & Araman, 1995; Kyle Jr. & Ludka, 2000), transportation methods (e.g. De Mol et al., 1997; Asikainen, 1998), and bioenergy supply chains (e.g. Mahmoudi et al., 2009; Mobini et al., 2011). To my knowledge, there have been no simulation studies conducted on the analysis of Parallam manufacturing, nor have any simulation studies been conducted that assess worker-machine interactions – both of which were assessed in this thesis.

### **1.2 Parallam Production Process and Issues**

The management team of the Vancouver plant had been having issues with the remanufacturing, or "reman" department keeping up with the production department of the mill, and was interested in improving the material flow and efficiency of the system to increase the throughput. Reman is not for re-working defective products, but instead is the final stage of the production process. The company currently schedules five workers in the reman department. The **sawyer** operates the sizer and the saw, the **sander** operates the sander and can assist at packaging, the **grader** operates the grading station and can assist at packaging, the **packager** works at the packaging station, and the **combilift forklift driver** drives the combilift forklift and can assist at packaging.

The Parallam manufacturing process (Figure 1.1, page 5) starts from the outside storage area where approximately 3 mm thick veneer sheets are stored, after having been purchased from a third party. The ideal moisture content of veneer sheets is between 2% and 4%. To achieve this,

they are dried in-house. Then, they get sorted by their moisture content and graded (mainly by wane and white specs) before they are sent to one of four feed stations. Pieces with higher than the ideal moisture content are sent back through the dryer. Veneers pass through one of two stranders (one above the other) to cut the veneers into <sup>3</sup>/<sub>4</sub> inch (1.9 cm) wide strips that are larger than 12 inches (30.48 cm) long. Short strands (less than 12 inches) are removed and used as hog fuel, while the long strands pass through a resin adhesive bath. The excess glue mix is blown off and recycled for a future production batch. The strands are dried to 10% moisture content at this stage before being assembled into billets and pressed at high temperature from all sides. At this point where the billets move into the remanufacturing, or "reman" department. The billets arrive at different speeds depending on their width (Table 1.1).

Table 1.1 - Billet Feed Speeds from the Press

Billet Width	Feed Speed
12 inch	9.7 feet/min.
14 inch	9.0 feet/min.
16 inch	7.9 feet/min.
18 inch	7.1 feet/min.
19 inch	6.8 feet/min.

The billets are first produced by widths, rotating through the standard sizes of 12 inches (30.48 cm), 14 inches (35.56 cm), 16 inches (40.64 cm), 18 inches (45.72 cm), and 19 inches (48.26 cm). For example, a "run" of 12 inch billets will be conducted first, based on customers' orders, then switch to 14 inch, and so on. After the 19 inch billets are produced, the press area is cleaned of excess strands, and it is reset to 12 inch to repeat the process. All billets are 11.1 inches (28.19 cm) thick, and are cut down in later steps. Generally, one entire rotation takes one week, depending on the number of billets in each width that are required. The lengths of the raw billets can vary in one foot increments, but are generally produced in standard sizes of 48 feet

(14.63metres), 54 feet (16.46 metres), 60 feet (18.29 metres), and 66 feet (20.12 metres). Batches of each length will be produced together, again based on customers' orders.

### **Billet Production**



### Remanufacturing



Figure 1.1 - Parallam® Production Process

While the physical make-up of Parallam allows for longer than 66 feet, the conveyors and decks in the mill do not. Therefore, the production length is kept at a maximum of 66 feet. The proportions of each width and length, as provided by the scheduler, are shown in Table 1.2.

-	Billet Length	Proportion	Billet Width	Proportion	
	48 feet	10.83%	12 inch	44.99%	
	54 feet	1.53%	14 inch	18.01%	
	60 feet	59.09%	16 inch	6.07%	
	66 feet	13.51%	18 inch	2.30%	
_	24-66 feet	15.04%	19 inch*	28.63%	
					-

Table 1.2 - Billet Length and Width Proportions

\*5% of these are trimmed in half to become 9.5 inch billets. The proportion value includes these 9.5% billets.

Assembled billets leave the production line and proceed to a large conveyor deck. If this conveyor deck is full, the billets will be stored outside and will be brought in later when there is more room. The billets must wait for at least two hours to cure (at room temperature, without pressure), then the outer layer of resin is removed in two passes (one for each set of two sides) through the sizer machine. Then, they are cut to the desired thicknesses based on the customers' orders. Most pieces are cut to standard thicknesses in various sets of standard patterns; estimated proportions provided by the scheduler are given in Table 1.3.

Thickness Patterns	Proportion <19 inch	Proportion =19 inch
Two 5.25 inch pieces	50%	40%
Three 3.5 inch pieces	20%	20%
One 3.5 inch piece and one 7 inch piece	20%	10%
Three 1.75 inch pieces and one 5.25 inch piece	5%	5%
Random sizes greater than 1.75 inches	5%	15%

Table 1.3 - Billet Thickness Cutting Patterns

Depending on the desired cutting patterns, the saw operator may have to store some cut pieces on a staging deck. For example, if two cuts are required (to obtain three pieces), the first piece will be sent immediately to the sander and the second will be stored on the storage area to be returned to the saw for its second cut. In some cases, depending on the operator, these pieces will be returned immediately and not staged. Then all pieces get sanded. Then they are visually graded and weighed where they are checked for defects such as high moisture content and delamination. The rejected pieces are packaged together and stored outside until they can be reworked. Some pieces may get individually wrapped, while others are left unwrapped. The wrapped pieces are packaged together and stored in the warehouse, whereas the unwrapped pieces get batched and wrapped as a batch before being stored in the warehouse. It is at the packaging station where packages are cut to various lengths depending on the desired customization of the customer orders, which can become a source of length processing times. In order to ensure the factory continually produces quality products, two 13 foot (3.96 metres) long billets are created approximately every 24 hours for testing (at the end of each run of a billet width). Reman can become a bottleneck in the process whenever there are problems, or when odd-sized pieces (like the quality control pieces) are processed, since the conveyor must be stopped until the problem (or skew) is repaired. When the deck is stopped and there is no more room outside, the production line must also stop since there is nowhere to put the assembled billets. In addition, the quality control billets must be handled manually instead of following the standard wrapping process in the department, further delaying the actual production of the Parallam billets.

### **1.3 Research Objectives**

The overall objective of this research was to provide input data to increase the throughput of the Parallam mill by improving the productivity and efficiency of the system. Two projects were conducted with the specific objectives as follows:

1) To evaluate the impacts of changes in the production process on the mill throughput, machine utilization, and queueing time; and

 To analyze the worker-machine interactions, specifically the addition of workers from other parts of the mill, on the mill throughput, machine utilizations, workers' utilizations, and queueing time.

The objectives were achieved by developing and running discrete-event simulation models, considering uncertainties and process interactions.

### 1.4 Thesis Structure

This thesis is organized into five chapters. Literature on discrete-event simulation from 1990 to 2015 is reviewed in Chapter 2 (with a few related studies from prior to 1990), and includes both literature from within the forest products sector (which is the primary focus) and from other industries where discrete-event simulation was successfully used. Chapter 3 describes the developed simulation model to achieve the first objective, while Chapter 4 describes the simulation model to evaluate the worker-machine interactions. Discussion of the conclusions, usage of the model, limitations, strengths, and possible future research is given in Chapter 5.

### **Chapter 2 Literature Review**

### 2.1 Synopsis

This chapter provides a comprehensive literature review of discrete-event simulation, mainly from 1990 to 2015. Some studies from prior to 1990 were included due to their importance to the knowledge. This chapter is divided into four main sections. In Section 2.2 simulation modeling is defined and the different types are compared. The evolution of simulation into a useful decision support tool is also discussed. Section 2.3 describes discrete-event simulation studies from industries such as health care and manufacturing that have used it extensively. Section 2.4 describes discrete-event simulation studies within the forest products industry. A discussion section is presented in Section 2.5.

### 2.2 Simulation

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; Kaizer et al., 2015). 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 & Sharda, 2007; Maidstone, 2012; Negahban & Smith, 2014), or to make decisions such as those related to capacity, purchasing, training, and technology (Allen, 2011). It allows for "what-if" questions to be analyzed when designing new systems or how certain interactions may occur when subjected to different conditions (Sadoun, 2000; Power, 2002; Banks et al., 2005; Hillier & Lieberman, 2015). The alternatives can be simulated as scenarios, and system performance statistics can be obtained for each scenario to compare them (Maidstone, 2012). Performance statistics could include throughput, utilization of resources, queue time and length at work stations, required staffing levels, 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 analyses can be conducted to determine where the model entities are being delayed, or which resources are being over- or under-utilized (Banks et al., 2005). The animation features in modern simulation software allow the 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).

There are four main types of simulation: 1) discrete-event, 2) system dynamics, 3) agentbased, and 4) Monte Carlo. Discrete-event simulation, which is used in this thesis, is defined as the changing of states at random points in time as a result of various "discrete events" such as the arrival and departure of customers (Hillier & Lieberman, 2015). It consists of entities (such as customers, or pieces of wood) that move between different states of the system (such as machine centres, or a bank teller) over time, and can be shown as a network of queues and servers (Greasley, 2009; Maidstone, 2012; Sadoun, 2000; Tako & Robinson, 2009). Discrete-event simulation is said to be "discrete" since the state of the system changes only at specific points in time instead of continually (Greasley, 2009; Nance & Sargent, 2002; Sadoun, 2000; Tako & Robinson, 2009). It allows for the analysis of stochastic systems which are impossible or difficult to analyze or solve analytically, such as queueing systems (Banks et al., 2005; Borshchev, 2013; Hillier & Lieberman, 2015).

System dynamics simulation involves the use of stocks and flows (Borshchev, 2013; Richardson, 2013) where stocks are accumulations of objects and the flows are the rates with which the stocks move between each other and into/out of the system (Maidstone, 2012; Richardson, 2013). Delays can be incorporated into the model as the time between a measurement and an

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action upon that measurement (Maidstone, 2012). These models are also referred to as "open-loop models" (Borshchev, 2013).

Agent-based simulation is the newest method of simulation where autonomous agents follow a series of predefined rules to achieve set objectives while interacting with each other (Maidstone, 2012). It is best used when the behaviour of the whole system is unknown, when there are dependencies between agents, or when there is no process flow (Borshchev, 2013). It consists of agents, such as people or body cells that have varying behaviours and interactions with each other, such as the spread of a disease among people (Maidstone, 2012).

Monte Carlo simulation does not involve agents, entities, or queues, and is a result of the application of randomness to input data (Borshchev, 2013), or to the outputs of a deterministic optimization model.

Computerized simulation methods have evolved over the last 50 to 60 years from programming languages to software packages that demonstrate the behaviours of the system visually (Nance, 1996; Nance & Sargent, 2002; Swain, 2013). Much of this evolution is attributed to the available computer power, specifically related to memory and speed (Smith, 2003), and this evolution has increased the use of simulation immensely (Jacobson et al., 2006; Swain, 2015b). Not only has the software evolved, but also the hardware in order to display complex 3D graphics (Swain, 2015b).

Discrete-event simulation has become an extremely useful tool (Swain, 2015b) with more than 55 packages currently available on the market (Swain, 2015a). According to a biennial survey (Swain, 2015b), each of the packages have their own typical applications and markets. Nikoukaran and Paul (1999) provided a classification system for choosing which software package to use for

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simulation, but found that there were no standards for any industry. They concluded that "the choice of software is a matter of convenience" (Nikoukaran & Paul, 1999). Although there are significant advantages of discrete-event simulation as described previously, there are also many disadvantages. First and foremost, 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).

Four review papers analyzed the existing literature on the use of decision support tools in the forest products sector (Awudu & Zhang, 2012; Shahi & Pulkki, 2013; Rahman et al., 2014; Segura et al., 2014). These papers focused mainly on optimization techniques, and only briefly touched on discrete-event simulation. Awudu and Zhang (2012) reviewed studies that considered uncertainties in the biofuel industry and concluded that uncertainties must be included in analyses of forest biomass supply chains. It was noted by Shahi and Pulkki (2013) that all types of simulation have been used in the forest products sector to determine the outcomes of various scenarios. Both Shahi and Pulkki (2013) and Rahman et al. (2014) recommended that models combine simulation and optimization techniques, since simulation models alone cannot guarantee the best solution. Segura et al. (2014) suggested that future models assess multiple objectives, and should focus more on the integration of economic issues with environmental issues. Forestry simulation models analyzed harvesting techniques (e.g. Talbot & Suadicani, 2005; Väätäinen et al., 2006), process flow in sawmills (e.g. Reeb, 2003; Baesler et al., 2004), process flow in furniture factories (e.g. Wiedenbeck & Araman, 1995; Kyle Jr. & Ludka, 2000), transportation methods

(e.g. De Mol et al., 1997; Asikainen, 1998), and bioenergy supply chains (e.g. Mahmoudi et al., 2009; Mobini et al., 2011).

### 2.3 Discrete-event Simulation Outside the Forest Products Sector

Discrete-event simulation has been used successfully in many industries, including manufacturing, business, health care and social care, and other services such as transportation or military operations. The use of discrete-event simulation in health care increased significantly throughout the 2000's (Günal & Pidd, 2010). There are models that study the progression of diseases such as HIV/AIDS (Brailsford & Hilton, 2001) and other diseases that are classified as epidemics (Hurd & Kaneene, 1993), but the vast majority of the models study facilities that provide care. Benneyan (1997) studied pediatric patient wait times, while the interaction of staff with various machines and patients with whom they must provide care were studied by Jun et al. (1999), Brailsford and Hilton (2001), Jacobson et al. (2006), and Hamrock et al. (2013). These studies focused entirely on economic outcomes, and not on environmental or social outcomes, while Homer and Hirsch (2006) also used system dynamics simulation to assess how uncertain environmental factors affect disease prevention.

Discrete-event simulation studies in manufacturing considered mostly the assessment of processes and factory layouts. Baudet et al. (1995) conducted a study on the production process of chemical products, testing three scenarios considering the inclusion of secondary products and a change in the batch release criterion. Patel et al. (2002) analyzed how changes to the number of operators, the number of repair booths, the routing logic for vehicles to testing stations, and the capacity of the department in an automobile manufacturing plant's quality assurance process, would impact the throughput. The effects of pre-defined factors (layout, scheduling rule, machine

downtimes, batch size, and transporter capacity) on the performance of an automotive parts manufacturing facility were analyzed by Ekren and Ornek (2008). Various combinations of the factors were modelled, and it was found that the interactions between the factors could considerably affect the performance of the facility. Baker (2013) described the benefits of moving from physical experiments to simulation for testing whether changes to a thermal transfer printing system have a positive effect on the production. The effects of machine automation of the total throughput time and resource utilization of an aerospace parts factory was studied by Caggiano and Teti (2013).

Smith (2003), Jahangirian et al. (2010) and Negahban and Smith (2014) reviewed papers in which simulation was used in manufacturing and business. Smith (2003) reviewed literature from 1969 to 2002 and Negahban and Smith (2014) reviewed literature from 2002 to 2013. Both categorized the literature into those focusing on system design and system operation, and those that developed simulation programs (software) for use in manufacturing. It was found that the number of papers per year using discrete-event simulation involving manufacturing system design and operation has increased significantly (Negahban & Smith, 2014). Within the categories, there are now many more studies about manufacturing operations compared to the Smith (2003) review. These reviews, in addition to Jahangirian et al. (2010), suggested an increase in the usage of models by industry in the future. They also noted that the combination of multiple types of simulation would likely become more common in the future, which was also noted by Brailsford and Hilton (2001) and Brailsford et al. (2010).

#### 2.4 Discrete-event Simulation within 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 assessed forest operations, primary wood products manufacturing, secondary wood products manufacturing, transportation and logistics, and the supply chains of bioenergy and biofuel plants, and are summarized in Table 2.1 on page 28 of this section.

#### 2.4.1 Forest Operations

Discrete-event simulation within forest operations has been conducted on the evaluation of different harvesting system configurations, evaluation of the impacts of mixed species plantations, and assessment of the usefulness of discrete-event simulation models.

Early simulation models were developed to determine the best equipment mix for wholetree chipping operations (Johnson & Biller, 1973). While this model did assess the interactions of different machines, it did not include a discussion on validation, and had only three replications of each of 12 scenarios. Wang et al. (1998) and Wang and Greene (1999) stated that many studies prior to the mid-1990's involved the analysis of either single machines, or were deterministic, numerical simulation. 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 due to the high cost of collecting data to perform it adequately (Baumgras et al., 1993).

Wang et al. (1998) analyzed the effects of interactions between stand conditions, harvesting prescriptions, and harvesting equipment, on the productivity and site impacts of harvesting. Three

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felling methods and two extraction methods were studied, conducting different activities such as clearcuts, shelterwood cuts, and single-tree selection. A study by Talbot and Suadicani (2005) investigated 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. The focus was to compare economic and environmental feasibility of the systems in Denmark forests. Myers and Richards (2003) developed a discreteevent 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. Väätäinen et al. (2006) determined the productivity and cost changes of five different cut-to-length logging concepts. Machine interactions and characteristics, and transportation distances were considered, but the influence of different logging site characteristics were not. The productivities of one- and two-armed tree planting machines, considering uncertain terrain and Nordic clearcut 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.

Ziesak et al. (2004) conducted a study to determine how applicable modern simulation software was for making forest products sector decisions. They used AutoMod® software to incorporate the aspects of forest environment, manufacturing resources, and detailed task characterization, to allow them to be adjusted individually. While it was determined that the model

was able to evaluate the performance of a wood supply chain (from forest to sawmill), more work was deemed to be required to improve data quality, and to integrate other activities of the supply chain. Similar 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 conducted studies of two different harvesting systems compared to an existing system. Three systems were analyzed: System 1 (the base case); System 2 consisted of the same machinery, but differed in terms of the operating procedures and policies; and 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.

A simulation system to investigate the impact of mixed species management of hardwood plantations on the proportion of clear (without knots) cherrybark oak was developed by Oswalt (2008). The model incorporated different combinations of plantation types (dense and scarce), and different combinations of treatments to the trees. Tree characteristics, such as mortality rate, diameter, volume, and crown size were uncertain parameters considered.

### 2.4.2 Primary Wood Products Manufacturing

All the papers found using simulation in primary wood manufacturing were conducted at sawmills. To the best of my knowledge, discrete-event simulation studies at other primary wood manufacturing mills, such as veneer or chipping, have not been conducted.

Aune (1973) was the earliest paper found that assessed sawmill processes instead of just breakdown patterns of logs, which were the main subjects of earlier simulation studies (e.g.

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Reynolds & Gatchell, 1969). It analyzed how changes in the raw log characteristics and interactions between machine centres affected the total productivity. It was found that such models are feasible, including for complex mills that have highly variable inputs. In addition, the productivity was found to be highly sensitive to changes in the characteristics of the logs and machines. Aune (1973), as well as the follow up paper (Aune, 1974), led to the development of future models studying sawmills, which will be discussed in this section.

Four papers described the development of object-oriented softwood sawmill simulation models that makes the modelling more flexible and user-friendly (Randhawa et al., 1993, 1994; Randhawa & Kuo, 1997; G. Zhang, 1993). Studies prior to 1993 focussed mainly on hardwood sawmills, which are procedurally different from softwood sawmills and can be more complex. It was not until the mid-2000's that further studies on hardwood sawmills were conducted using discrete-event simulation. One model, called the Softwood Sawmill Simulator (S3), was developed by Randhawa et al. (1993, 1994) and G. Zhang (1993). It was described by means of using a real system example, and the reports were produced from the model outlining the utilization of the machine centre. Some limitations in the programming environment were found, specifically working with large numbers of objects and the overall speed of the program. It was recommended that coding be converted to a version of C or C++ in the future to overcome the limitations. The paper by Randhawa and Kuo (1997) developed a methodology to make decisions in sawmills based on multiple performance measures. The performance measures were scaled based on their time and value, and then weighted for 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 paper concluded that the evaluation of multiple criteria required trade-offs involving the weights of each

criterion, and that the use simulation models would require an analysis of a much wider range of operating conditions.

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, the relationship between the line speed and the downtime.

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. While 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. Different machine configurations, log diameter distributions, speeds of the circular saw, and decrease in log positioning time were analyzed 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, the 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. Due to the work from the 1980's and 1990's proving the utility of discrete-event simulation for assessing forest products sector processes, many of the studies during the 2000's and early 2010's were similar, and were based more on case studies rather than attempting to build on the bank of knowledge.

In the mid-2000's, large quantities of hardwood trees were left standing due to being too short or too thin (Clément et al., 2005), since harvesting and processing is 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 eight feet (2.44 metres) long (Clément et al., 2005) and less than seven inches (17.78 cm) 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) cross-cutting first, and 2) rip-cutting first. An important result obtained from this study was that the use of the correct cutting pattern can result in an acceptable 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, United States. 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, and Pinion (2005) found that the use of a three or four deck sort (compared to the existing two deck sort) considerably minimized the decrease in throughput. A follow-up study conducted by Salichon (2005) determined that downtimes had a significant influence on the throughput when there are varying diameters of logs being processed. However, Salichon (2005) determined that an increase in the speed of the end-dogging log feeding system had little effect on the throughput except for small-diameter logs which 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 centres that could not process the higher material flow. Due to the expected increase in small-diameter logs in the future, Salichon (2005) recommended that changes to the machine centres be investigated to offset the lost production.

Rappold (2006) and Rappold et al. (2009) conducted studies 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 which one more precisely allocated the costs: 1) the activity-based costing method, 2) the volume costing method, and 3) the lumber yield method. To the best of my knowledge, these are the only studies that assessed lumber costing methods using discrete-event simulation.

### 2.4.3 Secondary Wood Products Manufacturing

Some studies were conducted in the rough mills where raw wood or lumber is broken down into the parts required for the furniture being constructed in other facilities (Kline et al., 1992; Wiedenbeck & Araman, 1995), while others were conducted in the furniture construction facilities themselves (Gupta & Arasakesari, 1991; Kyle Jr. & Ludka, 2000). These studies had similar purposes to those of the primary industry. No studies were found that conducted studies of the manufacturing processes of various engineered wood products, or the manufacturing of products such as kitchens.

Kline et al. (1992) conducted a study at an eastern United States furniture rough mill to demonstrate the evaluation of throughput, operation expenses, inventory levels, and delays due to bottlenecks. The bottleneck of the process was determined to be the ripsaw. They concluded that the use of animation provided enhanced usefulness to the mill model, and significantly reduced the time required to verify and validate it. Gupta and Arasakesari (1991) assessed the effects of the addition of a third packaging line, a change in the availability of the edgebanders, and changes in batch sizes being processed compared to the existing system, on the capacity and in-process inventory of a facility in Zeeland, Michigan, United States. The interactions of all machinery, including the breakdowns and downtime, were considered. The discussion of a model to evaluate a proposed layout of a dining room tabletop plant was conducted by Kyle Jr. and Ludka (2000). They indicated that models were designed to be both a capital improvement evaluation tool, and an operational planning tool. 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. Although specific results were not provided, the authors' stated that results were positive and provided great value to the partner company, yet again confirming the utility of discrete-event simulation models for the forest products sector.

As mentioned in the previous section, in the study by Clément et al. (2005), the average size of logs is decreasing in both length and diameter. Therefore, furniture rough mills, such as the one studied by Wiedenbeck and Araman (1995), also need to change their procedures to better utilize shorter lumber, not just the sawmills themselves. Wiedenbeck and Araman (1995) analyzed the effects of the lumber length on the equipment utilization and volume of the parts produced. The study considered cross-cut 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-arbour machine would increase the productivity in a rip-cut first mill.

### 2.4.4 Transportation and Logistics

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 semi-trailer; the number of trucks also varied. It was determined that there was no substantial difference between the truck with the draw-bar trailer or the semi-trailer, 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 transportation by barge to the mainland. The scenarios changed the number of barges and their locations. Asikainen (2001) 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 were varied from 20 km to 120 km, and the number of trucks were varied from one to four. It was found that two trucks would be the most cost competitive option at distances less than 40 km, a third truck should be added at distances over 40 km, and a fourth truck 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 Karttunen et al. (2012) also determined that the most economical waterway distances. transportation options used fixed barges with loading and unloading of barges being conducted with a wheeled loader and a belt conveyor.

The 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) that claimed it should be done at the energy plant. The different results could be due to the different types of biomass, government regulations, advances in comminution equipment, or different model assumptions. Eriksson (2014) also analyzed potential improvements to stump fuel delivery, and making it more cost efficient. Different machine configurations were studied in terms of the cost of delivered biomass, the resource efficiency, the total amount of delivered biomass, the total energy delivered, and the cycle time of the entire process. The model resulted in varied costs from €32/odt (over dry metric tonnes) to €105/odt depending on the transportation distance, and determined that self-loading systems had the lowest costs. Eriksson (2014) suggested that suitable storage could significantly reduce the supply chain cost. The study by Puodžiūnas and Fjeld (2008) developed a simulation model to estimate 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. They found that the removal of unfavourable sources of roundwood increased the productivity of the sorter, and decreased the truck waiting times.

Only one paper was found that used discrete-event simulation to analyze log yard truck operations (Beaudoin et al., 2013). They considered three different allocation strategies for three log loader models in order to serve four different types of trailer, which would arrive at the mill by two different entrances. There were some restrictions in the operations, since 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 – to decrease the average truck cycle time and total distance travelled by the loaders. They assessed three alternative policies: 1) first in first out, 2) empty the queue first, and 3) longest queue first. Further experiments were recommended before modifying the existing system to validate alternative strategies that did not penalize certain trailer types.

#### 2.4.5 Bioenergy and Biofuel Supply Chains

Some studies evaluated the feasibility and viability of supply chain operations at bioenergy plants (Mahmoudi et al., 2009; Mobini et al., 2011; F. Zhang et al., 2012). Mahmoudi et al. (2009) initially simulated one-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, and determined that if only roadside residues were considered, there would not be enough biomass to meet the annual demand of the power plant. They suggested reducing the transportation distance by changing the plant location, including other harvesting systems which would increase the amount of available biomass, and/or decreasing 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. They found that from years 1 to 3 and 6 to 9, the total biomass demand of the power plant would not be fulfilled. F. Zhang et al. (2012) conducted a study to determine the best location of a biofuel facility in Michigan, United States. They 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. They concluded that the smallest plant size provided the best performance measures.

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A limited number of studies assessed the supply chains of wood pellet facilities using discrete-event simulation (Mobini et al., 2013, 2014). Mobini et al. (2013) investigated the 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. They 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<sub>2</sub> emissions increased. Since wood pellets are expensive and cannot compete with fossil fuels, methods to improve their properties have been suggested (Mobini et al., 2014). One method, torrefaction, was assessed by Mobini et al. (2014). They determined that the cost of production and transportation of torrefied pellets at the international port in North Vancouver, British Columbia, Canada, increased by 38% compared to those of regular pellets. However, torrefied pellets were preferred to regular pellets for long distance delivery because of their increase in delivered energy.

One study assessed the differences between two biofuel supply chains in Finland and Germany (Windisch et al., 2013). The work-time expenditures for organizational and managerial tasks, based on the interactions of the stakeholders within the supply chains, were analyzed. 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.

Area	Purpose of Simulation	Papers	Important Uncertainties
Forest Operations	<ul> <li>Evaluate the impact of mixed species hardwood plantations</li> </ul>	Oswalt (2008)	Mortality rates, tree attributes
	Compare different harvesting systems and configurations	Johnson & Biller (1973), Baumgras et al. (1993), Wang et al. (1998), Wang & Greene (1999), Myers & Richards (2003), Talbot & Suadicani (2005), Väätäinen et al. (2006), Ersson et al. (2013)	Machine processing times, machine interactions, season lengths, forest and tree attributes
	<ul> <li>Determine the usefulness of simulation models for planning, optimizing, controlling, and training activities</li> </ul>	Ziesak et al. (2004), Hogg (2009), Hogg et al. (2010)	Forest attributes, work element times, machine failures and repairs
Primary Wood Products (Sawmills)	• Determine the feasibility of simulation for analysis of sawmill systems	Aune (1973, 1974), Randhawa et al. (1993, 1994), G. Zhang (1993)	Processing times, failures and repairs, log supply, log quality attributes
	<ul> <li>Compare different sawmill machine configurations and layouts to improve productivity and bottlenecks</li> </ul>	Lin et al. (1995), Dogan et al. (1997), Reeb (2003), Baesler et al. (2004), Thoews (2008), Thoews et al. (2008), Grigolato et al. (2011)	Machine processing times, log attributes, failures and repairs
	• Evaluate the impact of different log characteristics, particularly small logs	Chiorescu & Gronlund (2001), Clément et al. (2005), Pinon (2005), Salichon (2005)	Log attributes, quality (wane) parameters, machine processing times
	Compare different time-to-value ratios of logs	Randhawa & Kuo (1997)	Machine processing times, log attributes, failures and repairs
	Compare two lumber costing methods	Rappold (2006), Rappold et al. (2009)	Log attributes, machine processing times, failures and repairs
Secondary	Compare different cutting methods for short lumber processing	Wiedenbeck & Araman (1995)	Processing times, failure rates, raw material attributes
Wood Manufacturing	• Compare machine configurations and plant layouts	Gupta & Arasakesari (1991), Kline et al. (1992), Kyle Jr. & Ludka (2000)	Product demand, setup times, cutting parameters, processing times, failures and repairs
	Compare different biomass pre-treatment techniques	De Mol et al. (1997), Asikainen (1998), Eriksson (2014), Spinelli et al. (2014)	Storage loss, supply and demand, seasonalities, failures and repairs
Transportation	Compare different sources or types of biomass	De Mol et al. (1997), Puodžiūnas & Fjeld (2008)	Storage loss, supply and demand, log attributes, processing times, arrival times
and Logistics	Compare different transportation     equipment and techniques	Asikainen (1998, 2001, 2010), Karttunen et al. (2012), Eriksson (2014), Spinelli et al. (2014)	Operating times, failures and repairs, transportation distances
	• Analyze sawmill log yard strategies	Beaudoin et al. (2013)	Travelling speeds and distances, sawmill demand, loading and unloading times, arrival times
Bioenergy and Biofuel Supply Chains	<ul> <li>Compare different supply chain configurations for wood pellet production and transportation</li> </ul>	Mahmoudi et al. (2009), Mobini et al. (2011, 2013, 2014)	Weather conditions, logging schedules, cutblock locations, failures and repairs, fuel consumption, biomass availability
	Compare biofuel production facility locations	F. Zhang et al. (2012)	Biomass demand and recovery
	Determine work-time expenditures for managerial and organizational tasks	Windisch et al. (2013)	Stakeholder tasks, interactions between stakeholders, communication activities
	• Analyze the effect on cost of varying the importance of different criteria to plan biomass sourcing	Windisch et al. (2015)	Biomass characteristics, transportation distances, failures and repairs, machine productivity, distance between storages, seasonalities, moisture content, truck loading/unloading

#### Table 2.1 - Summary of Discrete-Event Simulation Studies in Forest Products

## 2.5 Discussion and Conclusions

Discrete-event simulation has supported 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. Its use allows the uncertain/stochastic variables to be represented in the system that could not be represented in other modelling types, such as deterministic models, without the use of considerable resources (Myers & Richards, 2003; Banks et al., 2005; Hillier & 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 in any engineered wood products facilities (such as those that make plywood, parallel-strand lumber, particleboard, medium-density fibreboard, or oriented-strand board), or in millwork facilities (such as those that make commercial or residential cabinets).

This thesis used discrete-event simulation to evaluate the processes at an engineered wood products facility and the interactions between workers and machines, similar to patient/machine studies conducted in healthcare studies (e.g. Brailsford & Hilton, 2001; Hamrock et al., 2013; Jacobson et al., 2006; Jun et al., 1999). Since 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.

## **Chapter 3 Process Evaluation and Improvement**

## 3.1 Synopsis

In this chapter, the development of new simulation models using the AnyLogic® 7 software package (The AnyLogic Company, 2016) to model the remanufacturing department in the Parallam mill is described. These models had not been previously developed; development required knowledge about the actual system, expertise in simulation modelling, and experience in using the software package. AnyLogic 7 allows models to be run (while changing some parameters) with a Java applet, without the need for the company to purchase the software unless they want to make future changes (Borshchev, 2013). To achieve this objective, time was spent in the manufacturing facility to understand the process, and to gather data and information needed in the models. Then, the models were developed, and verified and validated by comparing the model results with the actual throughput of the system as well as using expert opinion via discussions with the Production Manager. Next, the impacts of changes were assessed, as outlined in the scenarios, based on the throughput of the remanufacturing department. The best approach was identified as being discrete-event simulation, recommendations were provided to the company, and the findings were highlighted in a presentation for the management team at the Parallam mill.

## 3.2 Objectives and Scenarios

The main objective of this chapter was to evaluate the impacts of changes in the production process on the mill throughput, machine utilization, and queueing time. Specific objectives of this project are to:

- 1. Evaluate of the impacts of the replacement of the "sizer" machine;
- 2. Determine the impact of policy changes for custom orders, such as the elimination of a customer that is the source of a significant number of custom orders;
- 3. Find the overall bottleneck location; and
- 4. Assess alternatives to how the quality assurance billets are processed.

A total of five scenarios are analyzed. The results of Scenarios 2 to 4 are compared to those of Scenario 1, which is the base case. Scenario 5 is compared to a different base case since it is analyzed with different outputs. The scenarios are described below:

- Scenario 1 Base Case: The plant is operated from 7 AM Monday morning until 7 PM Friday evening, with the time on weekends for maintenance. One six-hour slot, usually on Wednesdays, is allotted specifically for remanufacturing department maintenance.
- Scenario 2 24/7 Operation: The plant is operated 24/7 leaving only the six-hour maintenance day on Wednesday without regular production.
- Scenario 3 4-sided Sizer: The billets are passed through the sizer with only one pass (replace the current 2-sided machine with either a 4-sided machine or create the ability to cut on the return pass). The plant is operated from 7 AM Monday until 7 PM Friday.
- Scenario 4 25% Customization: The amount of customization is restricted by allowing only 25% customization over a billet run anything over and above that would be rejected. This was intended to address very custom orders that required considerable cutting at the packaging station, and the complete elimination of those orders from the system.

Scenario 5 – QA Analysis: This scenario is not compared to the base case, but instead to
its own current situation involving the time-in-system. The current situation of the billets
passing through the entire system is the base case, and the scenario involves pieces being
removed from the line at the outfeed of the saw.

## 3.3 Model and Methodology

### 3.3.1 Model Inputs, Logic, and Outputs

The inputs of the model were the billet size properties, amount of customization, machine processing times, and machine downtime. These were determined to be the uncertain characteristics of the system through discussions with management, and observations on the mill floor. All the billet properties were assigned based on the proportions shown previously in Tables 1.2 and 1.3. The billet interarrival time in minutes (the time between each billet arrival) was set using Equation 3-1, where *billet length* is in feet, and *feed speed* is in feet per minute. Figure 3.1 shows the model inputs, outputs, and logic.

$$Interarrival Time = \frac{billet \ length \ (feet)}{feed \ speed \ (feet/minute)} \qquad Equation \ 3-1$$

The processing times were obtained by a time study, using a stopwatch while on the mill floor observing the flow of pieces at each station. They varied depending on factors such as the billet properties, the operator interaction with the machines, and breakdowns. The times for the sizer machine and grading station were recorded by billet width, and were also based on billet length, using the formula in Equation 3-2. The *number of passes* in Equation 3-2 is always 2, except in Scenario 3 when it is changed to 1. The *time per foot* is a probability distribution

calculated by fitting the data obtained by the time study. The saw times were calculated using Equation 3-3.



Figure 3.1 - Overview of Model Inputs, Logic, and Outputs

$$Processing Time = \frac{time \ per \ foot \ (min/foot) \times billet \ length \ (feet)}{number \ of \ passes} \qquad Equation \ 3-2$$

 $Processing Time = time \ per \ foot \ (min/foot) \times billet \ length \ (feet) \qquad Equation \ 3-3$ 

For the remaining stations, the length was not considered and the times were recorded and fitted based solely on their total processing time. The Microsoft Excel Add-in @Risk 7 (Palisade Corporation, 2016) was used to fit the obtained data related to processing times to probability distributions. The *billet length* varies only by the length assigned by the model as the length of the billet. Each station also experienced failures, in addition to other downtime events such as workers helping at other stations. The parameters of the distributions are summarized in Table 3.1.

Station	Widths	Probability Distribution of Processing Time (minutes)
	12 inch	$Pareto(6.34^{b}, 0.0531^{c})$
Sizora	14 inch	Uniform(0.0522 <sup>c</sup> , 0.0725 <sup>d</sup> )
51261	16 inch	Uniform(0.0573,0.0679)
	$\geq 18$ inch	Gamma(32.571 <sup>e</sup> , 0.00277 <sup>b</sup> , 0 <sup>c</sup> )
	9.5 inch	Triangular(0.0256 <sup>c</sup> , 0.0538 <sup>d</sup> , 0.0333 <sup>f</sup> )
	12 inch	Triangular(0.0350, 0.0434, 0.0434)
Saw <sup>a</sup>	14 inch	Pareto(6.78, 0.0303)
	16 inch	Pareto(7.76, 0.0470)
	$\geq 18$ inch	Uniform(0.0408, 0.0693)
Sander	All	Pareto(9.34, 0.850)
Grading <sup>a</sup>	All	Triangular(0.0130, 0.0250, 0.0190)
Piece Wrap	All	Triangular(1.10, 2.22, 1.19)
Cutting and Packaging	All	Gamma(17.0, 0.959, 0)
Packaging Only or Rejects	All	Gamma(11.1, 0.540, 0)
<sup>a</sup> Minutes per foot	<sup>d</sup> Max	imum value

<sup>a</sup> Minutes per foot
 <sup>b</sup> Scale parameter
 <sup>c</sup> Minimum value
 <sup>d</sup> Maximum value
 <sup>e</sup> Shape parameter
 <sup>f</sup> Most likely value

Since no appropriate data were available for failures or downtime, they were estimated using mainly triangular and uniform distributions, with the parameters of each outlined in Table

3.2.

Station	First Occurrence (hours)	Time Between Occurrences (hours)	Duration (hours)
Press	2 occurrences per day	-	Weibull $(0.5^{a}, 1^{b}, 0^{c})$
Sizer Breakdowns	Triangular(1 <sup>c</sup> , 30 <sup>d</sup> , 15 <sup>e</sup> )	Triangular(20, 45, 40)	Triangular(0.25, 6, 1)
Sizer Downtime	Uniform $(1^{c}, 6^{d})$	TriangularAV(1.5 <sup>e</sup> , 40% <sup>f</sup> )	Triangular(0.0167, 0.500, 0.333)
Saw Breakdowns	Triangular(2, 30, 15)	Triangular(20, 45, 40)	Triangular(0.25, 6, 1)
Saw Downtime	Uniform(1, 6)	TriangularAV $(2, 40\%)$	Triangular(0.0167, 0.500, 0.333)
Sander Breakdowns	Triangular(2, 30, 15)	Triangular(20, 45, 40)	Triangular(0.25, 6, 1)
Sander Downtime	Uniform(1, 6)	TriangularAV(1.5, 40%)	Triangular(0.0167, 0.500, 0.167)
Grading Breakdowns	Triangular(2, 30, 15)	Triangular(20, 45, 40)	Triangular(0.25, 6, 1)
Grading Downtime	Uniform(1, 6)	TriangularAV(0.75, 40%)	Triangular(0.0167, 0.500, 0.333)
Piece Wrapping Breakdowns	Triangular(2, 3, 2.5)	Triangular(0, 1, 0.25)	Uniform(0, 0.5)
Piece Wrapping Downtime	Uniform(1, 6)	TriangularAV(1.75, 40%)	Triangular(0.0167, 0.500, 0.0833)
Packaging Breakdowns	Triangular(2, 30, 15)	Triangular(20, 45, 40)	Triangular(0.25, 6, 1)
Packaging Downtime	Uniform(1, 6)	TriangularAV(2, 40%)	Triangular(0.0167, 0.500, 0.333)

#### Table 3.2 - Failures and Downtime Distributions

<sup>a</sup> Shape parameter

<sup>b</sup> Shape parameter

<sup>c</sup> Minimum value

<sup>d</sup> Maximum value <sup>e</sup> Most likely value

f +/- percentage

The entities are the billets, which then pass through the processes to produce the final products. Each of the stations has a conveyor deck prior to them, which serves as a queue where the billets wait to be processed. At each process, the properties of each entity that changed (such as width or thickness) were updated before they proceeded to the next process. Much of the model involved the occurrence of separate events to trigger other events, such as stopping the previous process while the queue ahead is full, and then restarting the process again when there is space. While the nature of the queue block within the software allowed for this to happen naturally, in this model there was animation built-in which made the use of "move to" process blocks that required the use of manual stopping and restarting events. As requested by management, exactly 3% of billets would be rejected at the grading station – data could not be easily obtained to confirm this value since the rejected pieces were not specifically tracked by the company. Once the billets entered the packaging station, the percentage of custom billets was set to 25% for billet widths less

than 19 inches, and 75% for a billet width equal to 19 inches, which was determined from the customers' orders and confirmed by management. The packaging station was split into two different process blocks for this purpose – one for those being packaged only, and one for those being cut and packaged with a higher cycle time. The model ends as soon as the package of billets is outside. The outputs of the model are the total volume throughput in cubic feet, throughput per hour, and the average queue time for each piece at each station. An analysis of the utilization at each processing centre was also conducted. Appendix A describes the customization required within the modelling software to create this simulation model.

### 3.3.2 Verification and Validation

There was substantial model verification, where the logic of the model was checked to ensure it was functioning correctly, and validation, where the results of the model was checked to ensure it represented the real system. Many billet properties were changed manually so that their results were known (i.e. the down-time was turned off completely, or the number of allowable cutbacks was increased to infinity), and the results of the model were confirmed to match what was supposed to occur. The processing times of each process were changed in similar ways (extremely low or extremely high) to ensure that a backup would occur when they were high or no backup at all when they were low. A software feature allowing on-screen export of model calculations was used to ensure that the billet properties were being properly calculated, that the processes were being stopped when the one ahead was full, and to check that the values being produced by the distributions represented reality. Much of this was done by obtaining a list of values, and comparing them to the data obtained, or by getting an expert opinion from the management team. Since the model was written using Java, the code was reviewed regularly to ensure that there were no errors in the calculations.

## 3.3.3 Assumptions

In consultation with management, several assumptions were made during the development of the model, as follows.

- The rejection rate (at the grading station) was assumed to remain constant at 3%.
- The proportion of individually-wrapped pieces was held constant at 25%, with one exception when the machine broke down, any pieces that should have been piece-wrapped were just sent through without it.
- Individually-wrapped pieces were wrapped together with non-wrapped pieces instead of being batched and wrapped together.
- The trimming at the grading station was not modelled at all, and instead the use of the trimming saw was modelled through the stochastic processing times.
- The saw infeed was split into two queues, with only a batch of 11 pieces passing straight through to the saw infeed at one time. Only when the entire initial billet (after all its cuts have been completed) passed through to the sander were additional billets allowed from the first queue into the second.
- The staging area at the saw was modelled to release only when it was full. The capacity was based on the number and size of pieces present.
- Changeover time at the sander was not considered, and was instead reflected in the stochastic processing time.

- Cutting at the packaging station was modelled by the use of a separate set of probability distributions for the random variables one for billets being cut that was longer, and one for billets passing through without cutting that was shorter.
- The workers' schedules were ignored it was assumed there were always workers available to work at each station.

## 3.4 Results

First, the model was run for 10 times using the base case scenario; each run was three months each (January 1, 2015 to April 1, 2015) and included a warm-up period of four hours to ensure that no bias was introduced to the outputs caused by an empty system at the beginning. The mean of the throughput of 10 replications was 618,740.537 ft<sup>3</sup>, the standard deviation was 17,858.432 ft<sup>3</sup>, and the half-width for a 95% confidence level was 12,775.152 ft<sup>3</sup>. In order to reduce the half-width to approximately 10,000 ft<sup>3</sup>, Equation 3-4 was used to determine the minimum number of replications, *n*. The z-value for  $\alpha$ =0.05 is 1.96, *s*<sup>2</sup> is the variance of the initial sample of 10 replications, and h is the desired half-width. This was calculated to be 13 replications. Because the total running time of the model was less than 5 minutes per replication, it was decided to run the model for a total of 15 replications to further reduce the half-width. It should be noted that the 95% confidence interval for the average throughput is not ±10,000 ft<sup>3</sup> as was desired when calculating the number of runs using Equation 3-4. Since the existing confidence interval is close to ±10,000 ft<sup>3</sup>, it is considered acceptable for this project.

$$n = z_{1-\frac{\alpha}{2}}^2 \times \frac{s^2}{h^2}$$
 Equation 3-4

The average total throughput in cubic feet is shown in Figure 3.2, the average throughput per hour is shown in Figure 3.3 (both with max/min bars), the average queue time for each piece per station is shown in Figure 3.4, and the average station utilization is shown in Figure 3.5.



Figure 3.2 - Scenario Analysis for the Average Throughput



Figure 3.3 - Scenario Analysis for the Hourly Throughput



Figure 3.4 - Average Queue Time per Billet at Each Station



Figure 3.5 - Average Utilization at Each Station

The high average queue time at the billet deck is a result of all breakdowns which eventually cause pieces to have to wait on the billet deck much longer, and that billets must remain there for 1-2 hours in order to properly cure. However, there are a substantial number of pieces with low processing times and short queue times and only a few pieces with very high queue times which resulted in high average queue time – the actual queue times at each station were exponentially distributed. At all other stations, there were many billets that had to wait in the queues, either due to breakdowns further ahead, or due to the bottleneck. The average queue time at each station number, j is the piece number, N is the total number of pieces, and r is the number of replications (15).

Average Queue Time for station 
$$i = \frac{\sum_{r=1}^{15} \left(\frac{\sum_{j=1}^{N} queue \ time}{N}\right)}{15}$$
 Equation 3-5

The packaging station is the bottleneck process since its utilization is the highest overall. However, the utilization is not 100% for two reasons: 1) breakdowns at the packaging station result in the utilization dropping and billets accumulating in the queue, and 2) the times at each station are stochastic and have variation from piece to piece, which results in an unbalanced flow. When the model was run without any breakdowns or downtime, the total utilization for the packaging station increased to an average of 90%. The utilization at each station was calculated using Equation 3-6.

% Utilization = 
$$\frac{\text{total working time}}{\text{total available processing time}} \times 100\%$$
 Equation 3-6

### 3.4.1 Scenario 1 – Base Case

The results for the base case are summarized in Table 3.3.

Average Throughput over 3 Months: $618,915.2 \pm 10,248.99$ ft <sup>3</sup>				
Average Throughput per Hour: $365.8 \pm 6.1$ ft <sup>3</sup> /hr				
#	Station	Average Queue Time (minutes ± 95% confidence interval)		
1	Billet Deck (Sizer Infeed)	$334.2\pm7.4$		
2	Saw Staging	$61.0 \pm 1.8$		
3	Saw Infeed	$36.0 \pm 0.7$		
4	Sander Infeed	$59.0 \pm 1.4$		
5	Grading Infeed	$34.4 \pm 0.7$		
6	Piece Wrap Infeed	$24.5 \pm 0.5$		
7	Packaging Infeed	$42.0\pm0.7$		

Table 3.3 - Base Case Results Summary

## 3.4.2 Scenario 2 – 24/7 Operation

For this scenario, the average throughput increased to 786,856.7  $\pm$  9,685.2 ft<sup>3</sup>, for a 27% increase from the base case. The average throughput per hour decreased slightly by 1.5 ft<sup>3</sup>/hr to 364.3  $\pm$  4.5 ft<sup>3</sup>/hr. As indicated by the modest change in the average throughput per hour, this scenario does not remove the bottleneck problem which would hamper future growth. In addition, the queue time at each station remained almost identical to the base case, which is also an indication that the change would make no overall difference to the bottleneck. The utilization remained almost identical to that of the base case since the increase in available production time by the addition of weekends also resulted in an equivalent increase in the up-time. Even though it was expected that this would be the result for this scenario, it was included in the project as a way for the company to quantify the increase in throughput in the short-term, so that they had an idea if the amount of increase in throughput would be sufficient to meet demand in the short-term while options for improvement were decided.

### 3.4.3 Scenario 3 – 4-sided Sizer

The average volume throughput increased by 1.2% to 626,564.7  $\pm$  8,648.0 ft<sup>3</sup>. The average throughput per hour increased by 4.5 ft<sup>3</sup>/hr to 370.3  $\pm$  5.1 ft<sup>3</sup>/hr. This is not a substantial increase

and should be considered as no increase at all. The queue time increased at the infeed to the saw for this scenario since pieces were being processed more quickly at the sizer but no change to the processing time was made at the saw to compensate. For the remaining stations, the queue time remained almost identical to the base case. The utilization of all processing centres except the sizer remained relatively the same. The sizer's utilization decreased since it was able to process more pieces with the shorter processing time, but the saw was not able to keep up. Also, since the average throughput per hour only increased slightly, the problems with the bottleneck have still not been alleviated. Therefore, the saw infeed deck would get full regularly, requiring a shutdown of the sizer, and eventually would require the press to send more billets outside to storage. The average queue time decreased for the sizer (on the billet deck) only, but increased for the saw. For the other stations, the average queue time remained almost the same as that of the base case.

## 3.4.4 Scenario 4 – 25% Customization

This scenario provided the second best results after the 24/7 operation scenario, in terms of average volume throughput. The average volume throughput increased 20% to 742,473.2  $\pm$  8,049.8 ft<sup>3</sup>. The average throughput per hour increased significantly by 73 ft<sup>3</sup>/hr to 438.8  $\pm$  4.8 ft<sup>3</sup>/hr. The queue time also improved at each station for this scenario, which is an indication that the efficiency improved throughout the system rather than in only one location as in the previous scenario. The utilization of the packaging area decreased compared to that of the base case, while it increased in all other major processing centres. The large increase in the average throughput per hour indicates that this scenario could provide an opportunity for future growth since it resulted in an evening-out of the bottleneck process. The average queue time decreased for all stations, which is also a good indication that the bottleneck has been evened-out and that the scenario has had an effect on the actual process efficiency.

This scenario has some significant potential drawbacks. Eliminating a customer may not seem like it is a big deal since the overall percentage of their orders compared to all others is small. However, since the customer purchases products from the other divisions of the company as well, they may not place any future orders with those divisions either, if they are cut off from purchasing Parallam to their custom specifications. Nonetheless, this scenario did highlight the need for a focus on the packaging area rather than the other areas of the mill.

### 3.4.5 Scenario 5 – QA Analysis

The QA billets were analyzed only by the time they spend in the system from start to finish, instead of how they affect the total throughput. This separation was due to some software limitations and time constraints. In order to reduce the half-width to approximately five minutes, Equation 3-4 was used to determine the minimum number of replications, *n*. This was calculated to be 25 replications. A summary of the results is shown in **Error! Reference source not found.**.





The base case resulted in an average time-in-system of  $171.7 \pm 12.4$  minutes. When the billets were removed at the saw outfeed, the time-in-system decreased 8.6% to an average of

 $157 \pm 11.4$  minutes. According to the company, this change would require at least \$70,000 in capital for the purchase and installation of new equipment. In order to realize the improvements, another scenario would need to be developed where the QA billets proceed through the entire system and the change in throughput is analyzed.

## 3.5 Discussion and Recommendations

Both the 24/7 operation scenario and the 25% customization scenario showed improvement in terms of total volume throughput. Removing the QA billets at the saw outfeed is only beneficial in terms of reducing the time to process QA billets. The change to a 4-sided sizer is not beneficial at all since there was not a significant increase in the throughput. During the completion of this project, the company decided to implement 24/7 operation to increase their short-term throughput in order to meet an increase in demand.

Overall, the company should consider the implementation of the 25% customization scenario in some form, but not in the form it was initially considered for this project. The complete removal of a customer just to eliminate their custom orders would likely have an impact on the future orders made by the customer with other divisions of the company, which would hurt their bottom line. However, since the packaging area was determined to be the bottleneck process, further research should be done to find different ways of decreasing the processing time when custom billets arrive, such as changes to the workers' assignments, and how a combination of those changes and these scenarios will affect the throughput. A variation of this was conducted as a second project, and is presented in Chapter 4. Since 24/7 operation had a substantial increase, it was recommended that the company continue with that to increase the throughput until the future research has been conducted.

As for the QA billets, it was recommended that the process be left as-is for now until changes are made in the packaging area. It was expected that changes in the packaging area would result in a better flow for the QA billets, even though their bottleneck is suspected to be at the saw. It was also recommended to consider alternative solutions to processing QA billets such as removing them completely from the system as soon as they exit the press. In addition, changes in the workers' assignments could be analyzed in order to free up workers to process these pieces separately. Another scenario should be run where these billets are run through the entire system with standard billets present to analyze the actual change in throughput so that changes can be better compared with the base case.

# **Chapter 4 Assessment of Worker-Machine Relationships**

## 4.1 Synopsis

In this chapter, the extensions of the previous models are described. This required extensive knowledge of the extended system (including processes that occur in other parts of the mill), and additional expertise in simulation modelling using the software package. More time was spent in the manufacturing facility, particularly in other parts of the mill such as the energy system, and the required data and information was gathered. The existing model was modified to incorporate the workers in remanufacturing, and modules were added for the workers from other stations. It was verified and validated by comparing the results of the model with the actual throughput of the system as well as discussions with the Production Manager to ensure their accuracy. As in the previous chapter, the impacts of the changes outlined in the scenarios were assessed, based on the outputs desired by management to determine their overall effect on improving the bottleneck in the packaging station. Again, discrete-event simulation was identified as the best approach, and recommendations were provided to the company.

In addition to the complexities and uncertainties from the project described in Chapter 3, there are additional complexities considered in this chapter: 1) workers have their own tasks, and would only be free to work in packaging when they are idle, and 2) the packaging station does not always require the extra workers – they are only requested from the other stations during the highly custom tasks. These complexities prevent the analysis from being done using deterministic methods, such as optimization or simply an Excel spreadsheet, and again required the use of a stochastic modelling method such as discrete-event simulation.

## 4.2 Objectives and Scenarios

The overall goal of this chapter is to analyze the worker-machine relationships in the mill, and to determine if a rearrangement of workers' assignments could make the remanufacturing department more efficient without compromising other essential mill tasks. Specific objectives are:

- Assess the impact of assigning the energy system worker to the packaging station during their idle time. The company wanted to determine how this would impact the entire mill, since many energy system tasks are time-sensitive and waiting longer to complete them could lead to more mill downtime.
- Determine the impact of adding a second packaging worker, either from another department or a new hire. The company already does this during busy times – they wanted to assess its value, and determine the feasibility of reassigning a worker from another station permanently.
- 3. Evaluate the addition of an automated outfeed conveyor that can stack the wrapped packages. This was interesting to the company since its addition would affect the relationship between the forklift driver and their utilization at the packaging station.

Eight scenarios were chosen in consultation with the management team, as outlined below.

Scenario 1 – Base Case: The existing system where there are five employees in the remanufacturing department – one "sawyer" to operate the sizer and saw machines, one "sander" to operate the sanding machine, one "grader" to operate the grading station, one "packager" to operate the packaging station, and one "combilift driver" to drive the

combilift and assist in the packaging station. Both the sander's and grader's priorities are to operate their own machines when the billet width is less than 19.8 inches. Otherwise, their priority is to help the packaging station when they are idle.

- Scenario 2 Addition of Energy System Operator: The energy system operator is the worker who controls and monitors the plant boiler, which runs on both natural gas and hog fuel from the mill. The operator also controls and monitors the dust collection system and responds to any issues that may come up. A large portion of the job is simply monitoring systems, so management was interested in the impact of moving this worker to the packaging station. Therefore, this scenario involved the addition of this operator to the packaging station when they are not conducting an energy-related task.
- Scenario 3 Addition of a New Worker: The scheduling of a sixth regular worker in the remanufacturing department was assessed in this scenario. This worker was assumed to be trained to assist with energy-related tasks if required, but the bulk of the time would be conducted in the packaging station as a second operator.
- Scenario 4 Combination of Scenarios 1 and 2: This scenario allowed both the energy system operator and the new worker to the packaging station, allowing the new employee to also conduct energy-related tasks if required. The energy system operator would act in the same manner as the combilift driver when they are idle of their own tasks, they would come and assist the two packagers at the packaging station.
- Scenario 5 Base Case with Automated Rollcase: Management was interested in determining the impact of installing a cross-conveyor system at the packaging outfeed (the rollcase) to determine how much of an increase in throughput could be obtained by having

the combilift driver more available to work in packaging. This was also weighed in terms of safety, since the existing system required each package to be lifted by the combilift and left unattended. For this and subsequent scenarios, the combilift processing time was reduced by 50%, which is strictly an estimate from consultation with management.

Scenarios 6 to 8 – Scenarios 2 to 4 with Automated Rollcase: These scenarios are identical to Scenarios 2 to 4, except that the combilift's processing time was decreased by 50% to simulate the addition of an automated rollcase.

## 4.3 Model and Methodology

### 4.3.1 Model Inputs, Logic, and Outputs

The inputs of this model were mostly the same as those from the previous chapter, with a few differences. The processing times at the packaging station were based on the number of workers at the station, and were obtained through a time study. Other additions to the inputs included the availability and priorities of the workers at their stations, the frequencies and durations of energy system tasks, and the preparation of the hog fuel bins. Table 4.1 shows the probability distributions used for these additional inputs, while providing the parameters used in the model.

Station	Туре	Probability Distribution (minutes)	
Energy	Interarrival Time	Exponential $(1/304.6^{a}, 0^{b})$	
System	Processing Time	$Lognormal(2.5^{\circ}, 1.3^{d}, 0.9^{b})$	
Other Tasks	Arrival Rate	$Triangular(2^b, 25^e, 20^f)^g$	
	Processing Time	Triangular(3, 60, 20)	
Combilift	Processing Time for Scenarios 1 to 4	Exponential(1/10.4, 2.3)	
Forklift	Processing Time for Scenarios 5 to 8	Exponential(1/10.4, 2.3)×0.5 <sup>h</sup>	
Cutting and	2 or more Workers	Pert(9.0, 32.7, 13.8) <sup>i</sup>	
Packaging	1 Worker	Triangular(13.7, 40.3, 17.0)	
Packaging	2 or more Workers	Triangular(2.0, 9.0, 5.7)	
Only	1 Worker	Pert(4.5, 18.6, 10.2)	

Table 4.1 - Probability Distributions for Processing Times and Mill Tasks

<sup>a</sup> Average time between tasks

<sup>b</sup> Minimum value

<sup>c</sup> Mean of the included normal

<sup>d</sup> Standard deviation of the included normal

<sup>e</sup> Maximum value

<sup>f</sup> Most likely value <sup>g</sup> Rate per day

<sup>h</sup> To account for the faster rollcase conveyor

<sup>i</sup> Same as Triangular

The model logic is mostly the same as the model in Chapter 3, except that workers are used at each station and there are different logic blocks in the software for energy system tasks, other mill tasks, and combilift forklift tasks. The additional downtime (other than breakdowns) was disabled for all processes after the saw, since it related to workers' delays in the previous project which are being included here. The workers at the sanding and grading stations, as well as the combilift driver, would be assigned to the packaging station if they were idle, and if they were required at the packaging station due to a high amount of customization. The press downtime duration was changed to a new Weibull distribution with a shape parameter of 5, scale parameter of 1, and minimum value of 0 to better represent the downtime after major maintenance had been done on the press. This resulted in the desired outputs of the volume throughput, the amount of total system downtime, the utilization of machines and workers, the utilization of employees at the packaging station, and the percentage of time packaging is covered by one, two, three, and four workers. An overview of the inputs, outputs, and model logic is shown in Figure 4.1. See Appendix A for a summary of the model construction blocks from the software.



Figure 4.1 - Overview of Model Inputs, Logic, and Outputs

### 4.3.2 Verification and Validation

In this model, much of the verification and validation was the same as that from Chapter 3. For example, increasing the number of allowable rejects to 100% would result in the model rejecting every piece, which it did. In some cases, there was even more verification and validation conducted due to the increased amount of complexities in the model compared to the previous model. The logic of the model was verified to ensure it was functioning correctly by running it slowly and watching the interactions with the designed software animations. The model was run in front of management where they provided feedback about its function and whether or not the entities moved through the system as they should. Some interim data were obtained representing the uncertain parameters, such as obtaining a stream of values from the sizer's processing distribution, and compared those to the real values obtained during the time study. These values could not be distinguished by management as to which were obtained from the model, or which were obtained from the factory floor, which is an indication of a valid model. The software feature to export values to the screen was used to indicate some data on the screen while the model was running, and the model was paused at times on the occurrence of certain conditions (such as a breakdown, the movement of a worker to a different station, or the addition of the combilift driver to the packaging station mid-process). This feature was particularly useful for obtaining data for the billet properties as the entities were created, since a visual verification of the properties was required for each billet entity to ensure they followed the correct processes based on the properties assigned.

### 4.3.3 Assumptions

Most of the assumptions in this model were the same as those described in Chapter 3, except that this model included the workers' assignments and their interactions with the machines. In addition, there were other assumptions made in this model, as follows:

- Only the combilift driver was allowed to join the packaging process after it had started, due to limitations in the modelling software. All other workers that joined the packaging station would only be assigned at the start of the packaging process. This could result in some bias in the utilization values for the workers, since they may not be assigned to the packaging station when they are idle, only due to the process having already started.
- Breakdowns were not considered for the combilift forklift, since there is a replacement forklift that can be used instead.
- It was assumed that the sawyer would never leave their station, and therefore, would not assist in packaging.

## 4.4 Results

Fifteen replications of the model were done for each case to keep the number the same as the previous model, as the calculation for number of replications was less than the 10 initial runs. Each simulation run was for one month (January 1<sup>st</sup>, 2016 at 12:00 AM to February 1<sup>st</sup>, 2016 at 4:00 AM), and included a warm-up period of four hours (reflected in the model from 12:00 AM to 4:00 AM on January 1<sup>st</sup>, 2016) to ensure that no bias was introduced to the utilization, average throughput or queue times caused by an empty system at the beginning. The graphs in Figure 4.2

to Figure 4.11 summarize the results in terms of all the outputs, which are the averages of the 15 replications.

The best scenario in terms of throughput (Figure 4.2) is Scenario 8, when there is an automated rollcase, and the energy and flex workers are assigned to packaging. It resulted in a 29.6% increase in throughput from 237,133.4  $\pm$  4,472.4 ft<sup>3</sup> to 307,359.9  $\pm$  4,772.2 ft<sup>3</sup>. Close behind is Scenario 4, with the energy and flex workers assigned to packaging with the existing rollcase. This resulted in a 27.5% increase from 237,133.4  $\pm$  4,472.4 ft<sup>3</sup> to 302,364.1  $\pm$  5,138.7 ft<sup>3</sup>. The average total downtime (Figure 4.3), where all machines are stopped at the same time, does appear to be lowest when adding both the energy worker and flex worker to packaging, but due to the stochastic nature of the breakdowns, there is no relationship between the scenarios. Figure 4.2 has max/min bars to illustrate the randomness in the system.



Figure 4.2 - Average Total Throughput for All Scenarios



Figure 4.3 - Average Total Downtime for All Scenarios

The machine utilization (Figure 4.4 and Figure 4.5) is highest at the packaging station compared to other machines for all scenarios, and there is only a 7% decrease in the utilization between the base case and Scenario 8 (from 80% to 73%). However, as the amount of productive time at packaging increases, the utilization at packaging decreases while the utilization at the other stations increases.

The utilization of the packager in Figures 4.6 and 4.7 is the same as the packaging station utilization shown in Figures 4.4 and 4.5, while the combilift driver's utilization is a bit higher than that of the packager. The sander assists the packager less as the number of workers increases, whereas the grader assists more as the number of workers increases. When there is no automated rollcase, there is approximately a 1% decrease in the packager's utilization compared to using the existing rollcase. For the combilift driver, it was expected that the utilization would increase when they are more available to work in packaging, but it makes sense that it decreased by about 3% since they are now subject to more packaging breakdowns than when they were working more

often driving the combilift. The combilift driver should always be working more than the packager when they are assigned to assist in packaging as well, which occurred in all scenarios.



Figure 4.4 - Average Machine Utilization for Scenarios 1 to 4



Figure 4.5 - Average Machine Utilization for Scenarios 5 to 8



Figure 4.6 - Average Worker Utilization for Scenarios 1 to 4



Figure 4.7 - Average Worker Utilization for Scenarios 5 to 8

Figure 4.8 shows the percentage of time each non-packaging worker is working at the packaging station, with respect to their total working time. Note that these values do not add up to 100% for each scenario since the percentages refer to the resources' times, not the total available time in packaging. In the base case with the existing rollcase, the sander is pulled away from their station to work in packaging 10.2% of the time, compared to 4.4% for Scenario 2, 1.1% for Scenario 3, and 0.4% for Scenario 4. In the base case with the automated rollcase, the sander is

pulled away from their station to work in packaging 13.5% of the time, compared to 6.1% for Scenario 6, 1.3% for Scenario 7, and 0.4% for Scenario 8. The grader's time at packaging increased only marginally (from 6.9% in the base case to 8.3% in Scenario 8). With the addition of the flex worker in Scenario 8, the utilization of the energy operator increased significantly, by approximately 40%. This is because the new worker is also able to assist with the energy system tasks, therefore the energy system operator spends much of their time in the packaging station. It should be noted that the results would be the same for the flex worker if that worker was prohibited from working in the energy system since the flex worker would spend all of their time in packaging. When the flex worker is assigned to packaging without the energy system operator, they are working in packaging over 73% of the time (Scenarios 3 and 7). But when they are also assisting the energy operator (Scenarios 4 and 8), they are working in packaging just over 55% of the time. As mentioned above, if this flex worker was prohibited from working in the energy system, the results for Scenarios 4/8 and 3/7 would be reversed.



Figure 4.8 - Average Worker Time at Packaging for All Scenarios

The percentages of time one, two, three, or four workers were allocated to the packaging station are shown in Figure 4.9. The only time there are four workers in packaging is when the energy system operator, the flex worker, the combilift driver, and the packager are assigned to the

packaging station. In all other scenarios, there were never enough workers available to have more than three in packaging at one time. In the base case, there was only one worker at the packaging station for 44.9% of the time. That decreased to 5.4% in Scenario 4 as the amount of productive time in packaging increases, and decreased to 1.6% in Scenario 7 when the automated rollcase was used. Also in the base case, there were only three employees allocated to packaging 12.2% of the time – a number that increased to 47.1% in Scenario 4 and to 58.5% in Scenario 7. Since there was no observed difference in processing times between two, three, and four workers, these results only show that there was much less time that packaging was only being assigned one worker when the number of available workers increased.



Figure 4.9 - Average Time at Packaging by Number of Workers for All Scenarios

The average queue times for each station are shown in Figures 4.10 and 4.11. At the billet deck, the average queue time decreased almost 25% from the base case (from 378 minutes to 284 minutes) when the energy operator and flex worker are assigned to packaging. Each station exhibited a decrease in queueing time as the amount of productive time at packaging increased,

which is an indication that the process was made more efficient. Note that there were a large number of pieces with low processing times and short queue times and a few pieces with very high queue times which resulted in high average queue time. Due to the stochastic breakdown frequencies and durations, some pieces could be waiting in the queue for an extremely long time. The average queue time at each station and average utilization are calculated using the same formulae as in Chapter 3 (Equation 3-5, page 41; and Equation 3-6, page 41).



Figure 4.10 - Average Queue Time in Minutes per Billet for Scenarios 1 to 4



Figure 4.11 - Average Queue Time in Minutes per Billet for Scenarios 5 to 8

The packaging station is still the bottleneck process since its utilization is the highest overall. However, the utilization is not 100% since there is a significant number of pieces with low processing times and only a few with high processing times. The times at each processing centre are stochastic and have variation from piece to piece, which results in an unbalanced flow. When the model was run without any breakdowns or downtime, the total utilization for the packaging station increased to an average of 90%. This did not increase to 100% since there were instances when the process is running smoothly and the packaging station is idle waiting for pieces.

### 4.5 Discussion and Recommendations

The results show that the addition of both the energy system operator and the flex worker (Scenarios 4 and 8) was the best in terms of throughput, providing an increase of 29.6% (from 237,100 ft<sup>3</sup> to 307,400 ft<sup>3</sup>) from the base case when the rollcase was automated and 27.5% (from 237,100 ft<sup>3</sup> to 302,400 ft<sup>3</sup>) when it was not. However, if the energy system operator is busy in packaging and an alarm goes off in the energy system, management expects it could take much longer for the problem to be rectified, causing further mill-wide downtime. In all scenarios, the total machine utilization for all machines except the packaging station continually increased from the base case as more productive time became available at the packaging station. For the packaging station, the utilization decreased as the amount of productive time increased, resulting in a reduction of the bottleneck. The utilization of all workers except the sander decreased as more time became available at the packaging station in Scenarios 4 and 8 was still lower than that of the base case, it was higher than Scenarios 3 and 7 since the amount of time the sander was required at the packaging station decreased, and the amount of time the sander machine was being used increased. The queue times per billet at each station decreased
compared to the base case in all scenarios, and as more productive time was available at the packaging station.

All scenarios where the rollcase was automated (5 to 8) provided increases in throughput of between 1% and 3% compared to the scenarios with the existing rollcase, and had similar improvements in worker utilization, machine utilization, and queueing times. Due to the significant concerns the company's management team has about the safety of the current practices where loads are left lifted on the combilift unattended, it is recommended that the automated rollcase be installed, even though its benefit on the outputs is not that significant. Therefore, it is recommended that the addition of only the flex worker to the packaging station be implemented, combined with the installation of the automated rollcase (scenario 7), which resulted in a 22.2% increase in throughput from the base case (from 237,100 ft<sup>3</sup> to 289,800 ft<sup>3</sup>).

While this project did result in a substantial increase in the total throughput, approaching the company's goals, it still did not completely eliminate the bottleneck from packaging. There are some other options that the authors feel need to be further studied, however, on consultation with the management team. Management expressed interest in studying the break schedules, and determining if rotation-style breaks are more beneficial over those where all worker have the same break schedule. In addition, a worker rotation system is interesting to study, in order to attempt to increase the utilization of the sander and grader workers.

## **Chapter 5 Conclusions, Strengths, Limitations, and Future Research**

### 5.1 Conclusions

Production operations are subject to many uncertainties, dependencies, and interactions between processes that affect the throughputs. The uncertainties in the Parallam process, such as customer orders, processing times, and the interactions of the workers and machines, prevent the use of deterministic models.

The use of discrete-event simulation modelling can incorporate the interdependencies, interactions, and complexities and provide an effective method of decision-making in the forest products sector. There had been no previous research conducted on the processes of engineered wood products manufacturing, and no previous research conducted involving the worker-machine interactions in factories. The overall objective of this thesis was to use discrete-event simulation to assess alternatives to improve the productivity and efficiency of the Parallam mill. Two projects were conducted, which were presented in Chapters 3 and 4. In the first project, the overall efficiency of the remanufacturing department was evaluated, and possible alternative solutions to improve it were tested. All of the alternative configurations were chosen in consultation with the management team, and involved the replacement of machinery, or changes in policies. It was found that the best scenario in terms of highest increase in throughput (27% increase) was to run the mill for 24 hours per day, 7 days per week. However, that change would not improve the actual efficiency or eliminate the bottleneck. The next best scenario (20% increase in throughput) involved the elimination of a customer that was the source of a high percentage of the custom orders that take considerable production time. While it was determined that eliminating the customer outright was not practical, it highlighted that the packaging station was the bottlenecked area and that further changes should be made in that area. It was also determined that the replacement of the sizer machine was not practical, since it was not actually the bottleneck, and that the operation of the mill up until the packaging station was relatively efficient.

The results prescribed in Chapter 3 created interest in the further analysis of the packaging station, and the subsequent development of the second project. The packaging station slowed down considerably when there was only one worker present at the station; the company was interested in determining how they could better assign the workers to increase the productivity of the department. This led to the assessment of the worker-machine interactions, in order to determine how the workers from all parts of the mill could be assigned to have more than one worker at packaging for as much time as possible. This second project involved the evaluation of alternative workers' assignments, and their impact on the efficiency and productivity of the mill. With the addition of an additional full-time worker in the packaging station, a 22.2% increase in the average throughput could be achieved. This worker should either be from a redundant in-house position, or a new hire – the addition of the energy system worker would not be feasible since the neglecting of their existing tasks could result in significant downtime. The addition of any more workers to the packaging station was not practical, since no significant improvement was attained, and it could result in space issues in the department, which could result in a decrease in productivity.

#### 5.2 Strengths

The main strength of the research is the analysis of processes in an engineered wood products manufacturing mill. To the best of my knowledge, no research has been conducted in the

past that used discrete-event simulation to incorporate the complexities and uncertainties in forest products mills other than sawmills.

For the first project in Chapter 3, the main strength was the utility of the model for industry. It was developed using a real case in consultation with the management team of the partner company. Billet properties were obtained from the company's scheduler, and other inputs were obtained through site visits and timing studies using the security cameras in the mill. This resulted in reliable data that led to a very realistic analysis of the system. Despite there being limited availability of machine downtime data, the presence of the industry experts during the site visits allowed for reliable estimates.

To my knowledge, the second project in Chapter 4 was the first study that assessed the combined interactions of workers and machines in the forest products sector, which is important due to their contribution to the uncertainties in the processing times of each station. Due to the need for workers to operate machines, and the flexibility of workers, these interactions are very important to consider when making decisions.

Since the models were created using Java, they can be easily amended to suit the user's needs. Java provides the ability to create an applet that will run without the software, therefore the users of the model will not need to purchase the software unless they want to make changes. The processing times data were all analyzed in Excel using the @Risk 7 add-in, and can be easily viewed and modified as required. The extensive capabilities of the simulation software allow for the inclusion of almost any desired event, or set of randomness. In addition, the model can be modified to suit any other system, including those for the production of other engineered wood products, as long as appropriate data is available or obtainable.

#### 5.3 Limitations

There are some limitations to this research. The very nature of discrete-event simulation prevents the optimization of processes without additional tools. Therefore, it might be possible that better solutions exist to improve the efficiency and productivity compared to those that were modelled. There were very limited data available for the frequency and duration of machine breakdowns, so they had to be estimated based on observation and management opinions. The company was in the process of implementing a new downtime tracking system during the completion of these projects, so getting good data from that in the future would help make the models better represent reality. A few sub-processes, such as calibration, were left out of the model in order to simplify the programming, and were instead part of the probability distributions for the corresponding main processes. While their inclusion would make for a better model, the tasks were conducted only a few times per day which would not have significantly affected the results. The final lengths of billets were also left out, and instead of creating individualized patterns per customers' orders, the altered processing times were accounted for in the probability distributions.

Initially, a full analysis of the QA billets was planned in Chapter 3. Due to a limitation in AnyLogic 7 that prevents different entity types from being in the same process blocks at the same time it was decided that only the time-in-system would be analyzed for these pieces. However, that prevented the study of the impacts of manufacturing the QA pieces on the same line as the revenue pieces. A workaround for the limitation was found between the first and second projects, but in consultation with management, it was decided to focus on the goals of the second project since they were considered to have more value. However, a more comprehensive model focusing solely on scenarios related to the manufacture of the QA pieces would better encompass the real system, and would provide even better information for decision-making in the future. In addition, AnyLogic 7 University did not allow for step-by-step operation of the model which resulted in time-consuming debugging using the on-screen features combined with model pauses. However, these pauses did not always work effectively either, since many would not activate instantly and the pause code had to be located well before the desired location.

The final limitation of this research is that neither of the models considered break times, even in the model of Chapter 4 when workers were included. No changes were made to the total available time of the workers. Any future models of workers should include the breaks, since they could have a significant effect on the final outputs of the mills.

## 5.4 Future Research

To the best of my knowledge, there are no previous studies using any type of simulation in the cabinet industry, windows and doors, or other engineered wood products (such as plywood, laminated veneer lumber, or particleboard). Due to the usefulness of simulation in other forest products sectors (e.g. sawmills, biomass supply chains, or bioenergy plants), these other facilities could benefit greatly from simulation studies. Therefore, research studies could be conducted using simulation in these facilities. It is also important to consider the interactions of workers and machines in all other forest products sectors that have used simulation. In many cases, the workers' assignments may have a significant effect on the productivity of a mill, compared to the analysis of strictly machines alone. This is particularly true in a time when the goal of many companies is to reduce costs by more effectively using resources.

There have been very few studies in the forest products sector that have analyzed economic, environmental, and social impacts together. It would be beneficial for studies to be conducted using simulation-optimization techniques to take multi-objective optimization models and incorporate the uncertainties and complexities to obtain a more realistic solution to an already complex multi-objective problem.

Specific future research for the partner company would involve the analysis of worker schedules, including a scenario with rotating assignments and rotating breaks. For example, one idea the management team had was to have all workers in remanufacturing fully trained on all machines and tasks in the department. Then, as an additional worker is required for the packaging station, they would leave their station idle. As soon as the queue for the idle station is full, and if the worker has not yet returned, the worker from the previous station who can no longer work their station due to the full queue would switch over to the idle station leaving their own station idle. Then, if the worker that moved over to packaging can be released, they would go to the idle station instead of back to their own. The rotation system would continue until the billet deck was the queue that was full, at which time billets would be released outside for storage. The same would be done with the breaks – one worker would leave their station for a break, and once their queue is full the worker from the previous station would move to it. In addition, it would also be beneficial for the company to analyze its supply chain from the procurement of raw materials right through to the delivery of the veneer to the factory, including the transportation and logistics and complexities of it.

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# Appendix A – Simulation blocks used in the development of the models

AnyLogic 7.2 was used for the development of the simulation models in this research. Each block from the "Process Modeling Library" used in the developed models are described here.

Symbol/ Name	Description	Block Parameters	Used in the Model	Parameters in the Model	Customization
source	Generates entities at the start of the model	• Interarrival time	• Start of the models	• Interarrival time was set as (billet length ÷ feed speed)	• Billet properties were added using codes
in o out Conveyor	Moves entities along a path at a given speed	• Feed speed	<ul> <li>Press outfeed to the sizer queue</li> <li>Outside to storage</li> <li>Re-entering from storage</li> <li>Saw staging back to the saw for a second pass</li> <li>Saw outfeed to the sander queue</li> </ul>	• Feed speed was set based on billet width (see Table 1.1, page 4)	• Codes were used to count the number of entities crossing the conveyor in certain processes (i.e. the press)
in outT outF Select Output	Routes entities to one of two outputs based on a condition	• Condition (probabilistic or deterministic)	<ul> <li>Billet deck full</li> <li>Sizer passes</li> <li>More than 2 cuts</li> <li>Stage after saw</li> <li>Recut required</li> <li>Sander storage</li> <li>Rejects</li> <li>Piece wrap</li> <li>Custom piece</li> <li>Scenario selection</li> <li>Worker selection</li> </ul>	<ul> <li>Process conditions (i.e. full queues, number of sizer passes, rejected pieces, customization required at packaging)</li> <li>Combinations of workers/machines</li> </ul>	• In the packaging module, the condition looked at the available resources using codes

Symbol/ Name	Description	Block Parameters	Used in the Model	Parameters in the Model	Customization
in o → Poout MoveTo	Moves entities to a new location, when the entities needed to stop moving at a different distance depending on the size of the queue	<ul> <li>X and Y coordinates of the new location</li> <li>Feed speed</li> </ul>	<ul> <li>Billet deck</li> <li>Saw infeed (2 blocks)</li> <li>Saw staging</li> <li>Return pieces from outside</li> <li>Sander deck</li> <li>Piece wrap</li> <li>Reject deck (enter)</li> <li>Reject deck (return)</li> <li>Packaging</li> </ul>	<ul> <li>X or Y coordinates (depending on direction of queue), calculated as (1 + queue size × billet width × pixels factor)</li> <li>Feed speed</li> </ul>	• NA
outPreempted outTimeout in o moo out Queue	A buffer of entities waiting to be accepted by the next process	• Capacity	<ul> <li>Sizer</li> <li>Saw (2 queues)</li> <li>Saw staging</li> <li>Sander</li> <li>Grading Station</li> <li>Piece Wrapping</li> <li>Reject staging</li> <li>Packaging</li> </ul>	• Capacity is dependent on the size of the entities in the system, calculated as (length ÷ billet width)	• Codes were used to control the flow of the entities so they all had an exit from the previous process
in <b>Out</b> Delay	Entities are delayed for a time equal to the processing times	<ul> <li>Delay (process) time</li> <li>Capacity</li> </ul>	<ul> <li>Curing time</li> <li>Packaging station</li> <li>Piece wrapping bypass</li> </ul>	<ul> <li>Delay time is obtained from the distributions in Tables 3.1 (page 34) and 4.1 (page 51)</li> <li>Capacity is always 1</li> </ul>	• For the packaging station, codes were written to determine the number of workers used, and the time used by each worker

Symbol/ Name	Description	Block Parameters	Used in the Model	Parameters in the Model	Customization
outPreempted outTimeout in III out Service	Seizes resource units, delays the entities for a time equal to the processing times, and releases the resource units	<ul> <li>Resource units</li> <li>Delay (process) time</li> </ul>	<ul> <li>Sizer</li> <li>Saw</li> <li>Sander</li> <li>Grading station</li> <li>Piece wrapping</li> <li>Forklift</li> <li>Energy worker</li> <li>Flex worker</li> </ul>	<ul> <li>The resource units are the machine and/or workers required for each process</li> <li>The processing times are obtained from Tables 3.1 and 4.1</li> </ul>	• NA
in out outCopy Split	Creates copies (through "outCopy") of the incoming entities, keeping the original (through "out")	• Number of copies	• Saw	• The number of copies was determined from the "cut sheet" properties set at the start of the model	<ul> <li>The properties of the original (size, cutting pattern) were transferred to the copies using codes</li> <li>Animation codes were created so the new entities look the same as the originals</li> </ul>
outPreempted outTimeout in out preparedUnits Seize	Seizes resource units	• Resource units	• Packaging (Chapter 4 only)	• Different combinations of resources for packaging were chosen, based on the scenario being run	• Codes were used to track the number of workers active at packaging, and for how long

Symbol/ Name	Description	Block Parameters	Used in the Model	Parameters in the Model	Customization
in o out wrapUp Release	Releases resources seized by the "seize" block	• Seize blocks	• Packaging (Chapter 4 only)	• All seize blocks used in the packaging station	• The tracking of active workers was ended using codes
in 아마가 out Batch	Combines sets of entities together into one new entity (i.e. packages)	• Package size	<ul><li>Packaging</li><li>Forklift</li><li>Rejects</li></ul>	• Package size determined by billet width and thickness	<ul> <li>Codes were written to hold the packaging block to ensure entities didn't get processed until the new batch was processed</li> <li>The combilift forklift process time and movement was controlled using codes</li> </ul>
in <b>or in out</b> Unbatch	Splits the previously batched entities back into their initial parts	• Batch to be split	• Rejects returning to the system	• The rejected billet packages stored outside	• The thickness of the billets was dropped by 1.75 inches using code to resemble being re-cut in the system

Symbol/ Name	Description	Block Parameters	Used in the Model	Parameters in the Model	Customization
<b>ዮዮ</b> Resource Pool	Defines a set of resources that can be seized and released in the system	<ul> <li>Number of units</li> <li>For machines, failure rates and durations</li> </ul>	<ul><li>Machines</li><li>Workers</li></ul>	<ul> <li>Each machine and worker had one unit assigned</li> <li>Failure and downtime rates and durations were set as in Table 3.2 (page 35)</li> </ul>	• Animation codes were created so the "workers" appeared in red when in use, and in black when idle
in <table-cell-rows> out Hold</table-cell-rows>	Blocks entity flow along a particular connection	<ul> <li>Initially blocked or not</li> <li>Blocking method (manual or by condition)</li> </ul>	<ul> <li>Press</li> <li>Sizer</li> <li>Saw (3x)</li> <li>Sander</li> <li>Grading station</li> <li>Piece wrapping</li> <li>Reject deck</li> <li>Reentering rejects</li> <li>Packaging station</li> </ul>	<ul> <li>All blocks are initially unblocked</li> <li>All blocks are controlled manually using codes</li> </ul>	• None within the blocks, only done through other blocks and events
Event	Triggers a specific event under a certain set of conditions	• Conditions (such as queue size and entity location)	• Various events such as full queues, the setting and resetting of hold blocks, and controlling movement of billets	• Queue sizes are monitored compared to their capacity	<ul> <li>Work in groups of two – for the first event (i.e. full queue) and the opposite (i.e. queue no longer full)</li> <li>"Hold" blocks are coded accordingly to block entity flow</li> </ul>