The Use of Simulation as a Decision Tool for Improvements in Sawmill Manufacturing

by

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Abstract

A simulation study was used to analyze the flow of products though a sawmill in order to determine where productivity improvements could be made. The sawmill analyzed is located in the interior of British Columbia, and processes a variety of species and products. The mill was selected for this reason, as it was important to determine how a change in the process will affect the piece flow and production of the various species. A simulation model of the mill was developed using the Arena 8.0 discrete event simulation software developed by Rockwell Automation.

Data consisting of mill layout and flow, breakdown patterns, machine process times and downtimes, conveyor speeds, and buffer capacities were collected from the sawmill. This information was used to layout the framework in a conceptual model. The conceptual model was then used to develop the simulation model in Arena. A face validity test, combined with comparisons of model output to actual mill output was used to determine the validity of the model.

After running several different scenarios processing Larch, White pine, and Ponderosa pine, it was discovered that the trimmer was the system bottleneck when both the small log and large log lines were running throughout the shift. Running under base case conditions, the model predicted an average board output of 13,147 boards. An increase in the processing capability of the trimmer resulted in the bottleneck to shift to the edger from the small log line. The OptQuest Analyzer program bundled with the Arena software was used to further analyze the shift in bottleneck to the edger from the small log line. By allowing the program to manipulate

machine settings for the trimmer and edger, it was able to maximize the average board output to 17,996 boards per shift when no edger set up times were considered. If the edger setup times are used, the average board output dropped to 16,708 boards per shift. These findings were presented to the sawmill management and based on the study, they proceeded to make improvements at the trimmer. The improvements resulted in an increase of 10% to sawmill output.

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1 Introduction

The main purpose of a sawmill is to convert logs into finished lumber. This is performed through a series of cutting processes. When logs first arrive to be milled they are usually cut to length. Once bucked, the logs are then debarked and placed on a holding deck to await the primary breakdown. Logs are loaded onto a carriage and rotated into position by the sawyer operator. This machine center is called the Headrig. Once aligned to the appropriate position, the carriage passes through a saw, cutting off slabs of lumber, which is also sometimes called a flitch. Although there are many different ways a log can be sawn at the Headrig, the most common are: live, cant, and around sawing (Todoroki and Ronnqvist 1999). When live sawing, all cuts are made parallel to the log. Cant sawing is also made with all parallel cuts, however a large section of wood is left in the middle, (coloured in grey in Figure 1), which is then processed later at the secondary breakdown center. All around sawing requires the sawyer operator to rotate the log while making a series of cuts to remove the cant. The different sawing patterns are shown in Figure 1.

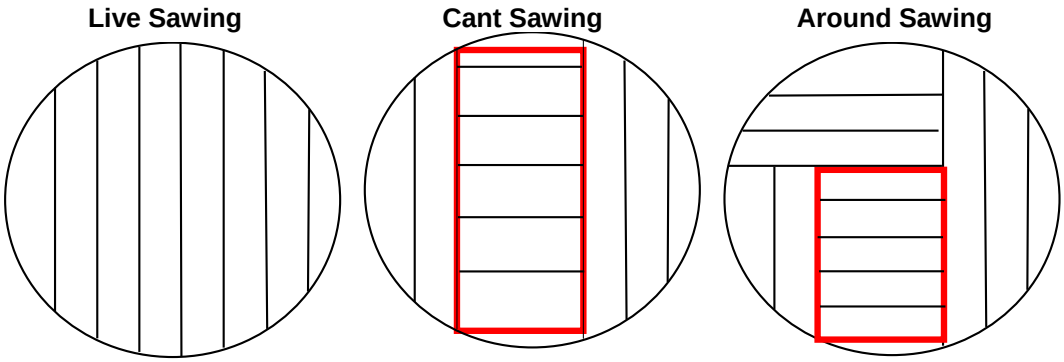

Figure 1 : Common sawing patterns

Cants are further broken down at a Re-Saw which alleviates the processing required at the Headrig and helps to increase throughput in the mill. The slabs or flitches are sent to an edger after being cut from the Headrig. The edger cuts the slab lengthwise to remove defects and

produce a parallel-edged piece of lumber. The final process in the sawmill is at the end trimmer which squares up the ends of the board and cuts to a specific length. After the final boards are processed in the sawmill, they are then transported for drying in the kilns. Once dry, the lumber is then planed, packaged, and ready to be shipped.

Sawmills are typically designed for cutting logs into lumber in one of two ways. Either cutting to maximize the volume recovery of the log, or cutting to maximize the value of the lumber removed from the log. Volume recovery considers the log geometry to determine the best pattern that will yield the highest volume of lumber possible. The sawing patterns for each of these combinations are predetermined. If subsequent logs are of the same size and shape, each sawing pattern will remain the same and therefore the end products are set. Value added cutting patterns are more dynamic. Although volume is still considered, the end decision must take into account the value of the end products sawn from the log and therefore a full range of possible options are evaluated. If two logs with the same shape and dimension are processed, yet the value of the end products are different, the cutting patterns will likely differ.

Historically, softwood lumber mills in British Columbia have been designed around volume based sawmilling. These sawmills maintained their competitive advantage through the high quality timber resources available. However, the effects of globalization, communication and transportation technologies have exposed companies to intense foreign competition. Although British Columbia sawmills still maintain a competitive advantage when it comes to fibre quality, there is increased pressure from South American sawmills. These sawmills have lower production costs combined with the benefit of much higher growth rates from plantation forests compared to Canada (Figure 2.)

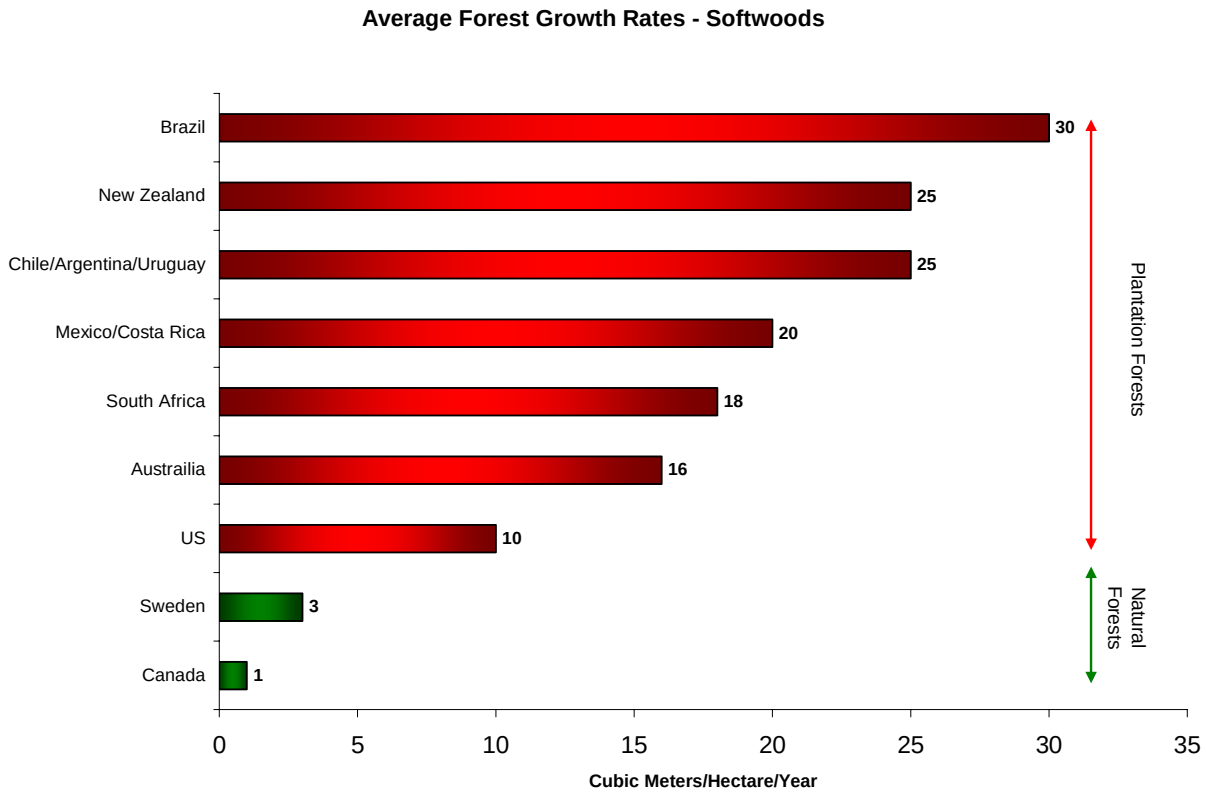

Figure 2 : Annual softwood growth rates (Schuler, 2007)

As a result of the changing marketplace, there has been a greater emphasis placed on value added sawmilling. A new business model that is focused on the end customer, and adding value to existing products is required for British Columbia companies to maintain their competitive advantage. In order to achieve this, sawmills must be flexible to quickly change their production process to capture changes in customer demand and emerging markets. This is a paradigm shift in operation, as many sawmills in BC are only designed to produce a high volume of commodity lumber to be exported to the US market. Unlike Europe, British Columbia has few sawmills that are designed as a flexible value added mill. These mills are comparatively small relative to other mills in the province, and target specific niche markets.

The strategic objective of this research was to gain an understanding of how a flexible sawmill works in order to determine how different sawmill designs can produce the same high value product at a lower cost. Because sawmills are a system of interrelated processes, it was important to understand how the manufacturing system reacts as a whole, rather than considering each manufacturing center in isolation. This was accomplished by working with an existing value added sawmill through the use of a simulation model.

To test the model in a real application, and to gain an understanding of how a flexible value added sawmill operates, the simulation model was used to assist the mill management with some operational questions. Specifically, the sawmill managers wanted to determine where the existing bottlenecks were, and what the impact of removing these bottlenecks would have on the flow and overall output of lumber on the system. This helps provide the mill management with information and recommendations as to where capital investments should be made that are most effective to increase mill output.

The simulation model provides mill managers with a tool that effectively analyzes their current operations, and the impact of alternative manufacturing scenarios. The simulation results can be obtained quickly and accurately, thereby providing the justification required to implement managerial decisions.

2 Literature review

2.1 Operations research as a decision science

Since the end of the Second World War, operations research has been increasingly used in numerous industries enabling companies to remain competitive under changing conditions (Randhawa et al. 2001). Operations research (OR) is a form of decision science that uses scientific methods to investigate a problem relating to the activities within an organization, and how an optimal decision should be reached (Hillier and Lieberman 2001). OR techniques fall into two categories; prescriptive and descriptive. Prescriptive techniques identify the optimal decision whereas descriptive techniques describe how things actually are. The decision made may not be an optimal solution (Turban and Meredith 1991). Mathematical programming, network models, and dynamic programming are examples of prescriptive decision tools while forecasting, Markov analysis and simulation are examples of descriptive decision tools (Turban and Meredith 1991).

Prescriptive OR tools have several advantages compared to descriptive OR tools. The answer is consistent and the solution is optimal. However, they may be unable to effectively deal with complex systems that are interrelated, and have stochastic elements.

Descriptive tools such as simulation have grown in popularity because of their ability to deal with issues of complexity and randomness that are inherent in many systems. A system is a group of procedures, resources, people or concepts designed to interact with each other in order to serve a goal or purpose (Turban and Meredith 1991). Manufacturing processes, warehouse operations, emergency rooms, telecommunications departments and biological processes are all

systems that exhibit complex interactions with random elements. Simulation models are increasingly used in business, engineering, science and social science as a tool used to analyze problems within these systems. Their increased use can be attributed to three factors: the increase in performance of computer hardware, the development of specialized simulation software, and the increase in the number of students who study simulation (Seila et al. 2003).

There are several limitations to simulation models that both the analyst and the client must consider. Cost, time, data requirements, expertise, and overconfidence are some of the common disadvantages in a simulation study (Robinson 2004). The time required to develop and test a simulation is often a lengthy process (Reeb and Leavengood 2003). This has been somewhat mitigated thanks to the rapid development of computer hardware and specialized simulation software. The quality of data used in a study will directly affect the results. A perfectly developed model that uses poor input data can be expected to produce inaccurate results. If the condition of how the data was collected and when it was collected is unknown, historical data can lead to incorrect assumptions for the current system being simulated (Chung 2004). Another concern with simulation is that multiple solutions can be generated which are often difficult to interpret due to the many components and interactions of the system. This can lead to difficulties in identifying an appropriate solution for the problem being solved, unlike a linear program maximization problem that provides a single solution. Finally, oversimplification of both data and processes can leave out critical elements (Chung 2004). This is not only limited to simulation but to mathematical programming techniques as well.

Since many systems are made of interconnected subsystems, and are both variable and complex, it becomes difficult to predict their performance or output. Simulation models are capable of representing the dynamic nature of these systems and are therefore an ideal tool for analysis.

Analytical tools such as linear programming, dynamic programming, or simulated annealing are not able to accurately predict a system's performance if it is subject to extreme complexity (Robinson 2004)

These complex, variable, interconnected systems are difficult to analyze. Variability is the stochastic nature within which the system operates. Variability can be either predictable or unpredictable. Operations are also interconnected, such that a change in one part of the system will affect other parts of the system. Complexity can be either combinatorial or dynamic. Combinatorial complexity is the measure of the size of difficulty in solving a problem based on the number of possible combinations of decision variables. Dynamic complexity is based on the interaction of components over time. This is the measured amount of information required for defining the state of the system as well as the uncertainty of the outcomes as a result of the interactions amongst the elements in the system. For example, an action may have a different effect on the system in the short run versus the long run, or may lead to an obscure result.

Although simulation is sometimes considered a method of last resort due to amount of time required to conduct a study, it is often the only way realistic information can be obtained. While it is possible to conduct experiments on existing systems, simulation is often preferred for several reasons. The cost of interrupting and experimenting with a real system is often far greater than building a simulation model. It may also take weeks or months to discover the full effects of the changes made. In a simulation model, once the programming is done, this can be obtained in a few minutes or hours. Another benefit to simulation is that the experimental conditions can be controlled in a model, whereas in the real system this may not be possible. Finally, if there is no existing system, modeling is the only option to conduct experiments on the proposed system (Robinson 2004).

2.2 Simulation applied to sawmilling

In the context of a sawmill, each machine center such as the Headrig, edger, Re-Saw, and trimmer are decision variables. These areas determine what products are cut from the log, and where products are routed. They are connected to each other through a series of conveyors. The decision of one machine center will impact the other centers, and effect of material flow through multiple processing units is difficult to estimate for complex mills (Aune 1974).

The process of sawing logs into lumber is stochastic by nature. There is randomness inherent not only in the system, but in the material being processed. Even logs with the same diameter, grade, and length may not produce the exact products each time (Randhawa et al. 1994). Along with the highly variable nature of inputs and processes interactions, simulation is ideal for sawmill analysis and design as it is much cheaper than experimenting with the real system (Dogan et al. 1997). It is often impossible to conduct experiments that might interrupt production in the mill. Changes to the actual mill layout are costly, in terms of both time and money and results from such actions may not be realized immediately. The use of a simulation model will enable an analyst to determine the result of changes to the system much easier and quicker than experimenting with the real system. As a result, simulation is becoming a preferred tool of choice to support sawmilling decisions.

Simulation tools used in sawmilling have developed along two main categories. The first focuses on the optimization of cutting patterns, referred to as process simulation. This prescriptive model derives a single optimal solution. The second focuses on the flow of products throughout the mill, referred to as flow simulation. It is used to investigate the impact of a change in the manufacturing process for the entire system. This can be observed from

changes in buffers and queue lengths, machine capacities, and product outputs. This descriptive model does not derive a single optimal solution.

2.2.1 Cutting pattern simulations

Cutting pattern optimization models focus on maximizing yield, products, or value from logs. In order to do this, shape and defect information is collected from a set of sample logs. With this information, the model is able to generate numerous possible cutting patterns. Depending on the production requirements specified by the user, the model will select the optimal pattern from simulated output. If a change in the cutting parameter is required, the simulation can be re-run to determine how the lumber recovery or value is affected. The sawing process is simulated for an assortment of logs while the optimization routine derives the best solution from the various patterns possible for each log.

Computer based log cutting simulations were developed in the late 1960's. These models were more flexible and faster than using manual log diagrams to determine the various effects of sawing factors, such as saw kerf, on lumber yield. However, most of these simulations were specific to hardwood sawing, or specific softwood breakdowns (Lewis 1985). An early cutting optimization model developed by Cummins and Culbertson (1972) maximized log yield values from log breakdown at the Headrig. The model provided an algorithm in which alternative cutting sequences were analyzed. These patterns were based on the assumption that the log geometry was a perfect cylinder. The Best Opening Face model was designed to deal with more complex geometry. This cutting model assumed the log geometry to be that of a truncated cone with no defects. This assumption was purported to be valid because the system was developed for small diameter second growth timber, which is typically straight and contain small tight knots (Lewis 1985). This model was later expanded to include sweepy and irregular logs to help overcome the limitation of the previous log geometry (Lewis 1985). These models were

designed to maximize lumber recovery, however they were unable to take into account internal defects.

As computers and scanning technology became more advanced, they were able to deal with more complex log geometry models. Accurate three dimensional log profiles could be obtained, as well as information regarding internal defects. This resulted in greater accuracy of the sawing models and maximization of value recovery. Concurrently, advances in scanning technology for edger and trimmer machines helped to increase lumber recovery and product value, as optimized edgers could either maximize volume, or scan for quality. Advancements were also made in the model formulation of optimization procedures. Todoroki and Ronnqvist (2002) developed an optimization model using dynamic programming techniques that linked production and sawing optimization to customer demands of different products and quantities. The optimization routine was implemented in the AUTOSAW log sawing simulator. This solution resulted in fewer logs being required to satisfy customer demands. Underproduction was eliminated, and overproduction of parts was reduced with this formulation (Todoroki and Ronnqvist 2002). SAWSIM is another log sawing simulation that takes explicit consideration of shape characteristics. It was developed by HALCO Software Systems Ltd to evaluate the performance of real-time primary breakdown optimizers. It also quantifies the difference in lumber recovery and value recovery between sweep sawing and cant optimization at the secondary breakdown (Leach et al. 2003). Current scanning technology has focused on the development of X-ray computed tomography (CT) to determine the internal log structure for defects and shape irregularities (Chiorescu and Gronlund 2000). While there have been several studies to replicate sawing and breakdown optimization using CT images (Guddanti and Chang 1998), the use of CT applications in a commercial sawmill has been limited due to several technological issues that must be addressed. These include radiation safety, aperture size,

scanning speed, and durability and reliability of machines in industrial environments (Rinnhofer et al. 2003).

Process simulations have also been applied to veneer log slicing. By obtaining internal log images using CT scanning, a graphical simulator enables users to interactively veneer the log. This allowed mills to evaluate alternative slicing scenarios (Schmoldt et al. 1996). Another example is the ROMI-RIP and ROMI-CROSS process simulators. These were designed to be used in rough mills which process lumber into furniture or dimension parts. The simulator analyzes the cutting of either "rip-first", or "crosscut-first" for the manufacturing process (Stiess 1997).

2.2.2 Mill flow simulations

While a significant amount of research has focused on cutting pattern optimization simulators, less attention has been given to mill flow simulation. The simulation technique most commonly used to model the flow of a whole sawmill is discrete event simulation (DES). In DES, an internal clock and global time variable manages the system events. Time is only advanced when the next event takes place (Chung 2004). It is only at these points in time when the state of the system is updated and represented. Typical system variables that are updated include queue characteristics (number in queue, wait time in queue, etc), process characteristics (number of work in process, total entities processed, etc) and user defined variables. These updates are often represented with animation. This type of simulation is well suited not only for sawmills but for stores, restaurants, transportation centers, and other manufacturing facilities.

The development of discrete event simulation is very closely linked with the development of computing in general. Computer simulations were first developed in the 1950's but really began to grow with the development of programming languages such as FORTRAN. Higher level

programming languages specific to simulation such as GPSS and SIMULA were developed in the 1960's (Robinson 2004). Early whole-mill simulation models were programmed using these types of special purpose simulation languages, GASP II, GPSSV, and SLAM (Aune 1974; Kempthorne 1978; Wagner and Taylor 1983). These simulation languages are based on the FORTRAN programming language, and contain specific modeling constructs such as manufacturing modules, conveyors, and random number generators that allow for easier programming

Later sawmill models created by Kline et al. (1992) and Dogan et al. (1997), were developed using SIMAN/Cinema, and Arena simulation software packages. These software packages included further advancements of DES software and included the ability to develop animations for the simulation. Both of these studies designed a simulation model to analyze the process of a hardwood sawmill. The Kline et al. (1992) model was used to demonstrate the application of simulation for the mill, and how productivity can increase by changing various process controls. The Dogan et al. (1992) model was used to examine specifically how the investment decision to upgrade the trimmer bottleneck in the mill affected the whole system. Both models incorporated the use of visual animations which reduced model development time, helped identify problems and bottlenecks, and conveyed the information to mill management efficiently.

While sawmill models have increased in sophistication with the advancement in simulation software, they were all designed with the purpose of analyzing the existing system and observing and comparing the effects of changing model parameters. With this information, they were able to provide an accurate estimation on how the mill would operate if these changes were implemented. Aune (1973) developed a model that measured the effect of varying log

supply characteristics on mill productivity of an existing band-headsaw mill. Kempthorne (1978) developed a model used for planning a new small log sawmill, and for improving an existing mill. Similar to Aune, the model looked at the impact of the log mix, however it also included the impact of varying machine downtimes on the Headrig utilization. Wagner and Taylor (1983) applied sawmill simulation to analyze a southern pine sawmill. In addition to studying the effects of various input parameters on mill performance, the model was useful in evaluating the profitability of sawing logs for a stand of timber that the company was bidding on.

Kline et al. (1990) simulated a furniture roughmill to assist in making management decisions for wood products manufacturing systems. By reducing the throughput rate at the crosscut saw, and changing the material conversion efficiency parameters, the queue leading into the ripsaw was reduced by 77 percent while reducing the average cost and waste, yet increasing average production. Lin et al. (1995) modified the previous model to evaluate four alternative mill designs. Widenbeck and Araman (1995) modified the same model to analyze the productivity of processing short lumber.

Dogan et al. (1997) simulated a hardwood sawmill to determine production bottlenecks. It was discovered that the trimmer was the bottleneck of the system, and a sensitivity analysis was used to determine the optimal speed. The methodology of the study, software used, and end result, were similar to this thesis. However, the method used to breakdown logs into lumber was different. In the Dogan model, specific board information was tracked from a log by painting one end, and collected at the green chain. The relationship between log type, quantity, and quality of lumber was then determined. In this thesis, specific cut patterns used at the Headrig determine what board was cut from each log.

Reeb (2003) conducted a simulation experiment in a softwood planing mill to determine the impact of adding an extra lumber grader. It was discovered that the added revenue generated by the extra grader was $95,992 per week based on a 40 hour week.

The simulation models described above were designed from the ground up to analyze specific mills. Two programs were developed in order to provide an easy modeling environment able to simulate a wide range of possible sawmill configurations. Adams (1984) designed DESIM (DEsign SIMulator). It requires user input data for raw material, machine information, buffer systems, and material processing instructions for the mill. The same program can be used to simulate alternative mills without requiring a complete re-programming of the model. DESIM was tested against an actual mill to determine how realistically it could simulate the operations of a hardwood sawmill. While existing validation techniques were not possible to use on the DESIM system, it was demonstrated that the system could realistically simulate the operation of relatively complex hardwood sawmills.

The second model is S3, and was designed by Randhawa et al. (1994). It was created in an object-orientated environment using a database library of objects. It was discovered that this type of model allowed for a high degree of flexibility when modeling different configurations. However, it was limited due to the Actor environment in which it was developed. Actor is an object orientated programming environment based in Windows (Randhawa et al. 1994). The model was restricted by its limited sawing complexity and slow run time thereby making it unusable as a real time decision support system.

2.3 Animation and simulation.

Simple animations were often used to represent discrete event simulations. However, advancements in animation began in the 1980's due to the introduction of SEE-WHY in 1976 (Bell and O'Keefe 1987). SEE-WHY was fundamentally different from previous animations, as it is a Visual Interactive Simulation (VIS) package. VIS allows for the interaction and manipulation of a running simulation model instead of only showing the animation. Users found it to be particularly useful as they could now actively experiment in their model. It is seen as one of the most important advances to discrete event simulation since special simulation languages were developed and is now present within all current DES software packages (Bell and O'Keefe 1987).

Some recent sawmill models have been developed incorporating animation (Kline et al. 1992; Dogan et al. 1997). The animation of these simulation models used a static picture of the floor plan and walls, while objects such as logs and boards moved throughout the sawmill. Animation of the lumber throughout the mill is dependant on the entity objects (logs and boards) and resources such as headsaws and trimmers. Different pictures are used to represent various machine states such as processing, waiting for material, or if the machine is down. System variables (e.g. logs entering the mill) can also be represented as graphs or histograms during simulation runs.

DES models with animation help to pinpoint the cause of problems during model development. It can reduce the time required for the verification, and validation process. For example, the use of animation facilitated the observation of how the speed of crosscut saws contributed to the steady increase in the length of the ripsaw queues from a hardwood sawmill (Dogan et al. 1997). It also helped to convince the company to invest in that project. The use of VIS allowed clients

to understand and experiment with the sawmill model (Dogan et al. 1997). If a client is involved with the design of the model, a more robust and trusted model is often developed. The client is more confident with the results of the model, since they can see their system in action, instead of being presented with only tables and numbers.

2.4 Simulation optimization

2.4.1 Theory and software

The combination of flow simulation with optimization programs has grown rapidly in the past few years. One purpose of combining optimization with simulation is to determine the correct input variable settings that will lead to optimal performance of the simulation model, and thus the real system (April et al. 2003). The input parameters are called factors, while the output performance measures are called responses. In the case of sawmilling, input parameters would include the number of machines, machine settings, layout, and buffers, etc. Responses can include total lumber produced, cycle time, and resource utilization.

There are four classical approaches to simulation optimization. These are; stochastic approximation, response surface methodology, random search, and sample path optimization. Although these four techniques account for most of the literature in simulation optimization, none of the four methods have been used in practical applications (April et al. 2003). This is because of the high technical knowledge required from the user, and the substantial computer time required to solve the problem (Andradottir 1998). Advancements made in metaheuristics, evolutionary programming, physical and biological processes, allow for the integration of simulation and optimization (Glover et al. 1999). Almost all modern discrete event simulation packages now contain an optimization module based on these approaches.

The general approach to this type of optimization is based on a black-box function evaluator. The metaheuristic optimizer selects a set of values for the input parameters, and analyzes the response generated from the simulation. It then uses this information to make decisions on the next trial solution as shown in Figure 3.

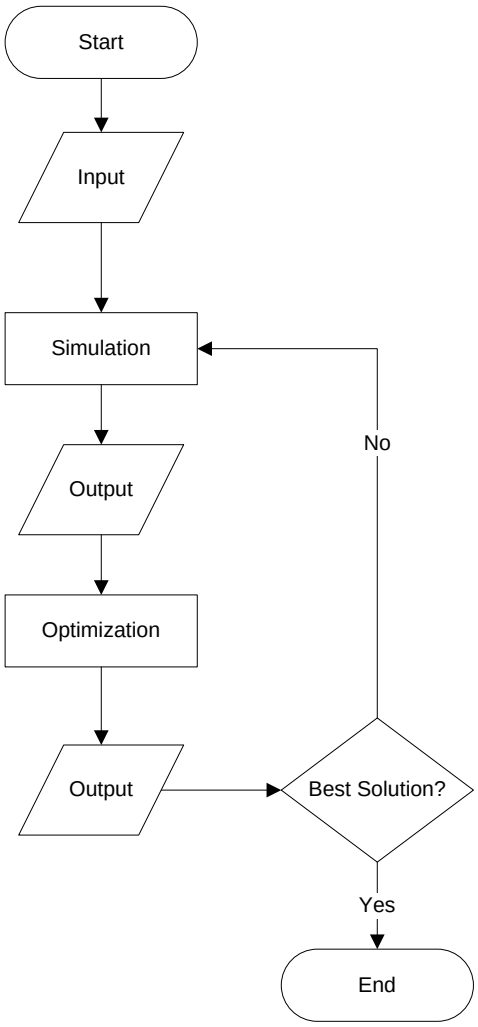

Figure 3: Coordination between optimization and simulation (Glover et al. 1999)

This process continues until a terminating criterion is reached. This is typically specified by the user based on the time devoted to the search, or until a certain accuracy is reached.

The optimization routines used in modern simulation packages are based on evolutionary approaches which search the solution space through building and evolving solution populations. Evolution occurs from combining two or more solutions from the current solution population. This allows exploring over a larger solution space with a smaller number of objective function evaluations than compared to sampling the area around a single solution (April et al. 2003). The following table lists some commercial simulation packages which use meta-heuristic optimizers.

Table 1: Commercial products with meta-heuristic optimizers(April et al. 2003)

Commercial Simulation Package	***Optimizer Used***	***Search Technology Used***
AnyLogic Arena Crystal Ball CSIM 19 Enterprise Dynamics Micro Saint ProModel Quest SimFlex SIMPROCESS SIMUL8 TERAS	OptQuest	Scatter Search
Extend @Risk AutoMod	Evolutionary Optimizer Evolver AutoStat	Generic Algorithm Generic Algorithm Evolution Strategies

2.4.2 Applications to sawmill simulation

Simulation optimization has been used to solve numerous real life problems and is most common in manufacturing environments. Optimization routines are commonly used with commercial sawing pattern simulations, however, little has been published with regards to the optimization of the entire manufacturing process of sawmills or secondary wood manufacturing mills. In one case, simulation optimization was applied to a production line from a secondary wood manufacturing plant in Chile (Baesler et al. 2002) A simulation model was developed in Arena 4.0, and was integrated with a genetic algorithm (GA) linked through VBA. Five

machines (polishing, sawing, finger joint, molder and fork lift) were selected as control variables. These were selected due to the availability of the machines that were considered critical by industry experts. Each machine had a range of feasibility to be tested, as shown in Table 2.

Table 2 : Variable number of feasible machines

Machine	Minimum Feasible Machines	Maximum Feasible Machines
Polishing	1	10
Sawing	1	4
Finger Joint	1	4
Molding	1	8
Fork Lift	1	7

Based on this, the entire solution set would require 8960 different configurations and require 31 days to run the simulation. The genetic algorithm heuristic enabled an efficient method to explore the solution space. Based on the parameters used for the GA, an optimal solution was discovered in 146 scenarios over 6.94 hours. This was found from searching only 1.6% of the solution space.

3 Description of the sawmill

The sawmill used to develop the simulation model for this thesis is located in the interior of British Columbia. It is a value added sawmill that produces about 35 million board feet of lumber per year, and is small compared to other mills in British Columbia. The mill cuts a wide variety of species including Fir and Larch, Ponderosa pine, White pine, Lodgepole pine and Hemlock. It is capable of producing a wide variety of products such as dimension lumber, boards, railway ties, and timbers used for post and beam housing in Japan.

The mill sorts their logs by species, grade, and diameter class out in the log yard. This helps to ensure a smooth flow of product through the mill, as similar products can be cut, and order tallies are easier to fill. Logs from the yard are loaded onto the log deck where they are cut to length (bucked), and sent to one of three debarkers.

Figure 4 : Log deck and circular saw bucker

After the logs have their bark removed, they are routed to one of the two primary breakdown lines. The first line, called the Headrig, is used to breakdown large logs into flitches and cants. At the Headrig, the log is loaded onto a moveable carriage. Once the log has been rotated in place by a pneumatic arm controlled by the sawyer, it is locked in place and then passes through the stationary saw. The mill under study uses a single band headsaw used to cut flitches (a rough cut board without any straight edges), and cants (a log that has at least one square face) from the log. There are numerous Headrig setups available for sawmills, and these include, dual or quad saws, however, the setup used in the study mill allowed for greater flexibility in cutting the highest value product from the log.

Figure 5 : Single band headsaw

Flitches are edged into boards at the edger, while cants require further ripping at a secondary breakdown center called the Re-Saw. The Re-Saw is used to alleviate processing capacity from

the Headrig. The study mill used a twin band Re-Saw to breakdown the cant into lumber. The edger cuts the flitch longitudinally in order to produce a parallel piece, and remove any defects.

The other primary breakdown line in the mill is called the chipper canter, and is used to breakdown small logs into lumber. As logs enter the chipper canter they are first scanned, and then pass through a chipper machine that will cut the log into a cant. From there, the cant passes through a set of vertically aligned saws that cut out boards. Once the boards are cut, they are sent to their own edger to remove any waney edges and defects to create parallel edges.

Once the boards from the Headrig area and the chipper canter area have been edged, they are grouped together in a buffer area to await end trimming. The boards are manually loaded onto a conveyor leading into the end trimmer. The trimmer is used to cut off any end defects and square the board into a specific length. Once the pieces leave the trimmer they are sent to the green chain where they are collected, sorted, and stacked by hand.

Figure 6 : Drop sort and stacking

Once a pallet of lumber is full it is moved to the dry kilns, where the lumber is dried to a specific moisture content. After this, the lumber is planed, packaged, and shipped. Section 5.1 provides a detailed description of the mill layout and flow of boards throughout the mill. The model developed for this thesis does not include the drying and planing processes.

4 Methods

The framework proposed by Law (2003) was used to design the simulation model in order to conduct an analysis of the mill process flow. This general framework shown in Figure 7 is typically described and recommended in simulation textbooks (McLean and Shao 2003).

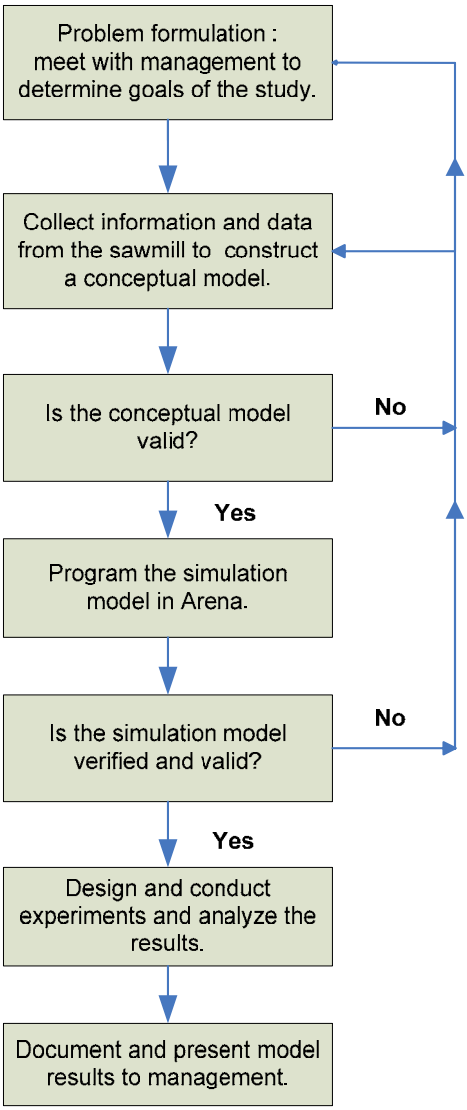

Figure 7: Seven step approach to simulation studies (adapted from Law 2003)

4.1 Problem formulation

To determine the goals of the project, an initial meeting was held with the members of the client sawmill. This initial meeting is an important first step as it establishes the problem and determines the appropriate level of detail required (Law 2003; Chung 2004).

Discrete event simulation was selected as the preferred tool for analysis because it is ideally suited for manufacturing systems and is able to describe the complex interactions that exist within the sawmill. Modern simulation packages include useful modeling tools that allow for the easy programming of processing units and conveyor systems. A simulation package also enables the programmer to develop animations of the sawmill in action.

The simulation package I used to develop the model was Arena 8.0 from Rockwell Software. This package was selected for the following reasons:

- A good balance between modeling flexibility and predefined model constructs
- Easy to learn Graphical User Interface (GUI)
- The ability to animate the simulation model
- Availability and knowledge of the simulation package

4.2 Data collection

Robinson (2004) identifies three different types of data that need to be collected during the model development phase of the simulation study. These consist of preliminary or contextual data, data for model realization, and data for model validation.

Preliminary data is required to gain an understanding on how the mill is set up and how it operates. The data I collected for this thesis consists of :

- Plant layout
- Material flow
- Pattern breakdown for canter, Headrig, and Re-Saw

The plant layout was obtained from an AutoCAD drawing of the mill. It was important to ensure that this drawing was up to date, since it provides the basic layout of a simulation model with animation. The layout identifies where the machines, conveyors and buffers are located, and how they are connected.

Log breakdown pattern information was gathered through observations and conversations with the head sawyer, quality control supervisor, and production manager. The use of multiple sources ensured the accuracy of this data (Law 2003).

Model realization data is data required to drive the computer simulation. It elaborates on the preliminary data collected, by providing specific information relating to the manufacturing process.

The model realization data collected consists of:

- Machine set up and processing times
- Machine and plant downtimes
- Conveyor lengths and speeds
- Buffer capacities
- Log lengths
- Small end diameters
- Large end diameters

Machine process times were collected from information provided by the millwrights and checked with the production manager. A time and motion study was conducted on machines that had variable piece-align times or production times required a time and motion study. The information collected from the study was used to determine an appropriate mathematical

distribution to represent these processes in the simulation model. Machines that required time and motion studies were:

- Headrig
- Re-saw
- Canter
- BAE Edger

An example of time study elements collected for the Headrig are shown in Table 3.

Table 3 : Headrig time study elements

	Event	Time Start	Time Stop
1	Load log onto carriage	Log is kicked onto carriage	Dogs bite into log
2	Regular cut	Carriage in cut start position	Carriage returns to start position
3	Cut with log rotation	Carriage in cut start position	Dogs bite into log
4	Drop out cant	Carriage in cut start position	Log is kicked onto carriage

Processing times were recorded for each event for the various log sizes and species that were observed at the head saw. Conveyor speeds were measured, and buffer capacities were estimated by the production manager. Some of the downtime data could be collected from the mill database, however short downtimes were sometimes not recorded by machine operators and therefore were collected using a time study. The uptimes and downtimes were measured for half of a day at the trimmer, a key machine in the process. Log parameter data (length, diameter) was collected from data reports generated from the canter line, and the Headrig line.

4.3 Conceptual model

A conceptual model was developed based on the key decisions and processes that will affect mill flow and on the data collected. The conceptual model forms the initial structure for the simulation model. The data collected was compiled and verified by the production manager. A simplified flowchart of the conceptual model is shown in Figure 8. It should be noted that there are no formal methods or procedures for developing conceptual models. As a result, it is one of the most difficult steps in developing a simulation model, often described as an art rather than a science (Robinson 2004).

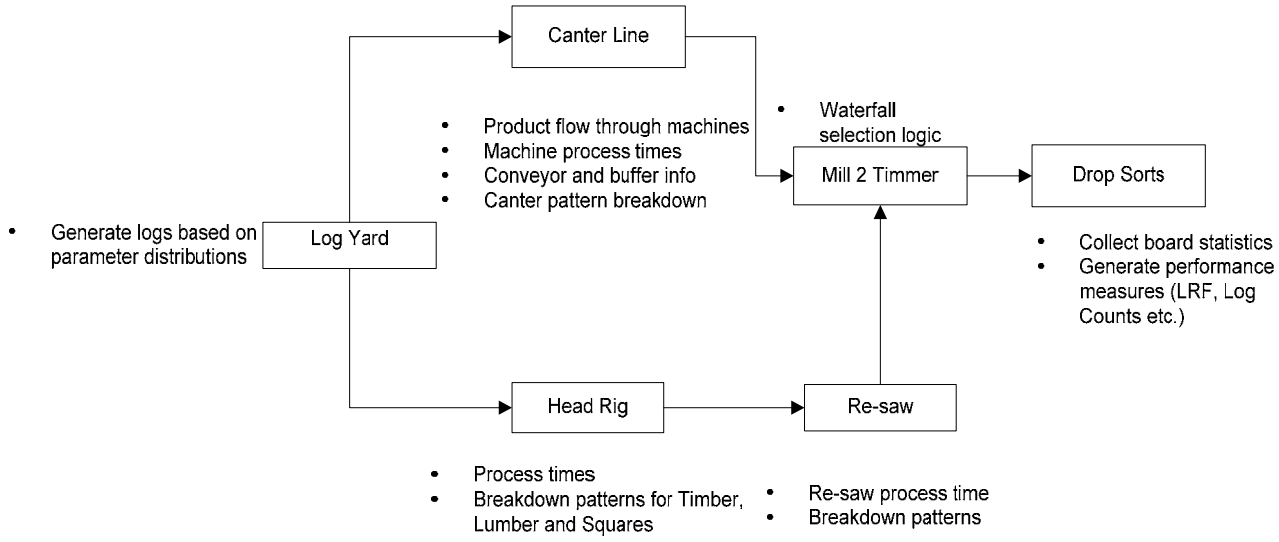

Figure 8 : Simplified conceptual model

4.4 Probability distribution generation

Variability of log parameters, machines process/align times, and downtimes were recorded from time and motion studies as described in section *4.2*. Incorporating this variability into the simulation model required generating probability distributions. This was achieved by fitting input distributions with Input Analyzer, a program that is packaged with the Arena software. The Input Analyzer generates mathematical distributions from collected data.

In analyzing the collected data, the program estimates the distribution parameters and provides three measures for fit. These are the mean square error, chi-square goodness of fit test, and Kolmogorov-Smirnov (KS) goodness of fit test. Theoretical distributions are ranked based on the lowest mean square error. In order to asses the fit of the theoretical distribution, the Input Analyzer provides a corresponding p-value for the chi-square and KS test. A p-value less than 0.05 indicates a poor fit of the distribution (Kelton et al. 1998). A screenshot of the output provided from the Input Analyzer is shown in Figure 9.

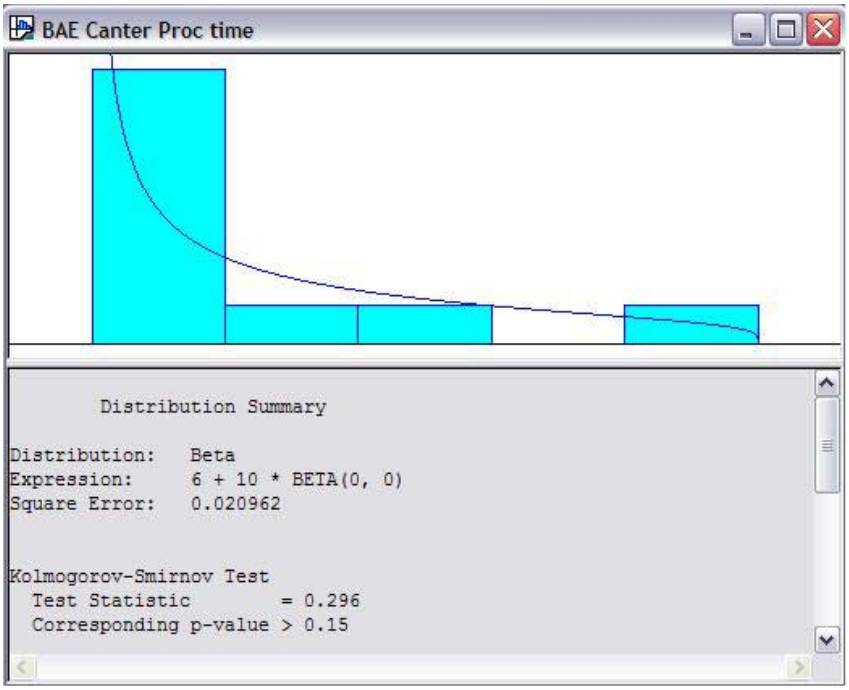

Figure 9 : Input Analyzer screenshot

This distribution with the best fit selected by the input analyzer was used in the simulation model.

4.5 Model programming

The model was programmed using Arena 8.0 from Rockwell Software. It was developed in the following steps:

1. Developed the basic flow of products throughout the mill.
    - Connected machine centers and conveyors
    - Entered conveyor speeds and lengths
    - Placed initial dummy information for machine process times and product breakdowns
    - Concurrently develop the animation of the mill flow

2. Used the Arena Input Analyzer to generate distributions for the machine process times and log parameters.
    - This information was then added into the model in place of the initial dummy variables

3. Created sub-models for the detailed logic required.
    - Programmed log breakdown logic used at the Headrig, for lumber, timber products, and Japanese square products
    - Programmed log breakdown logic used at the canter
    - Programmed breakdown logic required at Re-Saw for the cants from Headrig
    - Programmed the logic used to determine how boards enter the trimmer

4. Connected the sub-models to the main model.

5. Created statistical counters for board counts, logs processed, and other key indicators.

4.6 Model verification and validation

Throughout the programming stage the model was continuously tested for verification. Model verification is defined as "*ensuring that the computer program of the computerized model and its implementation are correct*" (Sargent 2003). Model validation is defined as "*substantiation that a computerized model within its domain of applicability posses a satisfactory range of accuracy consistent with the intended application of the model*" (Schlesinger 1979). The model is considered valid if the entire simulation model provides an accurate representation of the system for the particular objectives of the study (Law and Kelton 2000).

The following tests used to validate the model are described in detail in Section 6. They consist of both face validation tests, and statistical validation tests. Face validation tests compares the output of the simulation model to determine if it realistically compares to the output of the system. Statistical validation compares both model and system output by using a statistical test. The following tests were used to compare the model to the real system.

Face Validity Tests:

1. Comparison of daily board output between simulation and actual sawmill

This test was performed in conjunction with the mill management. The simulation output was analyzed by the mill management to determine if it represented the production observed in the mill.

2. Comparison of lumber recovery values at Headrig between mill estimates and model output.

Thirty simulation replications were conducted for each product and species type (Fir lumber, White Pine lumber, Lodgepole Pine lumber, timbers, and Japanese squares, cut at the Headrig. The recovery values from the model replications were compared to those estimated by the mill manager.

3. Comparison of piece counts from the canter between the simulation model and reports generated from the canter.

Two daily production reports from the canter were compared with the simulation model only running the canter. The model was setup to replicate the daily production as indicated from the report. This was based on the number of logs processed in that shift, and the ratio of patterns used. The simulation was run for 30 replications and the average, maximum, and minimum values were compared against the mill report.

Statistical Test:

1. Comparison of logs processed/minute for canter and Headrig between mill and model.

Using production reports generated from both the Headrig and canter, the average logs processed per minute from the shift was established. This was collected for 25 shifts from the Headrig and 30 shifts from the canter. Four different simulations (based on species and

product) were run for 10 replications at the Headrig. Two different simulations (based on different species) were run for 15 replications at the canter. The average logs processed per shift was compared for both the Headrig and canter data sets between the mill reports and simulation. In order to compare the data, they were first tested for normality. Since not all the data sets were normal, a non-parametric test was required (Chung 2004). A Wilcox rank sum test was used to compare the data sets.

4.7 Scenario analysis

After conducting several initial simulation runs, the sawmill bottlenecks could be observed from the animations developed in the simulation model. The bottlenecks observed in the simulation were consistent with the bottlenecks observed in the mill. Once this was established, alternative production scenarios were tested to determine the impact it would have on the system. Five different scenarios were analyzed, including the base case. Alternative production parameters were based on improvements that could be made in the mill. These included production scenarios with existing equipment (increasing production speeds within the machine capacity, reducing observed downtime), as well as the impact of a theoretical machine that could run at speeds twice that of the current bottleneck. Comparisons between the alternative production scenarios were tested using the Welch Confidence interval method (Chung 2004). Results of the scenario analysis were used to provide recommendations for the company.

A further analysis was conducted using OptQuest for Arena. OptQuest is a built in simulation optimizer that uses a scatter search meta-heuristic to derive a “best” solution. Instead of using limited educated estimates for the alternative production scenarios, OptQuest was used to analyze the impact of the system for the whole range of machine speed settings. Details of the OptQuest analysis is found in section 7.5. The optimization program was set up to maximize the total board outputs of the system. Production parameters were equal to the speed of the

machine creating the bottleneck. OptQuest could change these speed settings from a given minimum (base case production speed) to a maximum setting (double base case speed), by an integer value with a minimum step value of 1. This was subject to a system constraint that stated that the utilization of the trimmer operator could not dip below 80%.

5 Conceptual model

The following section describes the conceptual model used for developing the sawmill simulation in Arena 8.0. It describes the layout of the mill and the flow of materials, breakdown logic required at the Headrig, canter and Re-Saw, and model parameters and characteristics.

5.1 Mill layout and flow of material

The flow of material throughout the sawmill is based on a series of interconnecting conveyors, machines, and buffers. Conveyors are used for moving the work pieces throughout the mill to each machine center. The buffers are areas where the pieces from different conveyor lines merge. All three components have parameters such as machine processing speeds, conveyor speeds, and buffer capacity.

A scaled AutoCAD drawing of the existing mill layout was imported into the Arena program. This was used as the foundation on which the simulation animations were based. The conveyor lengths were determined from the AutoCAD drawing, while the speeds were measured during mill operation.

In order to simplify designing and programming the simulation, the plant was subdivided into four main areas Canter, Headrig, Re-Saw, and Trimmer Drop Sort, as shown in Figure 10. The mill is divided into two processing lines; the Headrig line and the canter line. These lines are combined at the Trimmer Drop Sort area. The Headrig line was referred to as “Mill 1”, and the canter line was referred to as “Mill 2”. Some of the machine names still maintain the nomenclature of where the machine is located, for example the mill 1 trim sort.

The log bucking and de-barking process was not simulated in the mill. At this processing center, the log-bucking operator cuts the logs from the log yard into process lengths ranging from 6 feet to 20 feet in 2 foot increments. The bucked logs are either kicked to the small log debarker or the ring debarker which is used only for larger logs. After debarking at the small log debarker, the logs are held on the canter log deck, while the logs debarked on the ring debarker are held on the Headrig log deck. Based on discussions with mill personnel, and the debarker operator, it was assumed that there were no issues supplying logs to both the canter and Headrig log decks, and therefore this process was not simulated.

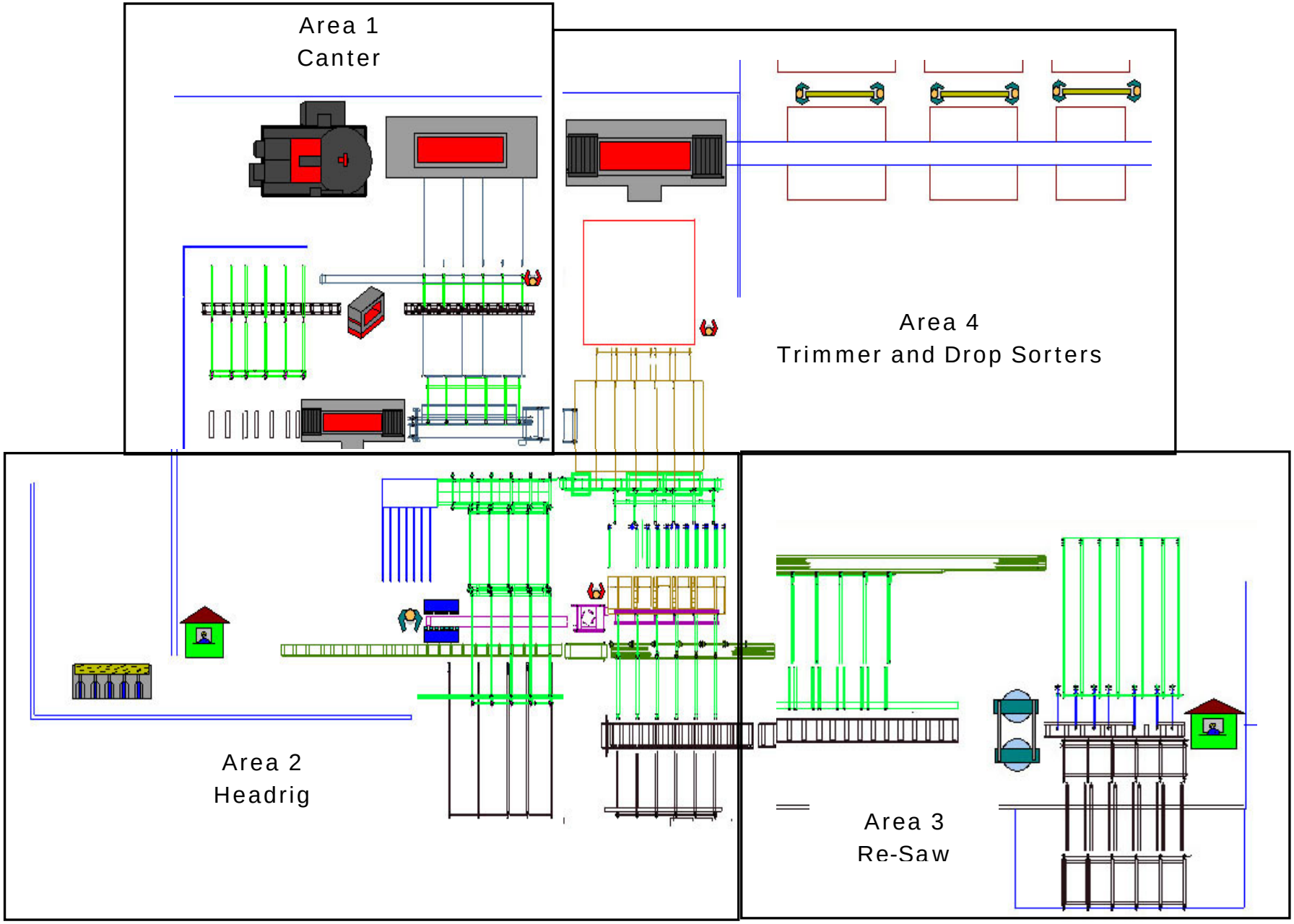

Figure 10: Subdivided plant layout diagram

5.1.1 Area 1 - canter Flow

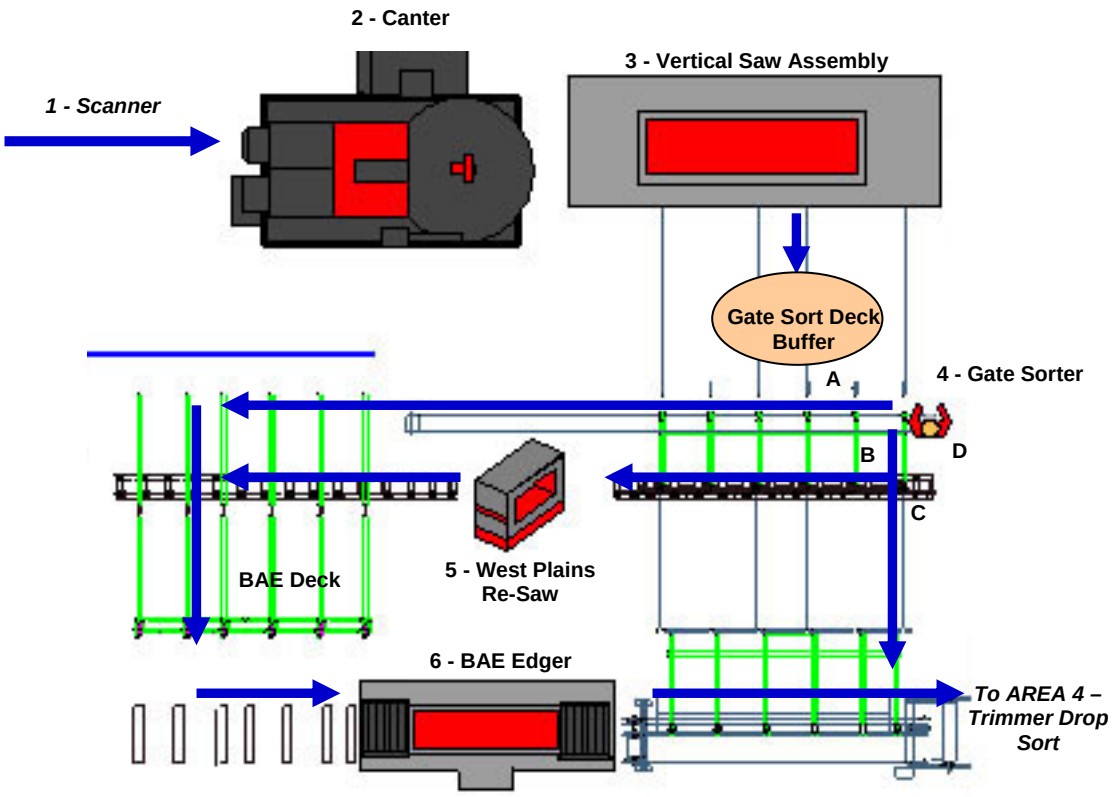

Figure 11: Canter flow diagram

The canter line is used to process small logs in order to free up production at the Headrig. It is sometimes run at various times throughout the shift, exclusively for an entire shift, or sometimes not at all. The canter line is used to process small diameter logs, usually up to a maximum of 10 or 11 inches in diameter. Referring to Figure 11, the flow of material is as follows:

1. Scanner

After logs are kicked off the log deck, they move along a conveyor and are scanned by a single axis light scanner. This scanner determines the log length and diameter. The

scanner is only able to accurately scan logs up to 16 ft in length. If a log is longer than 16 ft, the computer estimates the log diameters for that section.

2. Canter

Once the logs are scanned, the machine operator is presented with up to two possible patterns. A graphical picture of the pattern is displayed on a computer screen. The pattern shows the operator what products the optimization software estimates can be processed from the log. A detailed description of the scanning and canter process is given in section 5.1.2 and 5.1.3. Based on this, the operator will make a decision on which pattern should be used. The log passes into the canter and chipping heads chip the log down into a cant.

3. Vertical Saw Assembly

The cant then passes into the Vertical Saw Assembly (VSA). In this machine, a bank of saws are vertically aligned. They shift automatically to cut out the boards indicated by the sawing pattern selected by the operator. If the log has a large enough diameter, top boards will be cut out at the VSA, while the bottom will remain as a cant. This can be seen in Figure 13 under the 8.2 – 8.5 diameter pattern. After the VSA, both boards and cants pile up into the Gate Sort Deck Buffer. This buffer has an estimated capacity of 1000 board feet.

4. Gate Sorter

Boards and cants arriving to the Gate Sorter can be routed to four different conveyors. The percentage of boards and cants routed to each area was measured over a period of several hours during mill operation. Boards and cants are sent to the following areas:

A) Boards and cants go directly to the Bottom Arbor Edger (BAE) edger and bypass the West Plains Re-Saw.
B) Boards pass through the West Plains Re-Saw and then merge back to be processed by the BAE edger.
C) Boards that do not require any further edging bypass the BAE edger, and are sent directly to Area 4 – Trimmer Drop Sort.
D) Cants are dropped out of the system to be processed at the Re-Saw in Area 3.

5. West Plains Re-Saw

Some boards require processing through the West Plains Re-Saw as indicated above. Boards that are sent through the Re-Saw are often piled up in front of the machine. If the Gate Sort Deck is not very full, the Gate Sort Operator will use this opportunity to feed in any pieces to the West Plains Re-Saw. In order to simplify the simulation, it is assumed that any boards routed to the Re-Saw will be processed right away. After boards are cut at the Re-Saw, they are fed back onto the BAE deck.

6. BAE Edger

Both boards and cants are processed at the BAE edger. The cants aRe-Sawn up into individual boards in one pass. Boards, on the other hand, are aligned using laser lines

prior to entering the edger. Different process times and align times are used for boards and cants.

5.1.2 Canter log breakdown logic

The canter uses a scanning and cutting optimization program supplied by HALCO software systems called SETGEN. The program generates a list of cutting patterns based on each log class of length, taper and small end diameter. This results in a total of 3,402 possible cut patterns. This information is then stored in a set-table. The mill uses numerous set tables for the canter depending on species, products, wane allowances, market conditions etc. Some set tables are generated for a one time order, while others are repeatedly used. When a log enters the system it is scanned by a single axis light scanner. Based on that information, the control system looks up the corresponding pattern from the set-table. The control system implemented in the mill returns the pattern for either one or two set-tables. The canter operator must then decide which pattern should be cut.

Since there were 3,402 patterns per set-table, and the mill used numerous set-tables including several that were generated for only a one-time purpose, it was impossible to develop the simulation logic to accurately model this for all combinations. Consequently, simplifying assumptions were required in order to make the model development feasible. Working with the production manager the most commonly used set tables were selected and grouped into three main categories. These were called “dimension”, “dimension 1 inch”, and “straight 1 inch”. The dimension group targets 2x4, 2x6, 2x8 lumber, however, on some patterns one inch product is cut. The straight 1 inch group targets

1inch boards, while the dimension 1 inch group is a mix of both dimension and straight 1 inch. Figure 12 shows the different patterns for each of these groups for their maximum small end diameter class.

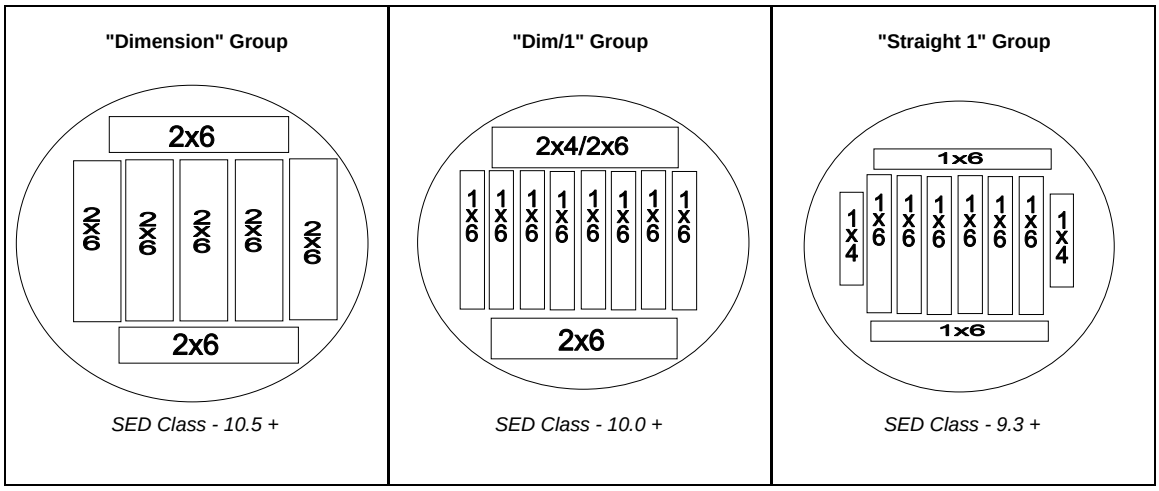

Figure 12: Pattern differences between the 3 set-table groups.

To reduce the possible patterns available for the set-table, all 3,402 patterns were viewed to determine the small end diameter (SED) class when a new board could be cut from the pattern. This SED diameter class was then subdivided into two selection ranges. One range is for “Regular” patterns, while the other column is for “Large” patterns. Regular patterns are for logs with a length less than or equal to 14 feet and a taper greater than or equal to 0.13 inches/ft. The Large pattern is for logs with a length of greater than 14 feet or a taper greater than 0.13 inches/ft.

Figure 13 further elaborates on the patterns used for the “dimension” group by showing the first six out of ten diameter ranges for both the Regular and Large pattern. The other four small end diameter ranges are from 8.5 - 9.1, 9.1 -9.7, 9.7 - 10.5 and 10.5 and above.

There are a total of nine patterns for the six diameter ranges shown in Figure 13. Not every diameter range will have a Large pattern associated with it.

From the diagram, the smallest possible log pattern is at an SED range of 4 – 4.2, which produces either one board with the Regular pattern or two boards with the Large pattern. If the log is longer than 14 feet, then two 2x4's will be produced. If the log is less than 14 feet but the taper is greater than 0.13 inches/ft, a 1x4 and 2x4 will be produced. This procedure was conducted for all three set-table groups.

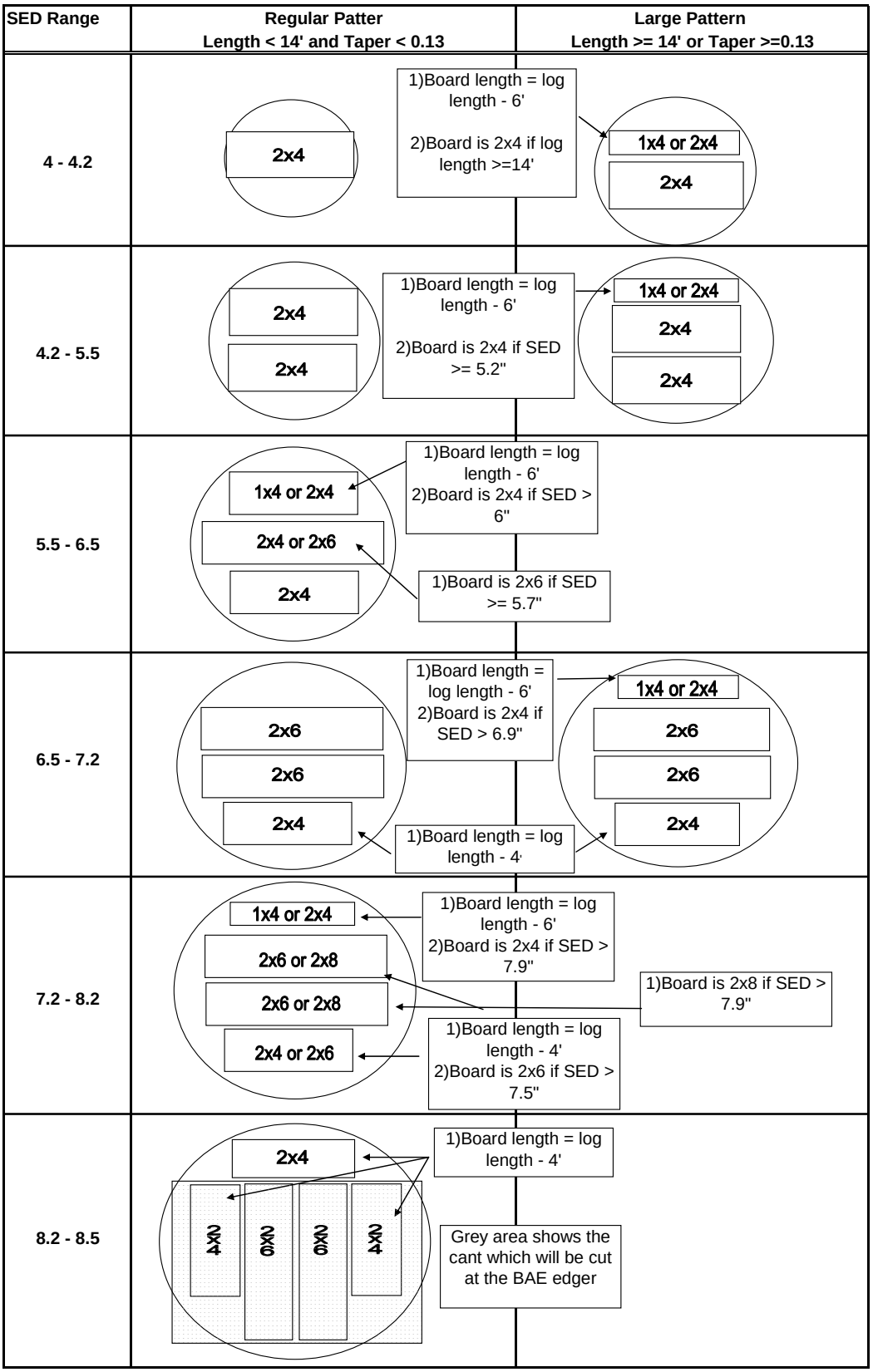

Figure 13: Selection of canter dimension cutting patterns

Under the dimension group there are a total of 10 SED ranges, and 16 patterns. The dimension 1 inch mix group also has 10 SED ranges, but with 14 patterns. The straight 1 inch group has 11 SED ranges and 19 patterns.

Prior to running the simulation, the user must select which pattern groups will be cut at the canter. A certain percentage of the logs can be cut for one grouping, while another percentage can be set to cut another group. For example, the user could set the canter to cut 54% of the logs with the dimension pattern, and the remaining 46% of the logs to be cut as straight 1 inch.

As indicated in Section 5.1.1 both boards and cants are produced at the canter. Cants that are processed at the BAE, (or dropped out to Area 3 - Re-Saw) are produced when a log has a large enough small end diameter. In the case of the dimension group, this small end diameter starts at 8.2 inches. This is shown by the shaded area of the pattern at the bottom of Figure 13. This cant will then be further broken down into the four corresponding boards at the BAE edger.

5.1.3 Canter logic

This section shows the framework of the logic used for developing the simulation at the canter section. This is similar to pseudo code used when developing computer code. The logic diagrams in Figure 14 and Figure 15 show the framework of logic used to develop the canter area.

Area 1 - Canter

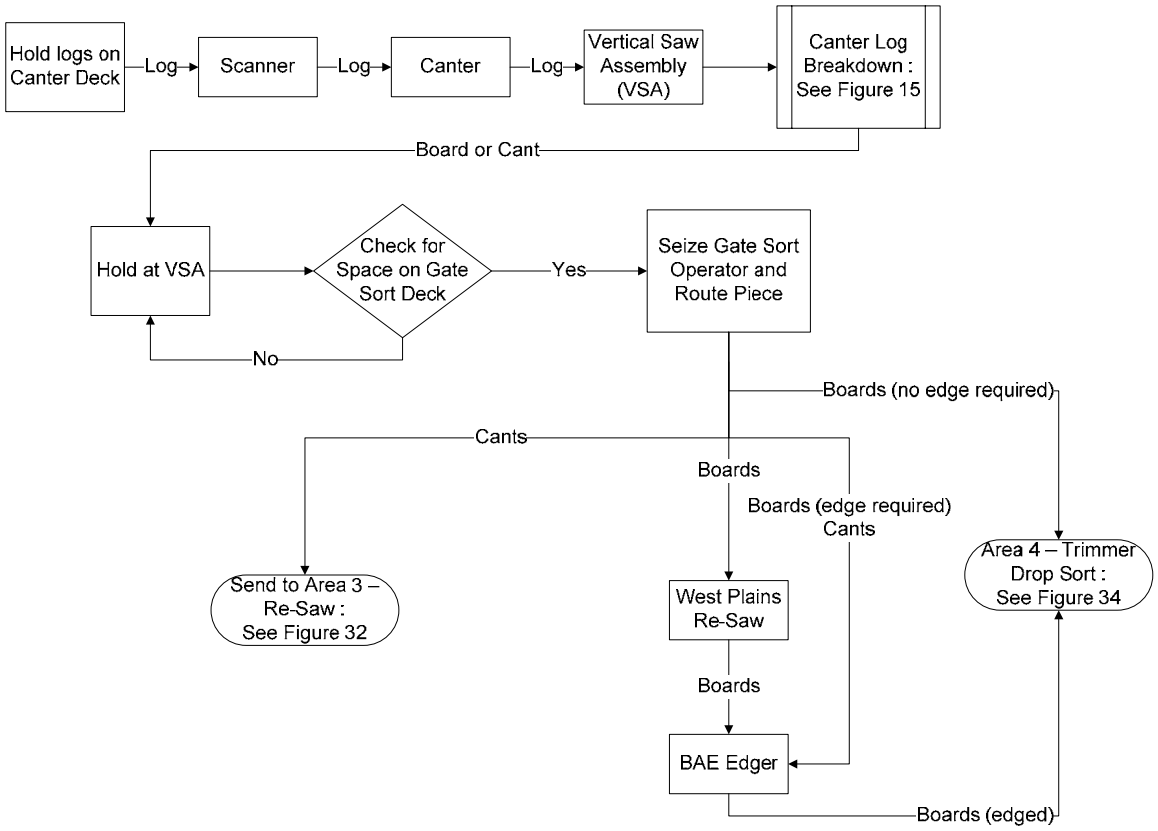

Figure 14: Canter process logic

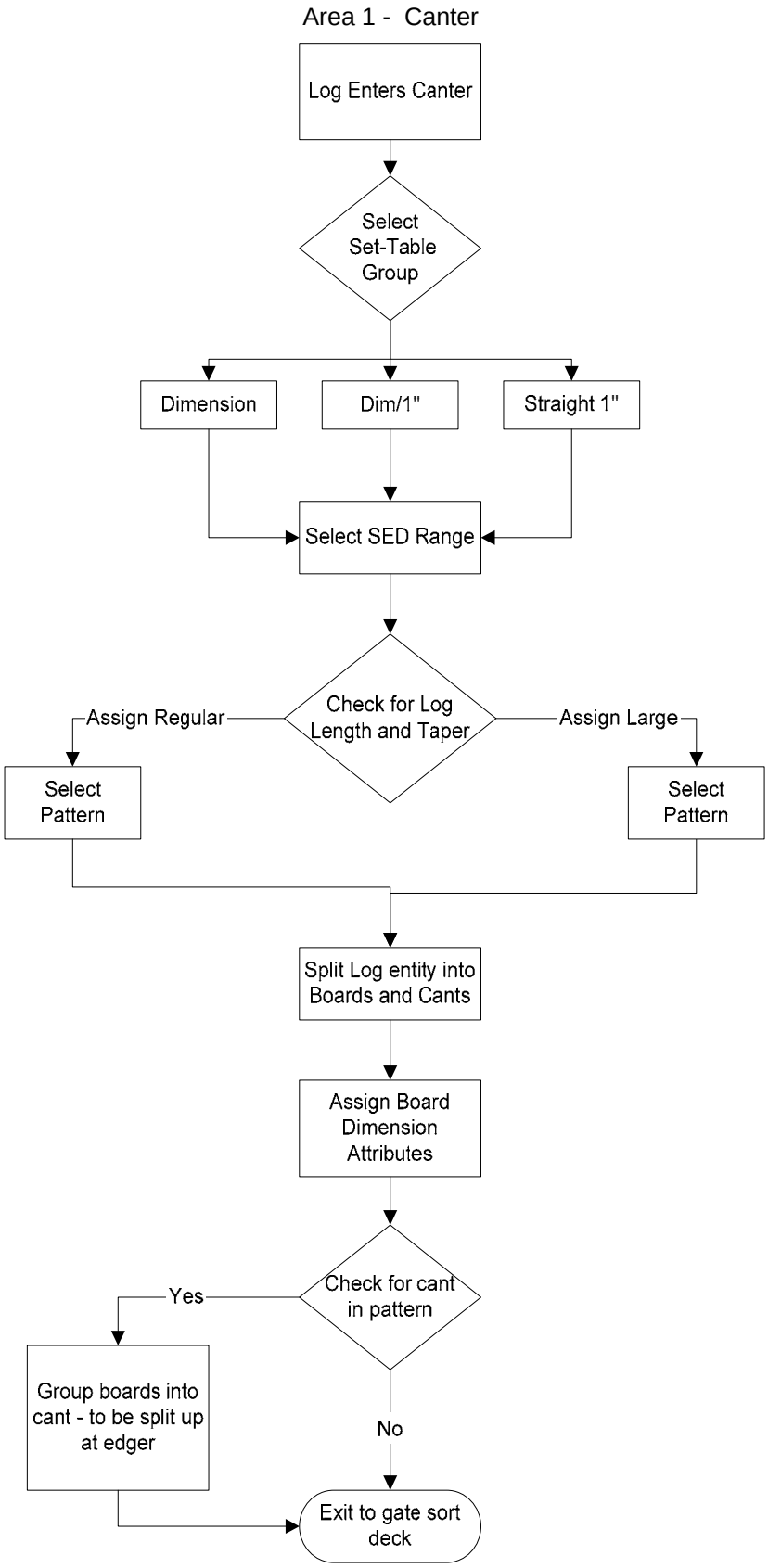

Figure 15: Canter breakdown logic

5.1.4 Area 2 - Headrig flow

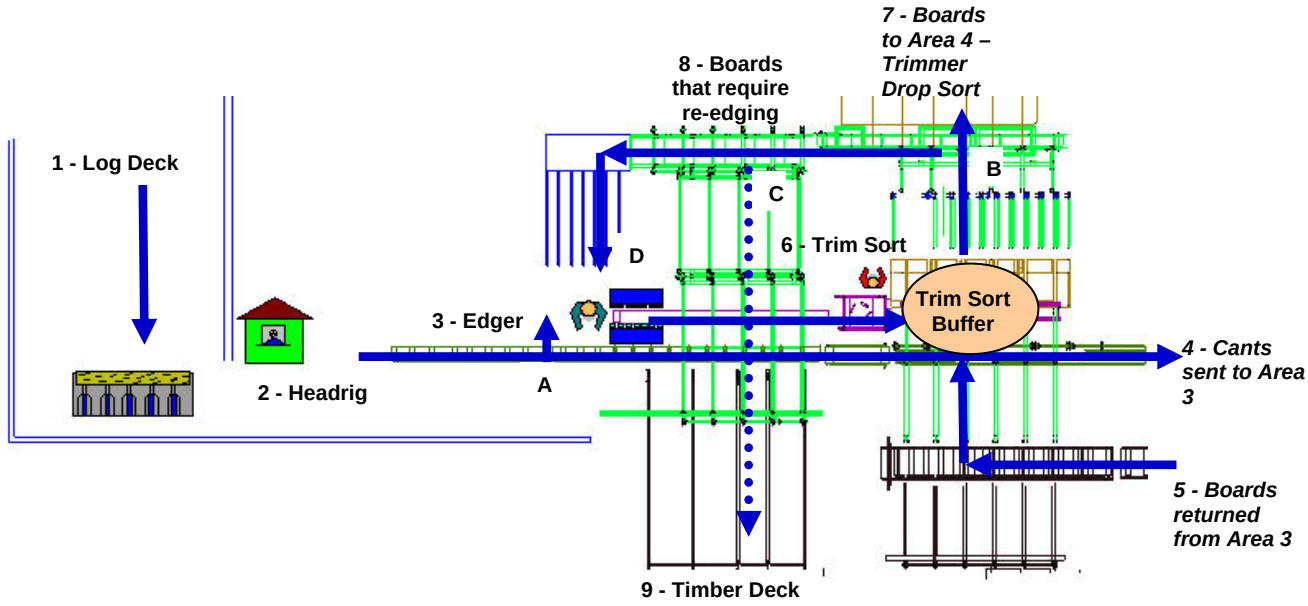

Figure 16: Headrig flow diagram

The Headrig is used to process logs with a minimum small end diameter of 10 inches. It is capable of processing logs over 35 inches, although those are rare. Referring to Figure 16, the flow of material through Area 2 is as follows:

1. Log Deck

Logs are stored on the log deck after being debarked. The log deck for the Headrig is much smaller than the log deck used at the canter, and it is only about 10 feet in length. As soon as the Headrig carriage is ready, a log is kicked off the deck and set on the carriage.

2. Headrig

The Headrig consists of a single band head saw that saws off flitches on the forward pass. Log information is obtained by a computer setworks program. This program is able to

determine the log length and diameter. The sawyer has full control over how the log is sawn. The log breakdown on the Headrig is a complex manual process, and changes depending on the grade of wood observed within the log. In order to reduce this complexity, four main breakdown patterns were considered. These are:

- Lumber
- Free of Heart Timbers
- Box Heart Timbers
- Japanese Squares

Detailed information regarding log breakdown patterns are described in section 5.1.5.

The log on the Headrig is sawn into a cant. The cant will have either 2, 3, or 4 sawn faces as shown in Figure 17. The operator's decision to cut a cant with 2, 3, or 4 faces is based on the type of pattern being processed, and the capacity of the infeed deck at the Re-saw in Area 3. It was assumed that if the queue leading into the Re-Saw is less than 20% full, the Headrig will cut a 2 face cant. If the queue is between 20% and 80% full, a 3 face cant will be cut. If the queue is over 80% a 4 face cant will be cut. This is done in order to regulate the cants sent to the Re-Saw. If only 2 face cants were sent to the Re-Saw, this area would quickly become a bottleneck as all the processing is required by the Re-Saw. If only 4 face cants were processed, the Headrig would become a bottleneck, and the Re-Saw would be always waiting for cants to process.

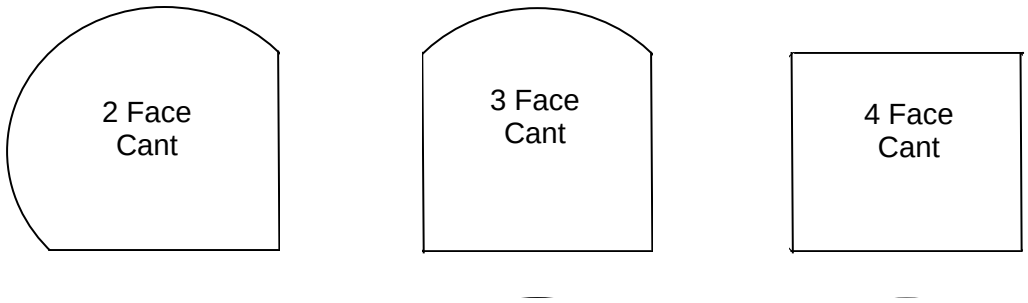

Figure 17: Cant types sent to Area 3 - Re-Saw

Cants from the Headrig are sent to directly on the conveyor to the Re-Saw in Area 3 (see 4, in Figure 16) and the flitches cut off on each pass are sent to the edger (see A, in Figure 16).

3. Edger

Flitches coming off the Headrig are moved off the main conveyor at point A. This is controlled by the edger operator. There is a small buffer capacity of about 3 flitches available. The flitches are fed manually into the edger machine, where the wane is removed to produce boards. More details on the logic used to calculate the boards produced at the edger is described in Section 5.1.6 After leaving the edger, the boards are then moved to the Trim Sort Buffer.

4. Cants sent to Re-Saw

As indicated in the Headrig section, cants are produced from the Headrig and set to Area 3 for further processing into boards by the Re-Saw. A twin band Re-Saw is used in the mill. In each pass, either one or both of the saws can be used to saw the cant. The Re-Saw is a circular system, whereby boards cut from the cant exit the system, while the

remaining cant is returned to the Re-Saw until all boards are cut from the cant. A detailed description of the Re-Saw process is described in Section 5.1.7.

5. Boards from the Re-Saw

Boards sawn from the cants processed at the Re-Saw exit from the merry-go-round loop. These boards are then transported to the Trim Sort Buffer.

6. Trim Sort

The Trim Sort is used primarily as a sorting station for boards coming from the edger and the Re-Saw, however sometimes boards are cut in two, or end defects are trimmed here. For the purpose of the simulation, it was assumed to only be a sorting station . The buffer is estimated to have a capacity of 1500 board feet as recommended by the production manager. There are three possible choices for the operator to route boards and timbers. Referring to Figure 16, boards that only require end trimming exit the area at point 7. Boards that require re-edging are returned to the Mill 1 Edger at point D. These boards will form into a queue that is 6 feet in length. When the edger operator is not busy with flitches from the Headrig, he will feed these boards into the edger machine. Timbers are moved to the Timber Deck at point C.

5.1.5 Headrig breakdown logic

The simulation selects a pattern to cut based on input from the user prior to the run. White Pine and Logdepole pine species are only set to cut lumber, while Fir/Larch can cut any of the 4 patterns (Lumber, Free of Heart Timber, Box Heart Timber, and Japanese

Squares). When a pattern is selected, the simulation first tries to fit the largest cant possible based on the small end diameter of the log. This cant size is indicated by the box in Figure 18. If the pattern is set for Timbers, the simulation will select the timber size with the highest priority to be cut first. This is also defined by the operator prior to running the simulation. Once the largest cant is fit into the log, the slab total is determined. The simulation program is set up to select two types of board thicknesses, which equal the thickness of the flitch. One thickness will have a higher priority over the other, which is defined by the user prior to the simulation run. The highest priority board thicknesses will be fitted first. The program will then check the Top Face Width. If the Top Face Width is larger than the minimum board width, then that choice will remain. If not, the second priority board will be selected and the Top Face Width rechecked. The program will continue to try to fit flitches until the Top Face Width is less than the minimum board width. If no boards can be fit, the slab total is set to be a slab, cut off, and disposed of as waste. The program considers the thickness of the saw blade when calculating the flitches to be cut.

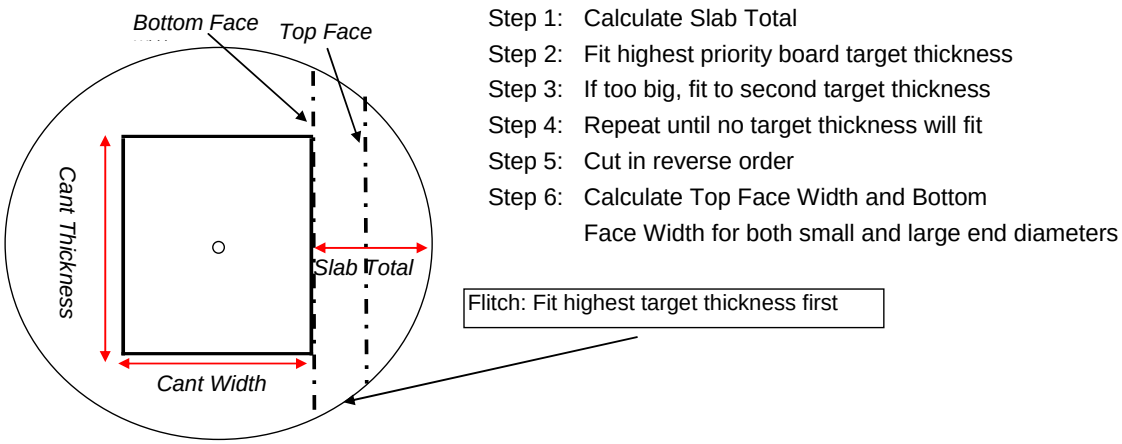

Figure 18: Flitch fitting process for all lumber patterns

The Headrig makes one cut in each pass. The logs are cut in order of the log face as indicated by the numbers in Figure 19. The cutting procedure for the Lumber and Box Heart Patterns are similar. The cutting procedure begins at face 1 and is cut in order to face 4. At least two faces will be cut, however it is possible for the Headrig to cut all products from the log. This is called free cutting, and is only performed when the Re-Saw is inoperable. Typically, the Headrig will cut two or three faces. The Free of Heart Timbers and Japanese square patterns are slightly different. This cutting procedure begins at face 1, however the second cut is rotated 180^0 to cut face 3. This is followed by rotating to face 2. The face 4 is never cut unless the sawyer is free cutting.

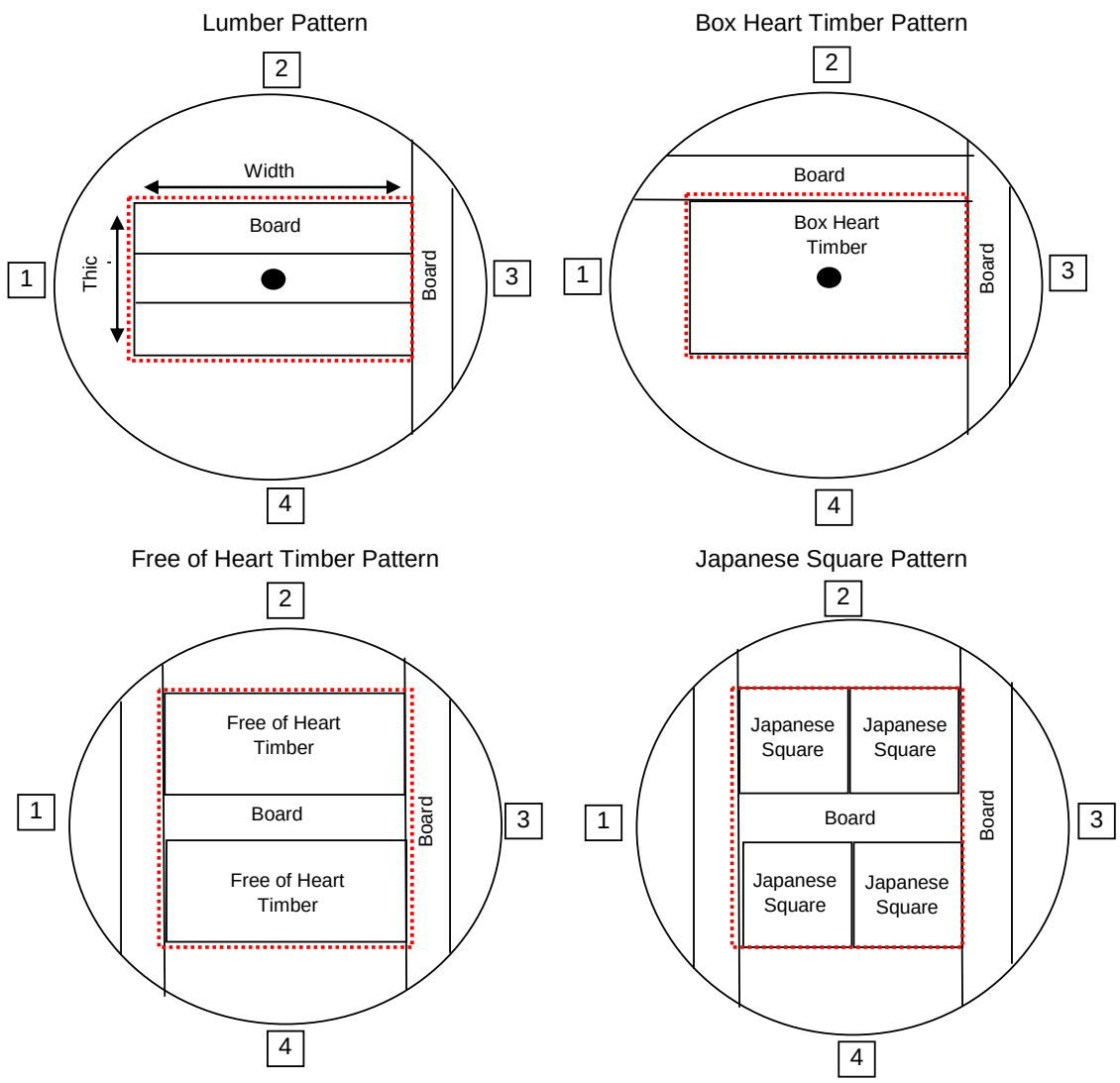

Figure 19: Headrig breakdown patterns

The Lumber Recovery Factor (LRF) was used to measure the amount of lumber cut from each log. It is calculated as the amount of lumber produced in thousand board feet divided by the volume of logs processed in cubic meters. An important assumption used in the log breakdown logic is that logs are defined as a truncated cones. This assumption does not take into consideration the true shape of the log, which might contain sweep, flare, or other irregularities common in logs. It also does not take into consideration any internal defects. As a result, the simulated LRF will be above the actual LRF. This

assumption of truncated cone log shape was required because of the lack of shape and defect data available from the mill. This following flow diagram shows the logic used to describe the log breakdown. The specific breakdown patterns are described above in section 5.1.5.

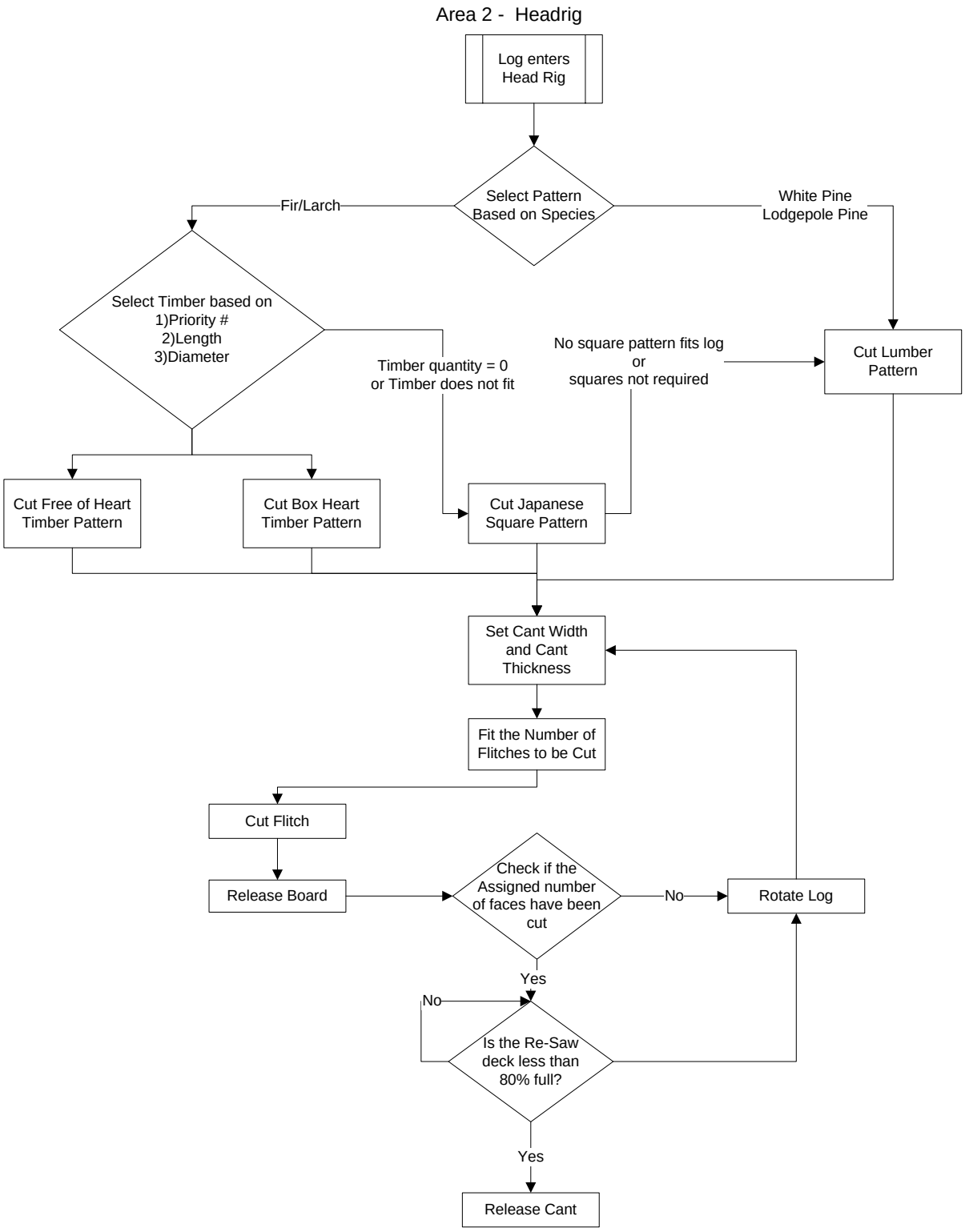

Figure 20: Process logic at the Headrig

5.1.6 Edger breakdown patterns

The edger process logic converts flitches into boards. The user can select the simulation to process two different flitch types: taper cut boards, or regular cut boards. The difference between these two is shown in Figure 21.

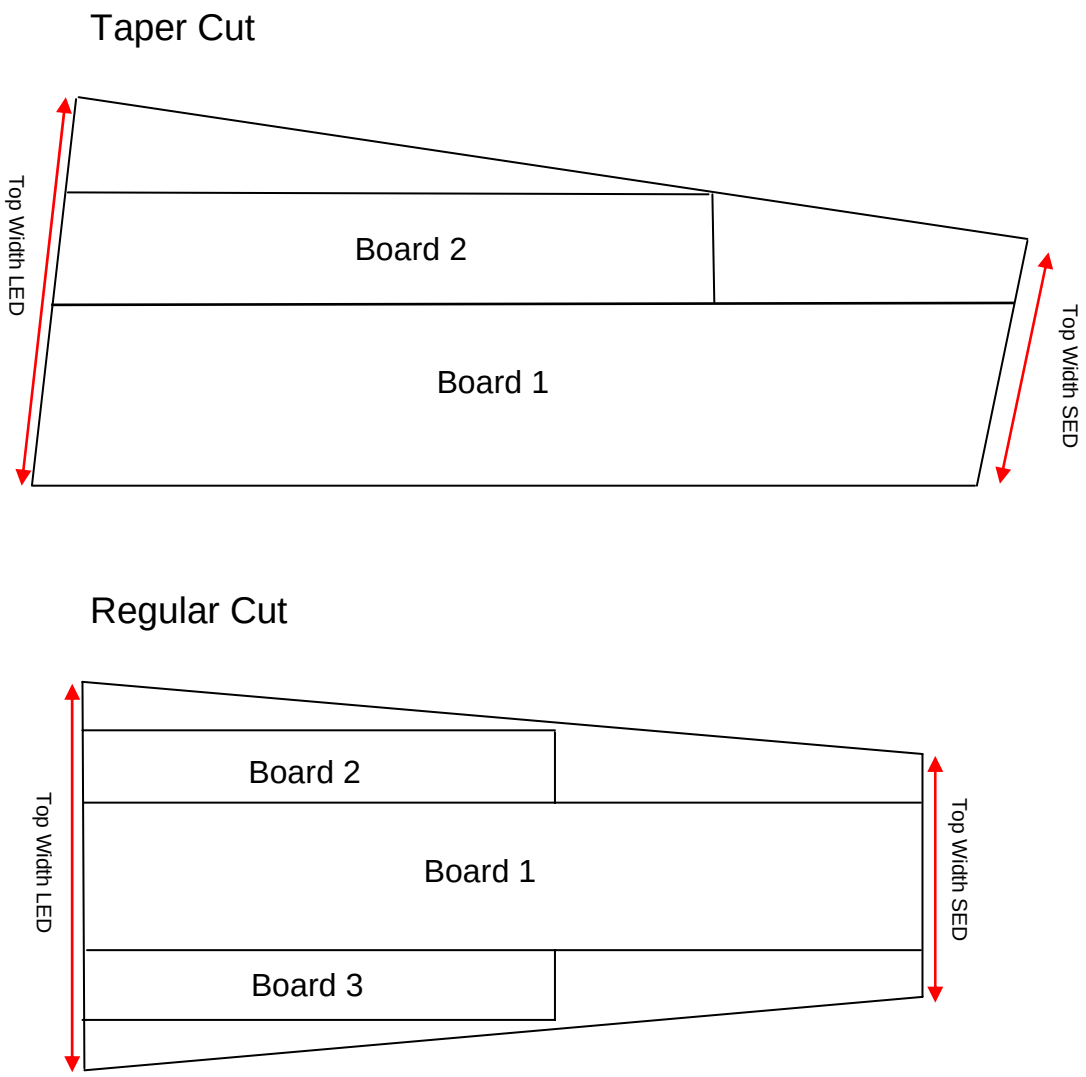

Figure 21: Flitch types processed at the edger

5.1.7 Re-Saw flow

The Re-Saw is a twin band saw designed to saw cants from the Headrig into lumber, timber, or squares. The Re-Saw operator will first cut out timbers or squares if they are present in the cant. Lumber is processed from the cant by cutting out "packages". A package is a combination of three boards. The Re-Saw is able to separate the three boards in one pass, and those boards then exit the Re-Saw loop and are sent to the mill 1 trim sort. Some of the boards cut from the Re-Saw require re-edging, and are therefore returned to the mill 1 edger via the mill 1 trim sort operator. Referring to Figure 22, a description of the flow of products is as follows:

1. Cants arrive from the Headrig along the conveyor and are dropped into the Re-Saw loop. The cants will collect along the infeed deck of the Re-Saw operator.
2. The cants move slowly to the Re-Saw operator. The Headrig operator checks the capacity of this deck to determine whether to cut 2, 3, or 4 face cants.
3. When the cant reaches the Re-Saw operator, they will align the straight edge of the cant along the in-feed fence and then run it into the twin band Re-Saw.
4. Cants, packages and slabs that still require to be processed are returned into the Re-Saw loop at 4.
5. Boards exit the system and are sent to the Trim Sort Buffer as shown in Figure 16. Boards that require edging will be returned to the Mill 1 edger from the Trim sort operator. Finished boards will continue on to Area 4.

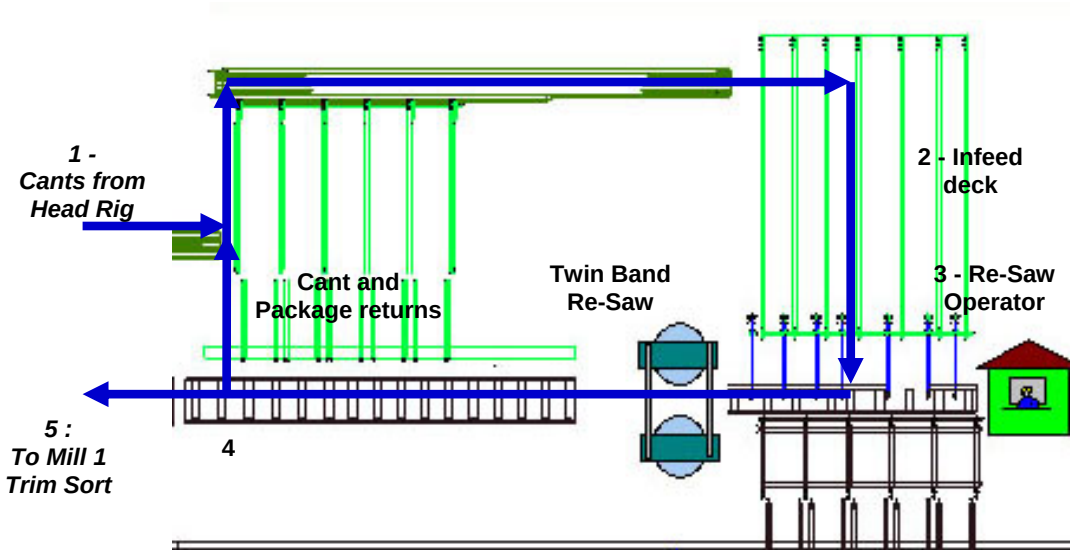

Figure 22: Re-Saw flow diagram

5.1.8 Re-Saw breakdown logic

Cants arriving to the Re-Saw are assigned a specific entity type. This information allows the simulation to select the appropriate breakdown logic. The entity types are a combination of the faces shown in Figure 17 and patterns as described in Figure 19. The possible cant types arriving to the Re-Saw are:

- 2 face lumber cant
- 3 face lumber cant
- 4 face lumber cant
- 2 face box heart cant
- 3 face box heart cant
- Free of heart timber cant
- Japanese square cant

As these cants are broken down when cut at the Re-Saw, the entity types will also change. Due to the number of possible breakdown combinations, only 2 examples are illustrated below. The first example is that of a 3 face box heart timber cant. A box heart timber is a timber where the pith, or center of the log, is centered in the middle of the timber.

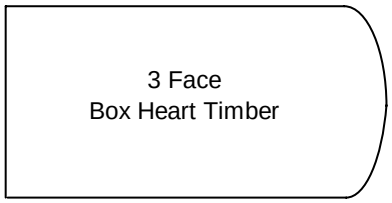

Figure 23: 3 Face Box Heart Timber enters Re-Saw

On the first pass the operator will cut out the box heart timber, and a 2 inch board. The dotted lines represent the blades of the twin band Re-Saw. These two products are sent to out to the mill 1 trim sort. The remaining right hand side is defined now as a 3 face slab entity, and is returned into the Re-Saw loop.

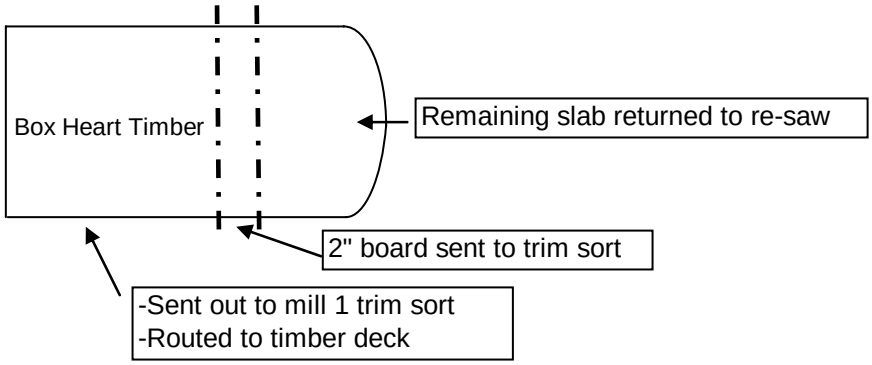

Figure 24: Pass 1 through Re-Saw

On the second pass, the 3 face slab is checked to see how many boards or packages can fit. In this example, one package can fit. The entity is now changed to a package and is returned to the into the Re-Saw loop. The right hand side is too small to make a board, and is therefore defined as a shim, and disposed of at the mill 1 trim sort.

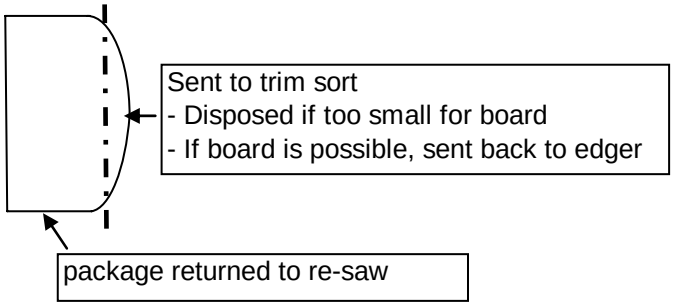

Figure 25: Pass 2 through Re-Saw

On the third pass, the package is cut producing 3 boards. These boards exit the system and are sent to the mill 1 trim sort.

Figure 26: Pass 3 through Re-Saw

The second example is that of a 2 face lumber cant.

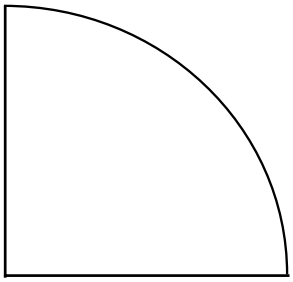

Figure 27: 2 Face lumber cant enters Re-Saw

On the fist pass the Re-Saw will cut to the cant width. This piece is then set as a 3 face lumber cant and returned to the Re-Saw loop. The middle section and right side section are boards that are sent out to the mill 1 trim sort. Since there is a wane edge on these boards, they are returned to the mill 1 edger. If the right side section has too much wane, then a board will not be made from this piece at the edger, and this piece is destroyed.

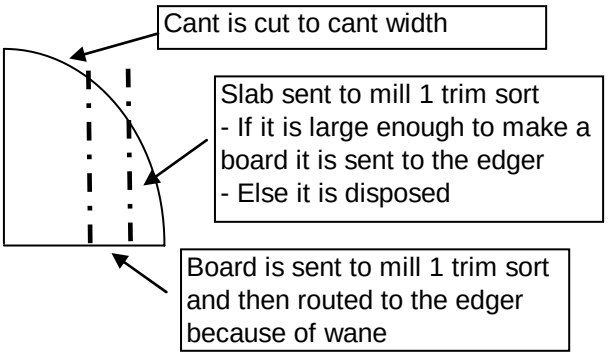

Figure 28: Pass 1 through Re-Saw

On the second pass, the new 3 face lumber cant is rotated 90°, where packages and lumber are fitted. In this example, two packages can fit. These are returned into the Re-Saw loop, as well as the slab on the right hand side.

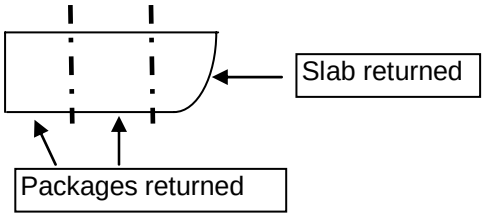

Figure 29:Pass 2 through Re-Saw

On the third and fourth pass the two packages are cut. These boards exit the system and are sent to the mill 1 trim sort.

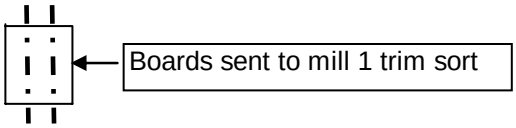

Figure 30:Pass 3 and 4 through Re-Saw

On the fifth pass the slab is cut. The simulation will determine what can fit within the slab. It will first check for packages, and then board thicknesses. The simulation can choose from two possible thicknesses. These are predefined prior to running the simulation. In this example, two boards and a shim are produced. All three pieces are sent to mill 1 trim sort.

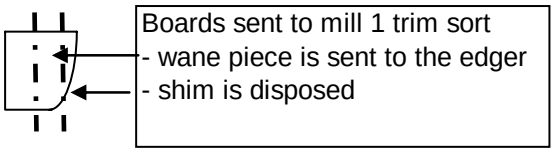

Figure 31:Pass 5 through Re-Saw

At the trim sort, the shim is disposed, the board with wane is returned to the mill 1edger, and the board with no wane is sent along to the Area 4.

As previously mentioned, breakdown patterns are based on what type of entity arrives at the Re-Saw. When entities leave the Re-Saw after sawing, new entity types are assigned. The Re-Saw is set up to cut the following entity types:

- 2 face slab
- 3 face slab
- 1 pack
- 2 pack
- Japanese square pack
- Board
- Free of heart timber
- Box heart timber
- Japanese square

Slab and pack entity types are returned to the Re-Saw for further processing while board, timber, and square entity types exit the Re-Saw to the mill 1 trim sort. As these entities exit the Re-Saw width, length, thickness and board feet attributes are assigned.

The target thicknesses of boards cut at the Re-Saw are species dependant. Each species consists of two possible targets to choose from, and the user can specify which one has priority over the other.

The breakdown logic used by the simulation is shown in Figure 32.

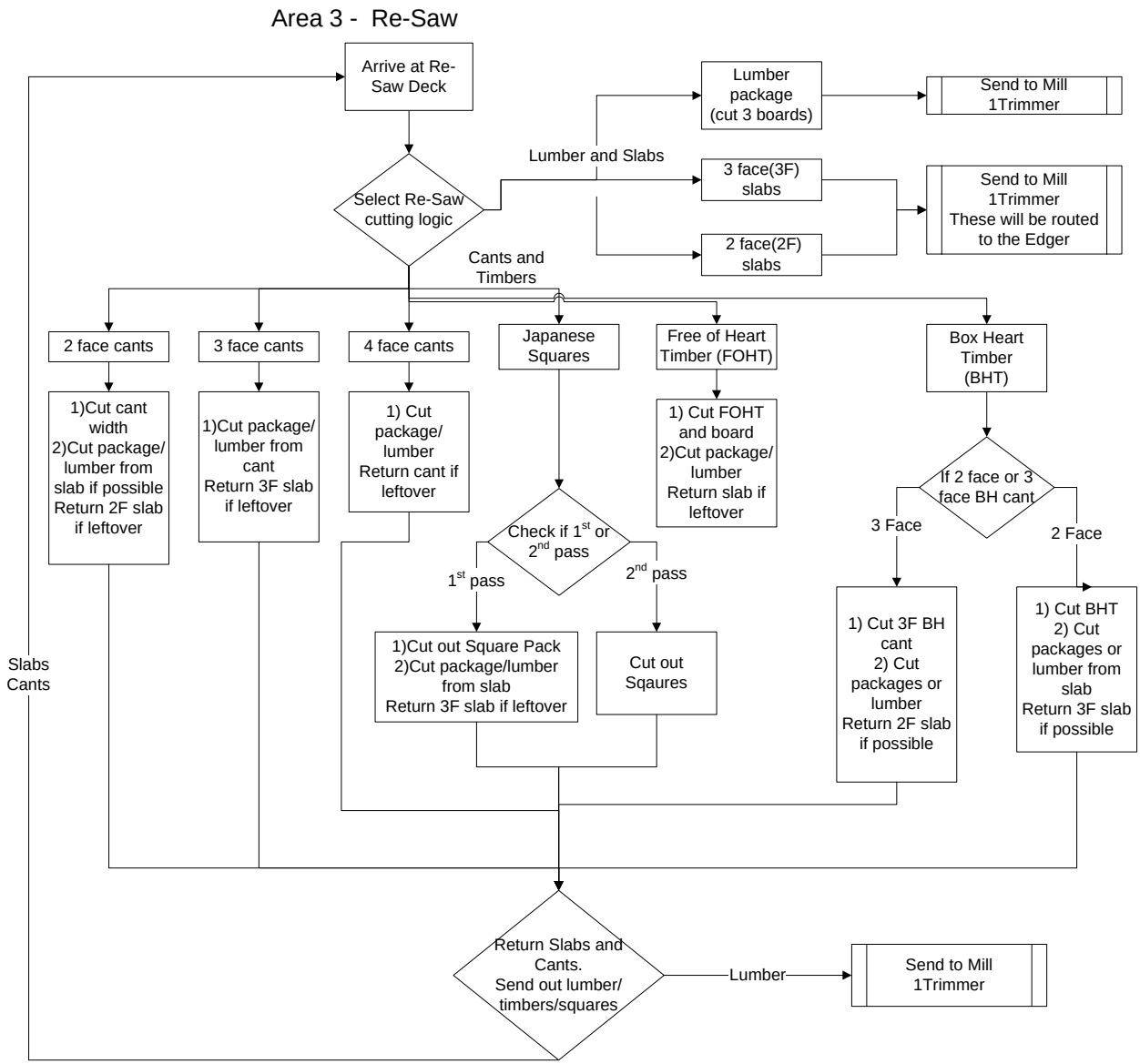

Figure 32: Flow logic for Re-Saw breakdown

5.1.9 Area 4 – Trimmer and drop sorters flow

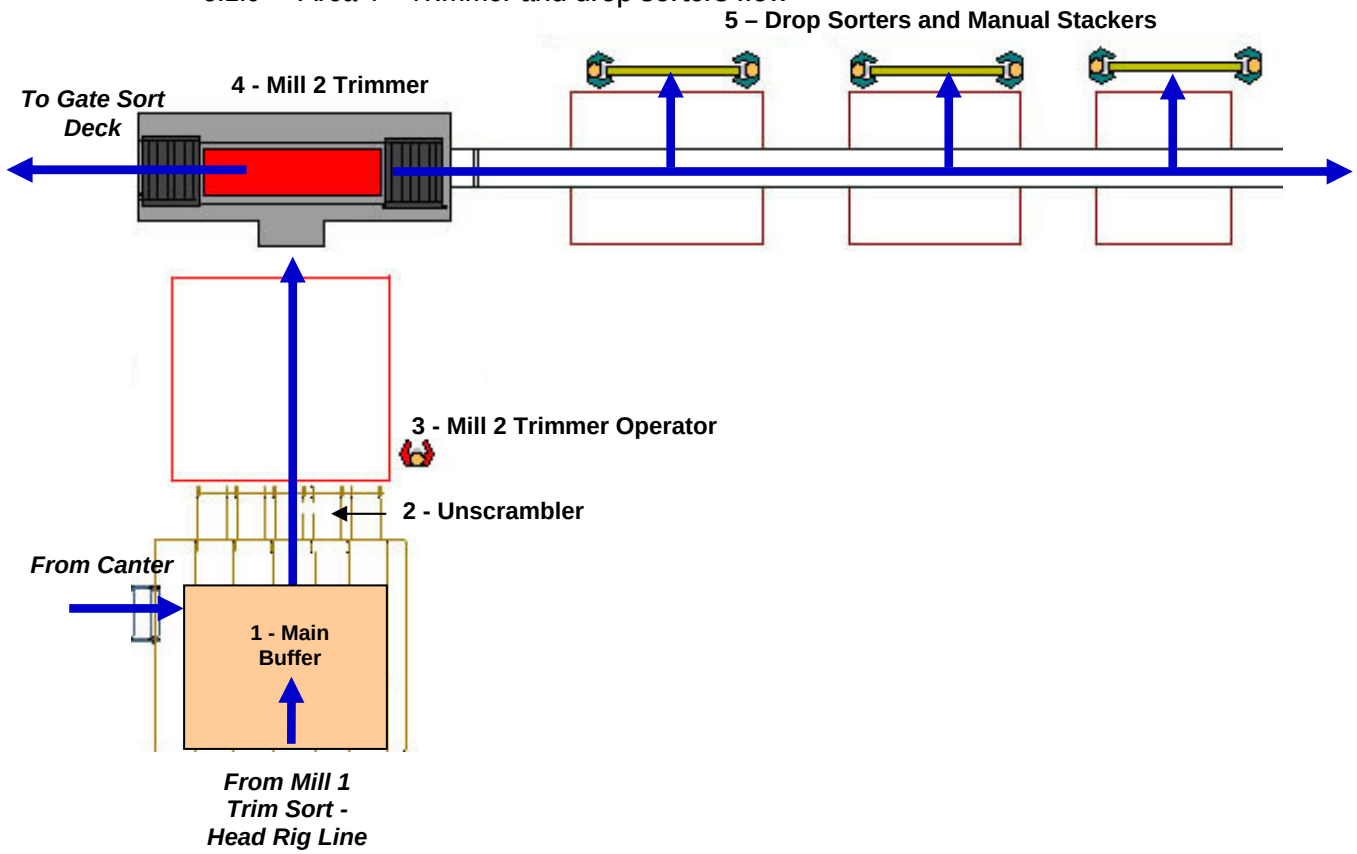

Figure 33 : Trimmer drop sort flow diagram

This area is the section of the mill where boards from both the Headrig and the canter line join up. The final processing area of the mill is at the mill 2 trimmer. After this boards are sent out to the drop sorts, stacked by hand, and sent to the dry kilns.

1. Main Buffer

Boards from both the Headrig and canter lines merge together in the main buffer. This is the largest buffer in the mill and the capacity is estimated at 3000 board feet by the production manager. Boards advance along the buffer where they arrive at the unscrambler.

2. Unscrambler

The unscrambler, also called a waterfall or singulator, is used to regulate the boards arriving to the mill 2 trimmer operator. Small lugs are used to carry boards up the unscrambler. About midway up, feet will kick off any excess boards from the lugs, back into the buffer area. This will often knock boards off from the lugs below as well, thereby creating a waterfall effect. Only two or three boards should move up the unscrambler. However this is not always the case. Sometimes the feet are ineffective and more than three boards are carried up the unscrambler. At other times, all the boards are knocked off the lugs. To complicate matters further, boards sometimes get crossed up at the apex of the unscrambler, causing the mill 2 trimmer operator to stop his work and fix the problem. Boards between 10 and 12 inches in width do not always clear the apex of the unscrambler and they will often fall back. The occurrence of these problems depends on the proportion of wide boards within the main buffer, as well as how full it is.

3. Mill 2 Trimmer Operator

Due to the frequent problems at the unscrambler, two operators often manually load boards onto the conveyor leading into the mill 2 trimmer. The first operator deals with any ensuing cross ups to ensure that the second operator has a smooth flow of boards arriving. The second operator must flip the boards by hand, visually determine what must be cut off, enter this into the computer, and load the board onto the conveyor. The conveyor leading into the trimmer travels at speeds of 40 to 50 lugs per minute.

4. Mill 2 Trimmer

At the mill 2 trimmer, boards are cut to their final length. There are 3 possible options at the trimmer: boards are slashed and disposed of, boards are returned back to the gate sort on the canter line, or boards are end trimmed. Boards returned to the gate sort are routed back to be edged once more at the BAE edger.

5. Stackers

Once the boards leave the mill 2 trimmer they are sent out to specific drop sorts. Two stackers manually remove boards from the sort, and stack them onto pallets. Once the pallet is completed, it is sent off to the dry kilns.

The logic for this are is shown below in Figure 34.

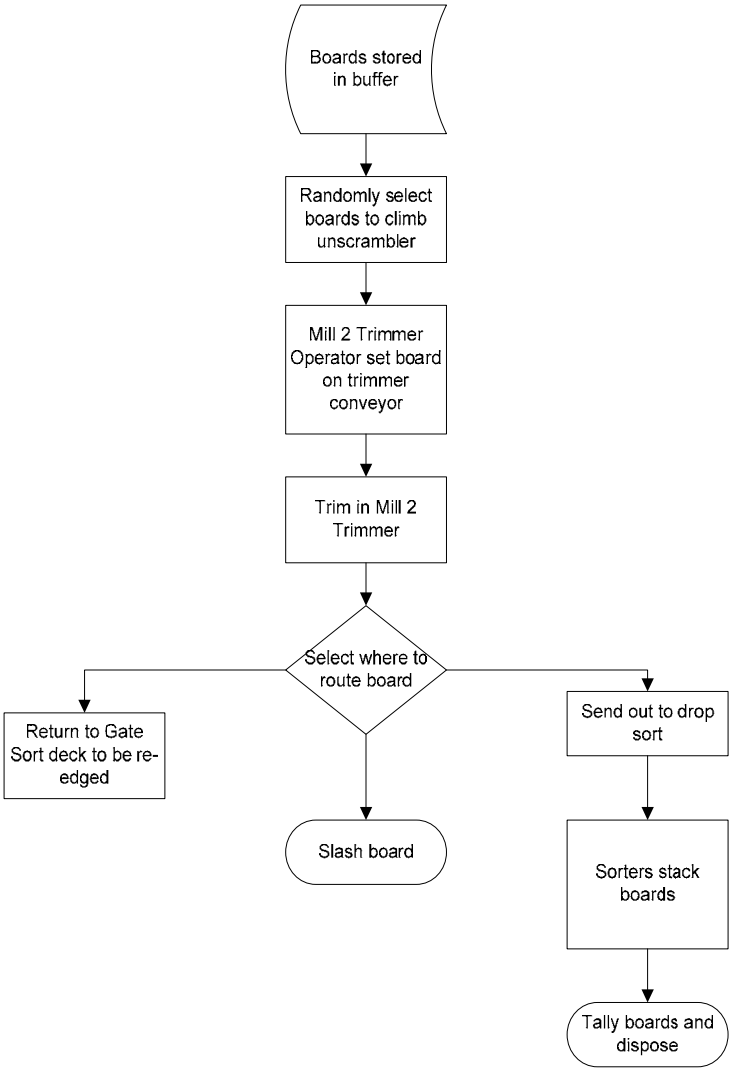

Figure 34: Trimmer drop sort process logic

5.2 Log parameters

The length, taper, small end diameter, and large end diameter was assigned to each log as it was generated in the simulation. As a result, the lumber recovery factor can be determined by the breakdown logic developed in the simulation.

Historic data of these log parameters were collected from production reports generated from the Headrig, and canter. Since both reports would only record the small end diameter and length, the large end diameter was estimated. In each report generated from the canter, the average taper of the logs processed during that shift was recorded. Analyzing 25 reports, the average taper calculated was 0.078 in/ft. Since no other information was available regarding the taper, a triangular distribution was used, with a minimum average value of 0, and a maximum average value of 0.3 in/ft. The simulation would generate a taper parameter based on triangular distribution, and consequently the large end diameter could then be calculated. This was used for both canter and Headrig logs.

The Headrig production reports were tracked for three species groups, Fir/Larch, White Pine, and Lodgepole Pine. The diameters ranged from 8 inches up to 35 inches in one inch intervals and lengths ranged from 8 to 26 feet in two foot intervals. The canter production reports recorded small end diameters at 3.5 inches and continued up to 9 inches in half inch intervals. Log lengths were collected starting from 8 feet up to 20 feet in two-foot intervals. There was no difference between pine species on the canter reports, and therefore all pines were included in this group. Figure 35 shows the distribution for length and diameter of the different species from the canter and Headrig lines.

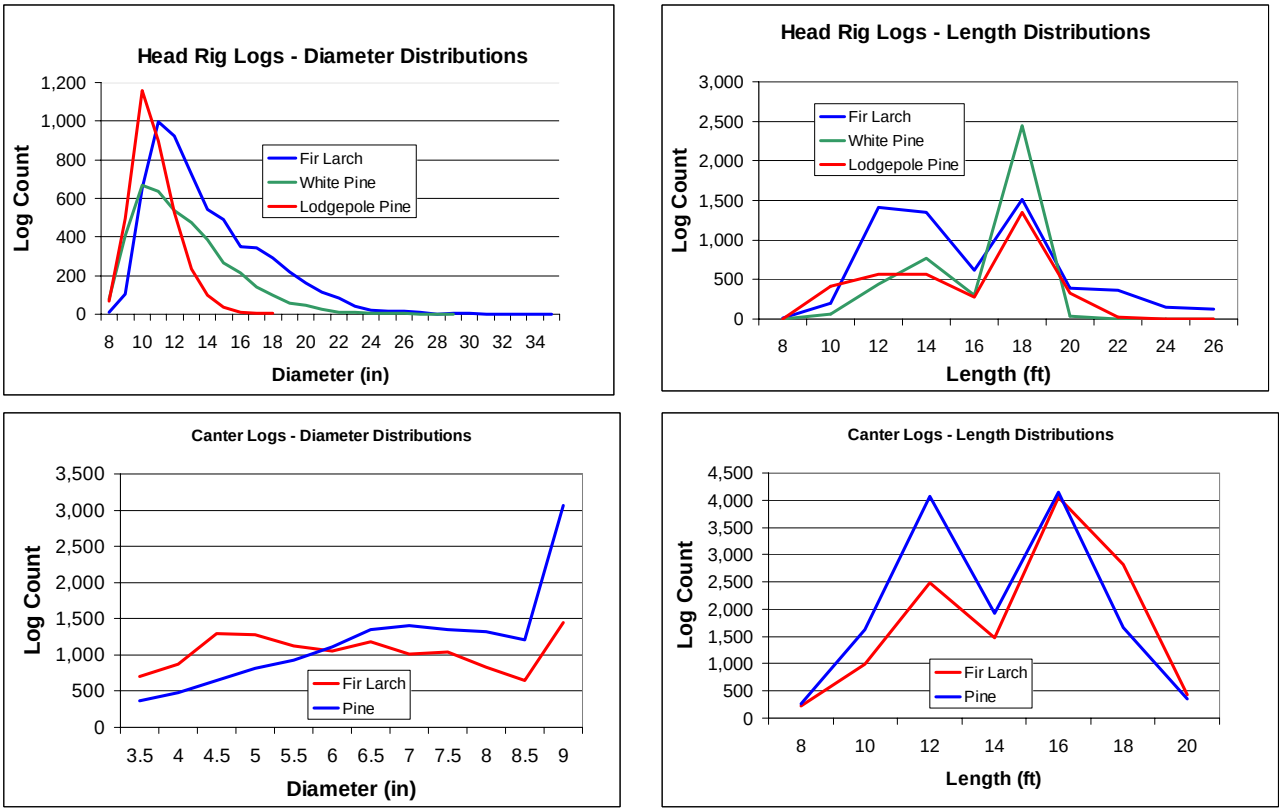

Figure 35: Length and diameter distributions

Rockwell Software's *Input Analyzer* was used to generate probability density functions for the length and diameter parameters for each of the species. The program ranks the fitted distributions based on the smallest square error calculated, and also provides a *p*-value from the chi-square goodness of fit test or Kolmogorov-Smirnov test. A larger *p*-value indicates a better fit. A *p*-value of less than 0.1, indicates that the distribution does not fit the data, whereas a *p*-value of above 0.15 indicates an acceptable fit of the distribution to the data (Seila et al. 2003). A summary of the functions used in the model are shown in Table 4.

Table 4: Log parameter expressions

Head Rig	*Distribution*	*Expression*	*Square Error*	*Chi Square p-value*
White Pine - Length	Triangular	TRIA(9.5, 18.5, 24.5)	0.182556	< 0.005
White Pine - Diameter	Gamma	7.5 + GAMM(1.76, 2.87)	0.000366	0.209
Lodgepole Pine - Length	Triangular	TRIA(7.5, 18.5, 22.5)	0.04512	< 0.005
Lodgepole Pine - Diameter	Gamma	7.5 + GAMM(0.635, 5.15)	0.002387	< 0.005
FirLarch - Length	Beta	7.5 + GAMM(1.66, 5.09)	0.001712	< 0.005
FirLarch - Diameter	Beta	7.5 + 26 * BETA(2.29, 6.95)	0.001158	< 0.005
Canter				
Fir Larch - Length	Normal	NORM(14.9, 2.83)	0.006271	< 0.005
Fir Larch - Diameter	Beta	3 + 6 * BETA(1.17, 0.974)	0.006272	< 0.005
Pine - Length	Normal	NORM(14.1, 2.77)	0.004945	< 0.005
Pine - Diameter	Beta	3 + 6 * BETA(1.39, 0.667)	0.004484	< 0.005

The estimated White Pine diameter was the only distribution that generated a *p*-value greater than 0.15. Since the other proposed probability functions did not statistically represent the observed data, continuous empirical distributions generated from Arena Input Analyzer were used in the simulation model instead. It is important to note that a change in actual raw material inputs, such as a shift to processing larger logs of a specific species, would invalidate the use of the empirical data in the model. New data would have to be collected and either a new empirical distribution used, or if possible, a valid probability function.

5.3 Machine processes

In order to define machine process times within the simulation, actual process times from the sawmill were collected. In a sawmill, the process times of a machine center are often equal to the rate of the conveyor speed. Variability occurs when there are manual set up or align times within that process. Although some machines are set to process at specific feed speed rates, variability occurs as work pieces are aligned prior to entering a machine. Time and motion studies were conducted at machine centers that had process variability, either from setup times, or because of the natural variation within the process. In each

time study at least 30 times were measured for each time element. Time studies were conducted for the following 5 machine processes.

- canter
- BAE edger
- Headrig
- mill 1 edger
- mill 2 trimmer operator

The first time study aimed at evaluating the canter processing time variability. The canter process time was measured for four separate manufacturing elements: Scan, Chip, VSA(vertical saw assembly), and Kick Out. Although the canter is set to run at feed speeds of 180 fpm and 240 fpm depending on log diameter, variability in the process times would occur if the log became jammed in the chipper, or time was required to align the log.

Another time study was conducted at the BAE edger. Although this machine is set to run at 150 ft/min when processing cants, or 480 ft/min when processing boards, process variability occurred from the operator aligning the piece into the machine. The operator alignment time was measured for both cants and boards.

The time study used at the Headrig was subdivided into four separate manufacturing elements: Loading, Line Pass, Log Rotation, and Drop Off. Loading measured the time required to set the log onto the Headrig carriage. Line Pass measured the time required to cut a flitch off the log. Log Rotation measured the time the operator required to rotate the

log in order to cut another face. Drop off measured the time required to drop the cant off the carriage and return to the start position.

The time study conducted at the mill 1 edger measured the time from when the operator touched the flitch arriving at the station, to the time the flitch was released into the trimmer.

The time study at the Re-Saw measured the entire process from when the cant exited the conveyor to be set against the fence, up to the point when the cant passed entirely through the Re-Saw.

Since the mill 2 trimmer would process boards at the speed of the trimmer lug loader conveyor, a time study was only used to determine the handling time of the operator feeding the machine. This machine handling time measured from the point when the operator would touch the board, until the time it was released onto the lug loader.

Once all the time studies were completed, the data was loaded into the Arena Input Analyzer software to generate probability distributions. A summary of the probability distributions for the process times used in the simulation are shown in Table 5. These distributions were selected by the input analyzer as having the best fit of the data, by measuring the square error, and either the Chi-square value, or Kolmogorov-Smirnov value. All process expressions recorded either a chi-square *p*-value or Kolmogorov-Smirnov *p*-value greater than 0.15. This indicates that there is not enough statistical

evidence to reject the null hypothesis that the observed distribution and the fitted expression are the same.

Table 5: Distributions selected from the Input Analyzer for machine process time studies

Head Rig Line Process Times				
Machine	*Distribution*	*Expression*	*Square Error*	*Chi-square p-value*
Head Rig - Load Time	Triangular	TRIA(4.5, 5.33, 15.5)	0.003868	0.233
Head Rig - Line Pass	Lognormal	4.5 + LOGN(5.58, 5.08)	0.011228	0.634
Head Rig - Rotate	Beta	7.5 + 10 * BETA(1.25, 1.39)	0.02447	0.154
Head Rig - Drop Off	Lognormal	4.5 + LOGN(3.24, 4.33)	0.044537	0.174
Mill 1 Edger	Exponential	4 + EXPO(4)	0.003598	0.54
Re-saw	Beta	4 + 28 * BETA(1.19, 2.44)	0.00533	0.198
Canter Line Process Times				
Machine	*Distribution*	*Expression*	*Square Error*	*KS - p value*
Canter - Scan	Normal	NORM(6.28, 1.01)	0.029893	> 0.15
Canter - Chip	Lognormal	3.44 + LOGN(1.3, 0.727)	0.042312	> 0.15
Canter - VSA	Erlang	3.49 + ERLA(0.457, 4)	0.017344	> 0.15
Canter - Kick Out	Beta	2.05 + 2.57 * BETA(1.67, 1.2)	0.089462	> 0.15
Edger - Board Align	Exponential	2 + EXPO(3.12)	0.005884	> 0.15
Edger - Cant Align	Beta	2 + 6 * BETA(0.749, 0.874)	0.038664	> 0.15
Mill 2 Trimmer Operator	Lognormal	LOGN(0.0252, 0.0131)	0.002465	> 0.15

5.4 Machine downtimes

Machine downtimes were collected from records kept in the mill database for each machine, as well as observations recorded at the mill 2 trimmer. These observations were required, as the downtimes experienced at the mill 2 trimmer were often very short but frequent, and were not logged within the mill database. Downtimes for the machine centers between each recorded failure were collected from the mill log book from January 2005 to July 2005. Information recorded in the mill log book indicated the total time the machine center was down, and the number of failures for that specific day. These downtime events were simulated within the model.

5.5 Run conditions

The nature of the simulation model will dictate certain preconditions required for setting up simulation runs. The three preconditions that must be considered are initialization bias, replication length, and run time.

5.5.1 Initialization bias

In most scenarios, terminating systems will result in transient output, whereas non-terminating output often reaches a steady state. Most steady state models will require any initial conditions or warm up bias to be setup within the simulation model. (Robinson 2004). The simulation was run in the same way the actual sawmill was operated. The mill clears out all boards at the end of the night shift and starts the morning with no boards in any buffer or queue and no work in progress. As a result, the simulation does not require any initialization bias as the beginning of each run will always start from an initial empty state.

5.5.2 Number of replications

In order to be able to analyze the model output, sufficient data must be generated. There are three methods for selecting the number of replications required to obtain an accurate estimate of the average performance. These are: rule of thumb, graphical, and confidence interval method. The simple rule of thumb method uses 3 to 5 replications (Robinson 2004). It does not consider the model output, and therefore if a model's output is highly varied, more replications are required. This method was initially selected, however 30 replications were used instead of the 3 to 5 because of the relatively short run time required by the computer. The confidence interval method statistically shows how accurate the mean average of a value is being estimated.

In order to use the confidence interval method, it is necessary to define limits on the interval that will be representative of the system modeled (Robinson 2004). This information of an acceptable confidence interval level of the real system was unavailable, and therefore the rule of thumb with a large number of replications was selected. This provided a balance between run time, and model output. After running the simulation for 30 replications, the confidence interval for the number of boards out of the system was calculated as ± 1.6% running under the Base Case scenario.

5.5.3 Run time

The selection of an appropriate run time depends on whether the system is either terminating or non-terminating. A terminating system has a definitive end point that determines the end of a simulation run, whereas a non-terminating system has no specific end point. In the case of a non-terminating system, the run time can be designed to include either multiple replications of a set length, or a unique long run.

The simulation run time was set to one shift of 460 minutes. The actual mill runs for 510 minutes with 50 minutes of break time. The simulation model does not factor in the break time and therefore is set to the total working time. This does not affect the total piece output.

6 Model verification and validation

Model verification is the iterative process of transforming the system under study into an accurate computer model. As the model is being developed, it is constantly debugged to ensure that there are no errors in the model logic, and also the model runs as expected. This occurs constantly throughout the model development process.

Model validation is the process of ensuring that the model represents the real system with certain accuracy. The simulation development process requires the modeler to include various assumptions and simplifications regarding the system and data (Chung 2004). Although in theory a model is either valid or not, in practice it is impossible to prove (Robinson 2004). The greater the number of tests that cannot prove the model to be incorrect, the greater the confidence that can be placed on the model validity (Robinson 2004). Several face validation tests and a statistical test was used to gain confidence in the model.

6.1 Face validation tests

A model is considered to be face valid if the client or experts in the process agree that the model outputs accurately represent the real system. Several face validation tests were conducted in order to build confidence in the model.

6.1.1 Board output comparison

A meeting was held with the mill production managers to determine if the number of boards processed within the mill during a given shift was an accurate representation of the actual sawmill production. The model was run for 10 working days and the average board output was collected. Three different scenarios cutting Fir/Larch were tested

running both the canter and Headrig together. In each scenario the canter was set to cut the dimension 1 inch mix pattern. Each scenario changed the Headrig cutting patterns. In the first scenario, the Headrig was set to cut lumber. The daily average output was 13,000 boards. In the second scenario, the Headrig was set to cut only Japanese squares. The average total output was 14,000 boards and 830 Japanese squares. In the final scenario, the canter was set to cut free of heart timbers as well as Japanese squares. The average output was 13,600 boards, 540 Japanese squares, and 250 timbers. In each of the cutting scenarios presented, the mill management agreed that the output from the model was representative of the actual mill output.

6.1.2 Lumber recovery factor comparison of the Headrig

Lumber recovery factors (LRF) of the Headrig from the model were tested against point estimates from the mill. This was used to test the validity of the breakdown logic used at the Headrig line. Accurate LRF data from the mill was difficult to obtain as both the canter and Headrig lines would be run throughout the shift, and therefore the recorded LRF would be a combination of lumber originating from the canter and Headrig. A LRF study for each of the species considered would be the only method to determine the true LRF from the Headrig. The variance of the real LRF data will be higher than shown in the sawmill model due to the assumption that the model uses truncated cones as logs, and ignores the physical shape of the log and internal defects. The production manager's expertise was used to determine the average LRF from the sawmill for each species considered. These LRF's were compared to the simulation model outputs from 10 replications of 100 logs.

The Fir Larch species LRF from the model closely represents that of the mill average. The model average of the 10 replications was 0.248 compared to the mill managers estimate average of 0.250. This is shown in Figure 36. The maximum LRF average of the simulation run was 0.258, and the minimum LRF average was 0.237. These are represented by the top and bottom points on the bar in graph.

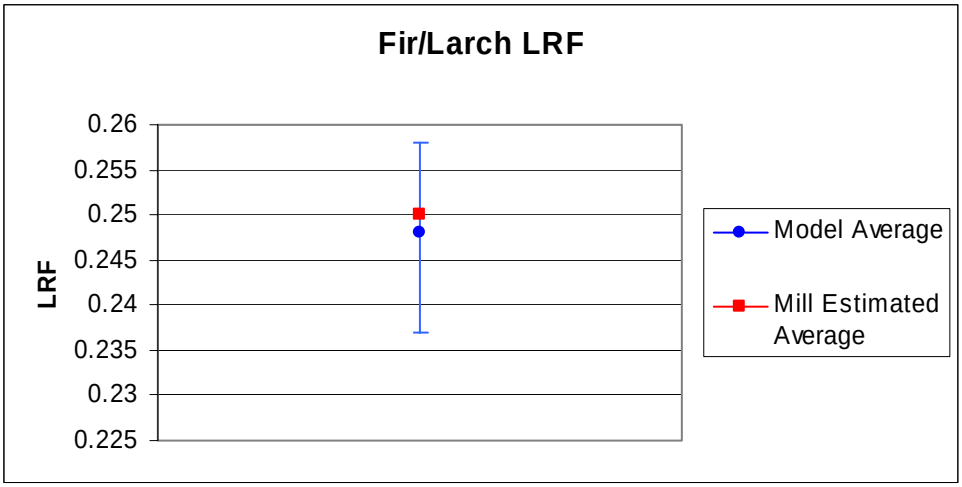

Figure 36: Fir/Larch LRF results from the mill estimated average and simulation outputs. The simulation outputs represent the overall average(1000 logs processed) and the minimum and maximum average replication in a 10 - 100 log replications.

Figure 37 shows the results from the simulation cutting white pine. The simulation model average under this cutting pattern was 0.237 which is slightly higher than the mill estimated average of 0.230. However, the mill average LRF is still within the model's maximum average value of 0.241 and minimum average value of 0.227.

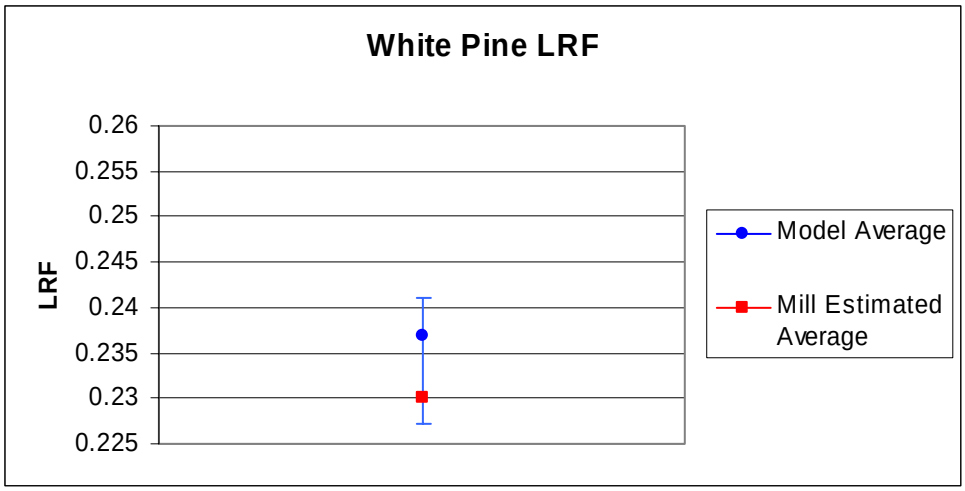

Figure 37: White Pine LRF results from the mill estimated average and simulation outputs. The simulation outputs represent the overall average(1000 logs processed) and the minimum and maximum average replication in 10 - 100 log replications.

The model did not accurately predict the mill's LRF for the Lodgepole Pine species, which can be seen in Figure 38. The mill estimated average was 0.255, however the overall model average of the simulation run was 0.233 with a minimum average value of 0.227, and maximum average value of 0.239.

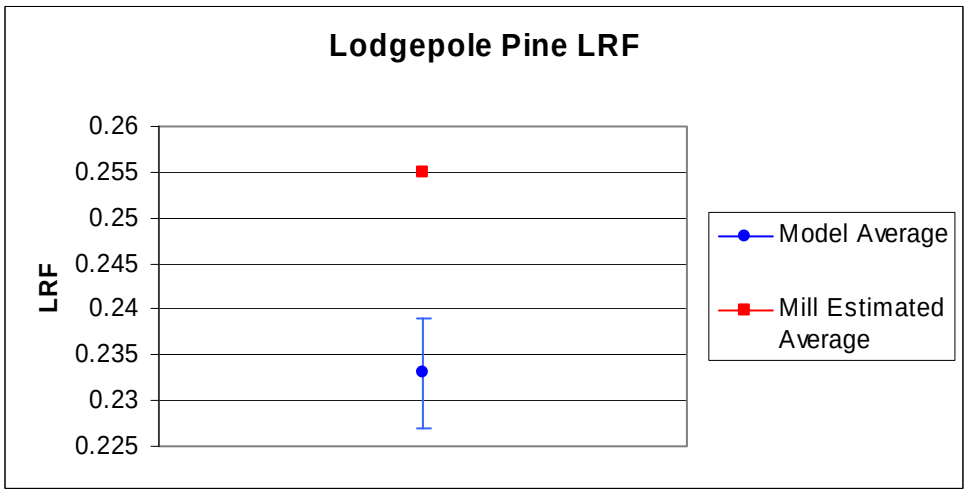

Figure 38: Lodgepole Pine LRF results from the mill estimated average and simulation outputs. The simulation outputs represent the overall average(1000 logs processed) and the minimum and maximum average replication in 10 - 100 log replications.

A possible explanation for the model LRF difference is that the complexity of the cant breakdown at the Re-Saw is far greater in the mill than is captured in the model. Products such as flooring, paneling, ties, are not taken into consideration in the simulation model. It is also possible that the mill managers have overestimated their LRF for Lodgepole pine.

The average model lumber recovery factors for the Fir/Larch timber products (Japanese squares, Free of Heart Timbers, Box Heart Timbers) are shown in Figure 39. These values are consistent with the LRF expectations indicated by the production manager.

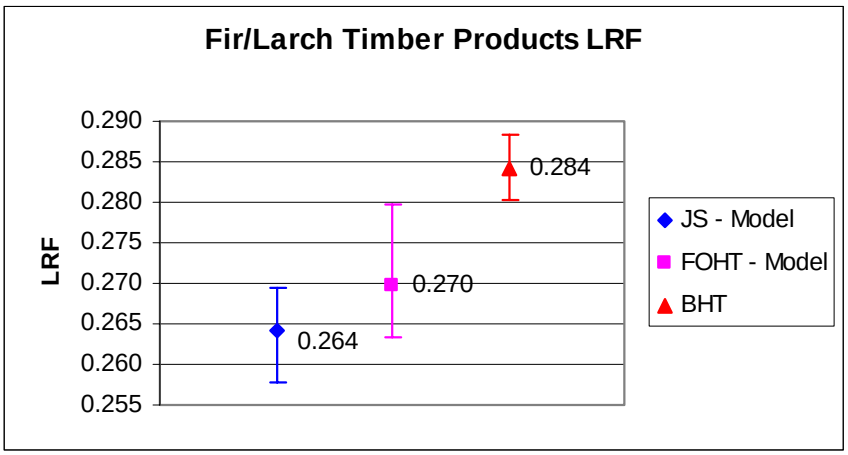

Figure 39: Fir/Larch Timber Products LRF for 1000 sample logs, 10 replications of 100 logs. Results indicated for the overall average, maximum replication average, and minimum replication average.

6.1.3 Canter board output validation

In order to validate the breakdown logic for the canter and determine the accuracy of the sawing patterns, a test was performed between the model and the actual mill. For this test, the simulation model set up to only run the canter line. The number of boards cut from the simulation was compared to the shift reports collected at the canter. The model output was compared against two single mill runs. One mill run was specific to Pine,

while the other run was specific to Larch. It was difficult to determine an appropriate run time for the canter since the actual running time was sporadic throughout the shift. This was impossible to setup in the simulation model. Instead a single shift report was selected, and the simulation model was setup to run the same number of logs as specified in the report. Initial results indicated that the model was overproducing boards by about 7%. A disposal factor was implemented into the model in order to increase the accuracy of the results. This disposal factor randomly selects 7% of the boards produced at the canter and disposes of them prior to leaving the canter machine. This ensures that an accurate number of pieces will be flowing through the mill from the canter.

The canter test selected for the pine species was set to process 2601 logs. The shift report indicated that a total of 10,592 boards were produced. The breakdown patterns selected in the simulation model was 64% selected to process the dimension 1 inch mix pattern, and 36% selected to process the dimension pattern. In order to compare the actual mill production to the simulation model, 30 replications were run cutting exactly 2601 logs for each replication. The results are shown below in Figure 40. The model results for the 30 replications resulted in a total average of 10,702 boards. The minimum replication average was 10,476 boards, and the maximum replication average was 10,933.

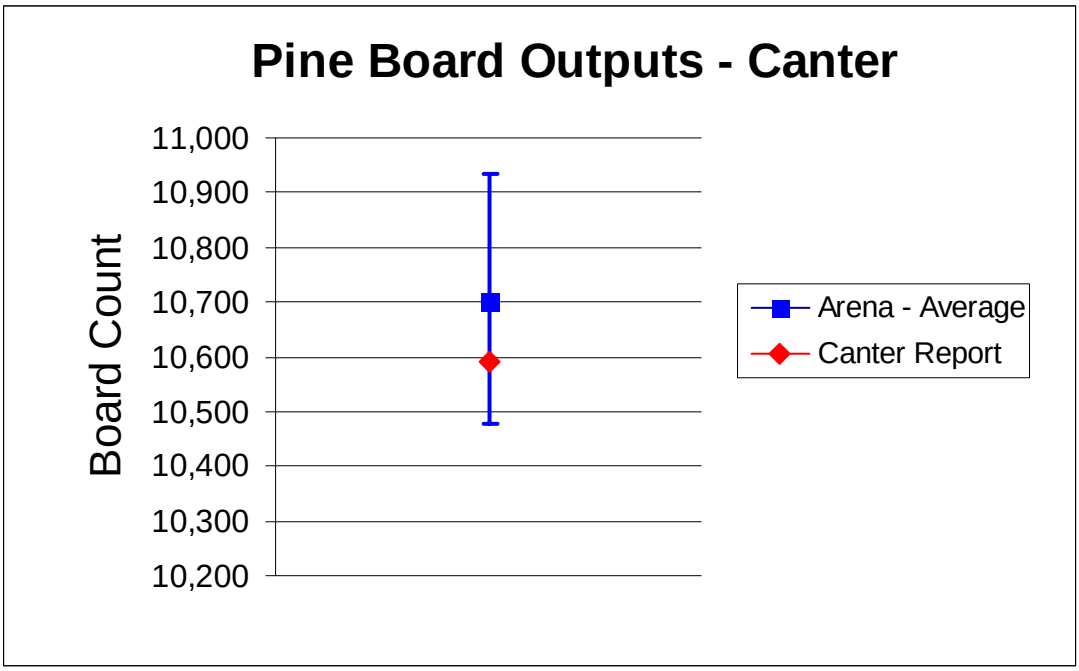

Figure 40: Comparison of board outputs from a canter report and simulation model. The canter processed 2601 Pine logs on this shift. The bar shows the maximum and minimum replication averages from the simulation.

A similar test was conducted for Larch processed on the canter line. The production report processed 3,040 logs and produced 9,808 boards. Another 30 replication simulation was run with the set table patterns allocated to 100% dimension pattern, as reflected in the actual run. The results from the simulation run compared to the production report are shown in Figure 41. The simulation model resulted in a total average board output of 9,771, with a maximum replication average of 10,033 and a minimum replication average of 9,583.

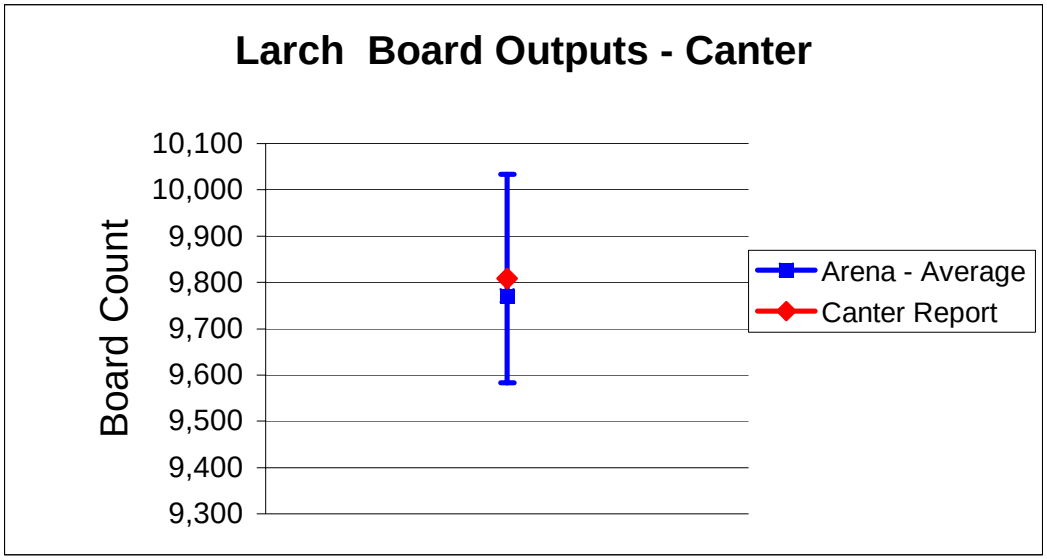

Figure 41: Comparison of board outputs from a canter report and simulation model. The canter processed 3040 Larch logs on this shift. The bar shows the maximum and minimum replication averages from the simulation.

Based on the results of the simulation it was concluded that the breakdown patterns for the canter were accurate in predicting the number of boards processed.

6.1.3.1 Board Type output

The simulation model was also tested to determine not only if the number of boards processed at the canter was accurate, but if also the type of boards processed were accurate. The specific board outputs generated from both the Pine run and Larch run as described in the section above are shown in Figure 42 and Figure 43. The graphs compare the minimum and maximum averages from the simulation run to the canter production reports. Based on the results from this test the simulation model does not accurately predict the specific board types cut. While the model predicts the general trend of the board types, the total boards reported on the mills canter report are usually outside the minimum and maximum replication average of the model.

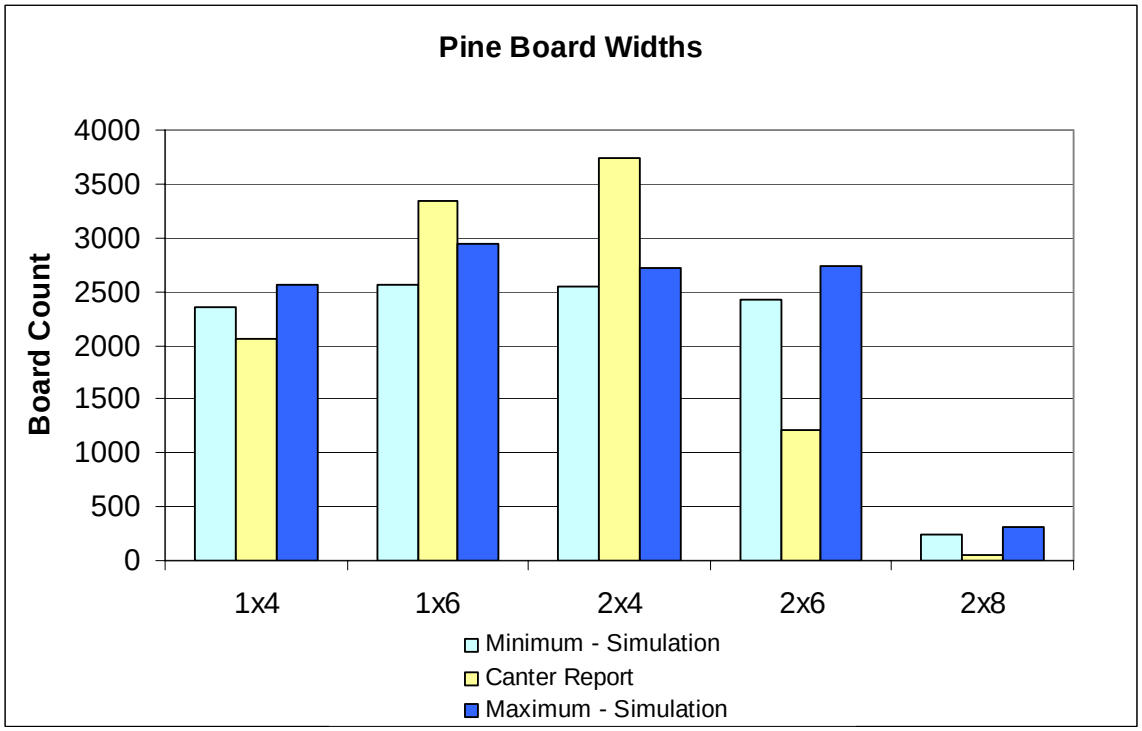

Figure 42: Comparison of Pine board widths between the cater report and simulation model. 30 replications, of 2601 logs were run. The canter report and model minimum and maximum averages are graphed.

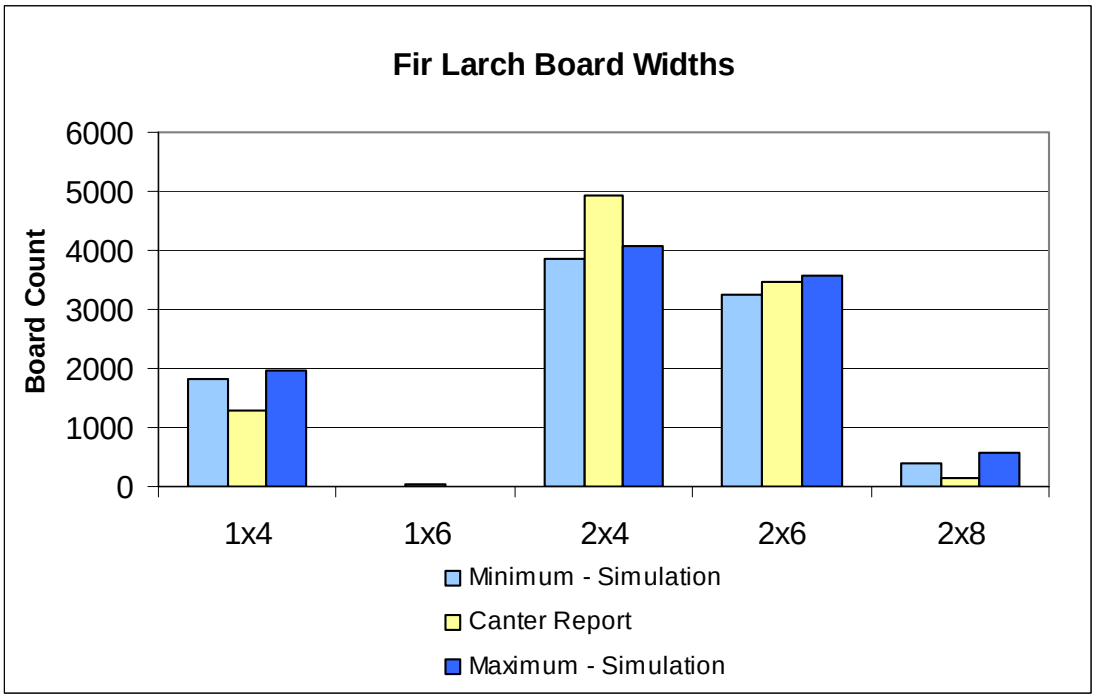

Figure 43: Comparison of Fir Larch board widths between the cater report and simulation model. 30 replications, of 3040 Larch logs were run. The canter report and model minimum and maximum averages are graphed

6.2 Statistical validation

Combined with Face Validation, Statistical Validation techniques were also used to increase user confidence in the model. Statistical validation tests were used to test log processing times from both the Headrig and the canter.

6.2.1 Log processing validation

In order to validate the number of logs processed at the canter and Headrig lines, the number of logs processed per minute was compared between the model output and mill data for the canter and Headrig. The log per minute parameter was selected instead of logs per shift due to the random run schedule of the canter line. Mill data containing 25 random shift reports from the Headrig, and 30 shift reports from the canter were used to compare against the model results.

A total of 40 replications were simulated on the Headrig. These consisted of 10 Fir lumber replications, 10 White Pine lumber replications, 10 Lodgepole Pine lumber replications and 10 Japanese square replications. 30 canter only replications were run based on 15 Pine replications and 15 Larch replications. In order to compare the data, an appropriate statistical test was selected based on the data characteristics. The following flow chart describes the method in selecting the appropriate test.

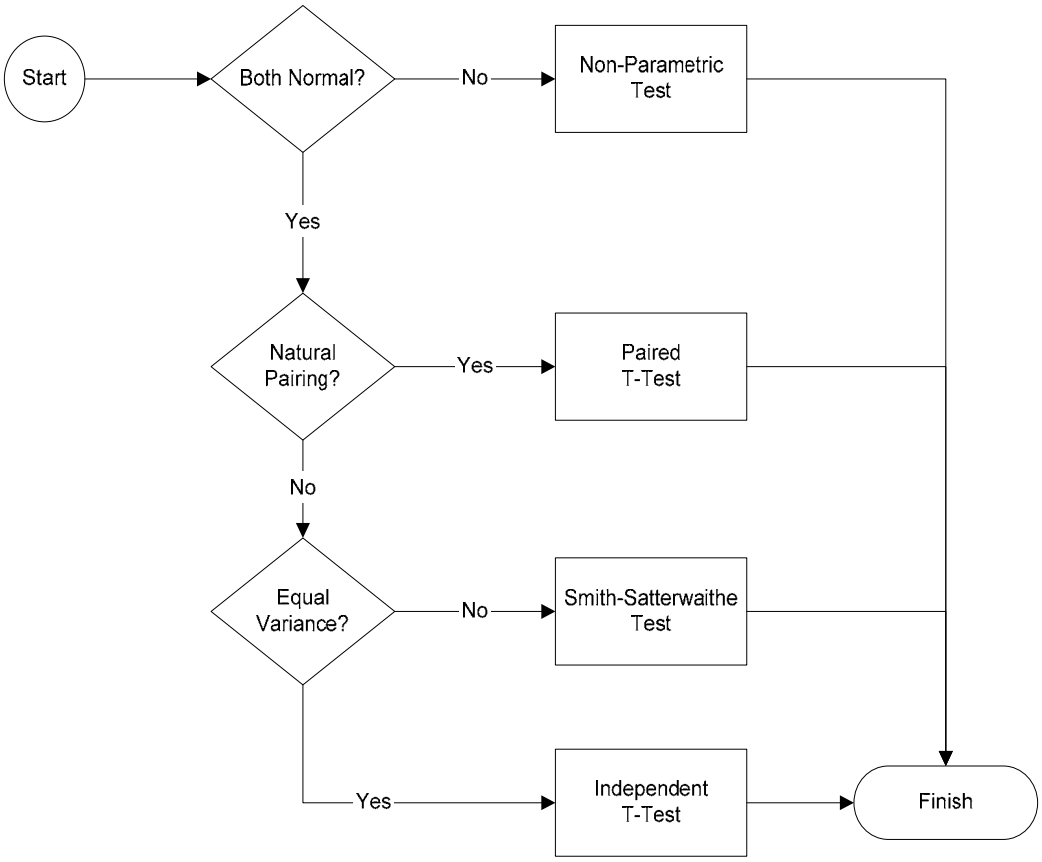

Figure 44: Hypothesis test flow chart (Chung 2004)

The four sets of data were tested for normality. Using the Kolmogorov-Smirnov test it was discovered that both the Headrig mill data, and canter mill data accepted the null hypothesis that the two data sets are normally distributed. However, the null hypothesis was rejected from the Arena outputs for both the Headrig and canter.

Table 6: KS test for normality of mill and model output

Data Set	Data Points	KS Test	p-value	
HR Mill	25	0.222	0.148	Accept
Canter Mill	30	0.0854	>0.15	Accept
HR Arena	40	0.194	0.0878	Fail
Canter Arena	30	0.283	0.0142	Fail

As a result, the two data sets were tested using the non-parametric Wilcox rank-sum test.

For this test, the data points from the two systems are merged, and ranked in ascending order. The following calculations are required for the rank-sum test:

$$U_1 = W_1 - \frac{n1(n1+1)}{2}, U_2 = W_2 - \frac{n2(n2+1)}{2} \qquad [3]$$

where:
W_1 = Sum of the rank in system 1
W_2 = Sum of the rank in system 2

and:

u_1=Min(U_1, U_2)

Mean : $$\mu_{u1} = \frac{n1n2}{2} \qquad [4]$$

Variance: $$\sigma_{u1}{}^2 = \frac{n1n2(n1+n2+1)}{12} \qquad [5]$$

Z-test: $$Z = \frac{u_1 - \mu_{u1}}{\sigma_{u1}} \qquad [6]$$

The Headrig data set was compared between the mill and model with α = 0.05. Based on the calculations above the Z-test value was -0.102. As this is less than the Z-critical of -1.645 there is not enough evidence to prove the Headrig data sets for the model and mill are significantly different.

The same calculation was used to compare the canter data sets, again using α = 0.05. The Z-test value was calculated as -0.355. This is again less than the Z-critical of -1.645. Again, there is not enough evidence to prove that the data from the mill and model are not equal. Based on this information I concluded that the actual and model results are not significantly different.

7 Scenario analyses

Based on the information provided from the simulation model while testing the verification and validation, it became apparent that the mill 2 trimmer was the bottleneck in the sawmill when both the Headrig and canter were being run. The model was tested when either the canter or the Headrig was run. It was clear that the trimmer was not the system bottleneck. Under these conditions, the mill was only constrained by how fast logs were processed at the primary breakdown. Since the sawmill typically runs both lines during a shift, this was selected for the model to analyze how the bottleneck would respond to different trimmer parameters. For the analysis, five different scenarios were created, and the model output was compared between them. These five scenarios consisted of the following:

1. Base Case – Trimmer Lug speed set to 40 ft/min
2. Trimmer Lug speed set to 50 ft/min
3. Trimmer Lug speed set to 50 ft/min and a 10% reduction in trimmer downtime
4. Trimmer Lug speed set to 80 ft/min and a 10% reduction in trimmer downtime
5. Trimmer Lug speed set to 80 ft/min, a 10% reduction in trimmer downtime, and BAE feed times are halved

Each scenario was tested as 1 shift run for 30 replications. The Headrig was set to cut the Fir/Larch lumber pattern. The canter was set up with the same parameters of the Larch run described in the validation process in section 6.1.3 . Both primary breakdown centers were set to process for the entire shift.

7.1 Base case results

Under the base case scenario, the trimmer lug loader conveyor speed was set to 40 ft/min which is consistent with that observed in the sawmill. The trimmer lug loader conveyor enters the trimmer, and this speed is essentially the process speed of the trimmer. Under this scenario, the average number of boards out of the system was 13,148. The trimmer operator was busy on average 97.56% of the time. The average volume of the large buffer leading into the trimmer area was 2422 board feet (fbm) of a maximum 3000 fbm. The trimmer lug loader conveyor was utilized on average 92.59%. The BAE edger was utilized on average 96% of the time.

7.2 Alternative scenario results

In scenarios two through four, alternative parameters relating to the conveyor speed and machine downtime at the trimmer were selected. Scenario five adjusted the BAE edger parameter in addition to parameters set in scenario four. This was used to determine how the bottleneck would respond under alternative sawmill operation levels. These parameters were manually changed in the model, prior to each scenario run. Table 7 shows the results of each scenario on the metrics described in the above section.

Table 7 : Simulation model results from alternative scenarios

	Average Boards Out (pieces)	Trimmer Operator Busy (%)	Large Buffer Volume (fbm)	Trimmer Conveyor Utilization (%)	BAE Utilization (%)
Base Case	13,148	98%	2422	93%	96%
Scenario 2	14,019	94%	1667	89%	92%
Scenario 3	14,280	84%	409	81%	91%
Scenario 4	14,693	66%	278	66%	92%
Scenario 5	17,294	88%	1353	85%	86%

7.3 Statistical analysis of alternative scenarios

To determine if the scenarios are statistically different from each other, the Welch Confidence interval method was used. This method was selected because it assumes the worst case scenario where both data sets have non-equal variance, and is based on the Smith-Satterthwaite *t*-test. The calculation of the Welch Confidence interval is as follows:

$$d.f. = \frac{\left[\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right]^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{(n_1 - 1)} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{(n_2 - 1)}} \qquad [7]$$

where:

d.f. = *degrees of freedom*
s_1^2 = *sample variance of first alternative*
s_2^2 = *sample variance of second alternative*
n_1 = *sample variance of first alternative*
n_2 =*sample variance of second alternative*

The confidence interval is calculated as:

$$\overline{x_1} - \overline{x_2} \pm t_{d.f.,1-\alpha/2}\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad [8]$$

where:

$\overline{x_1}$ = the mean of the first alternative replications
$\overline{x_2}$ = the mean of the second alternative replications
t = the t value for the degrees of freedom estimated above

If the confidence interval covers the value 0, then there is no significant difference between the two simulation models tested. The results of the Welch Confidence interval are usually presented as [min value, max value]. Using α=0.05, the results of the Welch confidence interval method are summarized in Table 8.

Table 8: Welch confidence interval results for alternative scenario comparison tests

Comparison	Scenario	Degrees of Freedom	*t*-value	Confidence Interval
1	Base Case vs. Scenario 2	41	2.0195	[-1356, -385]
2	Scenario 2 vs. Scenario 3	57	2.0024	[-935, 412]
3	Scenario 3 vs. Scenario 4	58	2.0017	[-1120, 294]
4	Scenario 4 vs. Scenario 5	50	2.0085	[-3491, -1710]

Based on the results from the Welch confidence interval method, there was a significant difference in the first comparison when the trimmer lug loader conveyor was increased to 50 ft/min. There was also a significant difference in comparison 4 when the additional BAE adjustment was made. There was no significant difference in comparison 2 and 3 as the confidence interval passed through zero.

7.4 Discussion of scenario analysis

In the first comparison test between the base case and an increase of feed speed to 50 lugs per minute, there is a clear improvement in output. The Welch Confidence does not contain zero, and therefore it can be concluded from this test the two scenarios are different. Based on the average output, there is an increase of 6.6% total board output when increasing the feed speed from 40 to 50 lugs per minute. This is within the ability of the mill to achieve this feed speed rate, however due to the manual labour involved at this station, two trimmer operators would be required to ensure that there is a smooth loading of boards onto the trimmer lug loader.

With the trimmer downtime reduced by 10% in scenario 2, there was only a marginal increase in the average board output. It was assumed that the sawmill could take measures to reduce the downtime of the trimmer by 10%. There was no significant difference between these two scenarios as indicated by the Welch Confidence method. Even when the trimmer lug conveyor speed was increased to 80 ft/min, the increase in average board output was only marginal. This was not significantly different than running at 50 ft/min with the 10% reduction in downtime as shown in Figure 45.

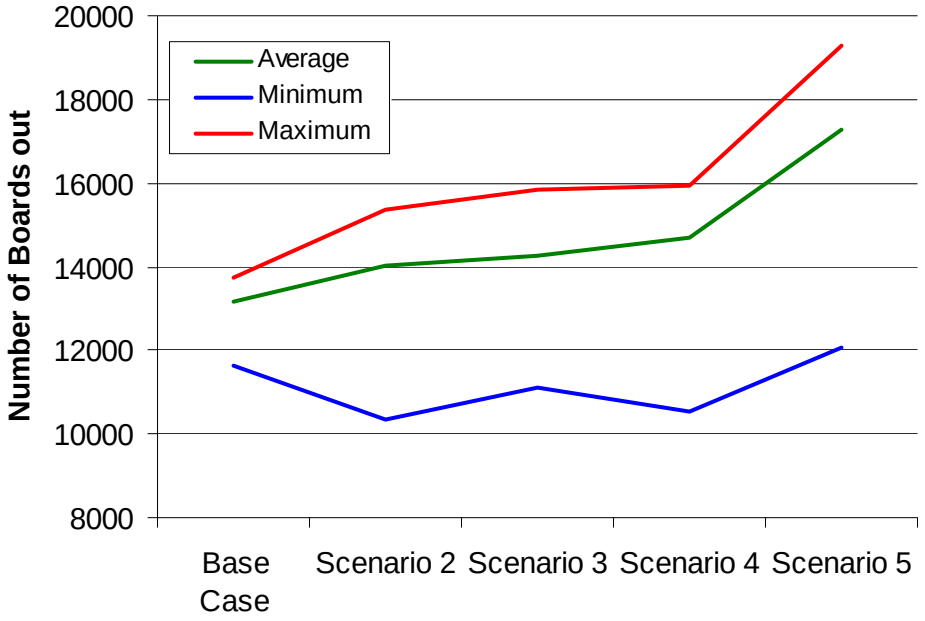

Figure 45 : Average board output from each scenario

The reason that comparison test two and three prove not to be significantly different even though lug speed is increased with a reduction in downtime, is that the bottleneck of the system shifts from the trimmer back to the BAE edger, as shown in Figure 46.

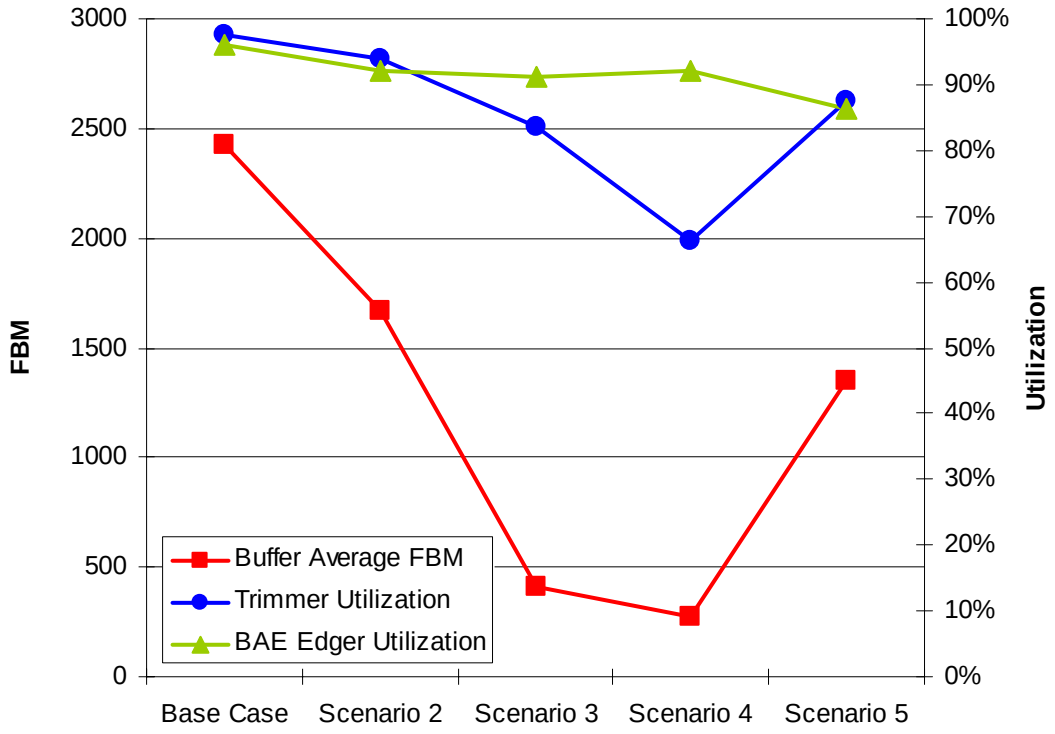

Figure 46: The change in model attributes under alternative scenario run conditions

With the increase in lug speed to 50 ft/min there is a noticeable decrease in the average volume of boards in the large buffer prior to the trimmer. There is also a slight decrease in the average trimmer utilization. Adding the reduced trimmer downtime has a larger effect on the volume of lumber in the buffer and also a noticeable decrease of the trimmer utilization. Under these conditions, the buffer is on average 14% full, as the trimmer is able to reduce the boards waiting in that buffer. The trimmer operator will sometimes be waiting for boards as indicated by the reduced utilization percentage. When the trimmer speed is increased to 80 ft/min, this becomes even more evident. The buffer is 9% full on average, and the trimmer operator utilization is now at 66% on average. However, the

BAE edger utilization is still 92% under scenario 4 indicating that the bottleneck has now shifted to this point.

This is made clear when the process time at the BAE trimmer process time is halved in scenario 5. With the increased process speed, the BAE trimmer is now able to feed lumber into the main buffer at an increased rate. This is shown in scenario 5 from the increase in board volume in the main buffer, to an average value of 1353 fbm. The trimmer operator is now busy 88% of the time as there are now boards to supply the lug loader. The Welch Confidence test indicates that the board output from scenario 4 and scenario 5 are significantly different as the confidence interval does not pass through 0, as shown in Table 8.

Realistically, it is difficult for the trimmer operator to work at speeds in excess of 50 lugs per minute. The operator will not be able to deal with boards that are not perfectly aligned when reaching the lug conveyor. Since the waterfall system used to regulate the board arrivals to the trimmer often results in cross ups, an assistant is required for the entire shift to ensure a smooth delivery of boards to the operator. If the trimmer area is completely redesigned to automatically process boards at 80 lugs per minute, the added capacity must be offset by an increase of production elsewhere in the sawmill.

I focused on the canter line of the sawmill in order to improve output. This is because under current sawmill operations, the canter is not run at full capacity throughout the shift. The entiRe-Sawmill needs to be designed with the goal of achieving a unified balance of operations. Historically, the sawmill was split as two unique manufacturing

lines; the Headrig and the canter. However, this was changed such that both lines fed into the single trimmer at the back end. Under this design, the sawmill is poorly balanced and both process lines cannot run at 100% capacity. An increase in just the trimmer will not achieve a balanced design. This can only be done with improvements to the BAE edger as well as the trimmer. The Headrig and Re-Saw are already in balance and therefore alternative scenarios were not considered for this section of the sawmill. Any changes with either machine center will require a corresponding change in the other in order to maintain the balance.

If the mill management decides to use scenario 2 where the trimmer lug loader conveyor is increased to 50 lugs per minute they can expect to gain improvements of around 7% in board output. This will however require an additional worker to assist the trimmer operator, and will also not balance out the production on the canter line. If the management decides to improve the trimmer and BAE process feed speeds with the purchase of new machinery, they can expect an average increase in board output of around 30% and a greater balanced design throughout the sawmill.

7.5 Using OptQuest for analysis

The shift of the bottleneck from the trimmer to the BAE edger was explored in more detail using OptQuest. As described in section 2.4, OptQuest uses metaheuristics to determine a best solution to the user's objectives. Based on the results from the scenario analysis performed in the previous section, the main bottleneck is the mill 2 trimmer. However, if substantial increases to the trimmer speed is made, the bottleneck shifts to the BAE edger and Headrig. Assuming that further performance gains cannot be achieved from the Headrig, OptQuest was set up to determine the optimal combination of

trimmer lug speeds, and BAE edger feed speeds in order to maximize board output. The simulation optimization was set up such that the trimmer downtime was reduced by the same amount as used in the previous four scenario analyses.

Two OptQuest runs were conducted, each with slightly different assumptions concerning the BAE process times. In the original simulation, the logic concerning the BAE process time is shown in Figure 47.

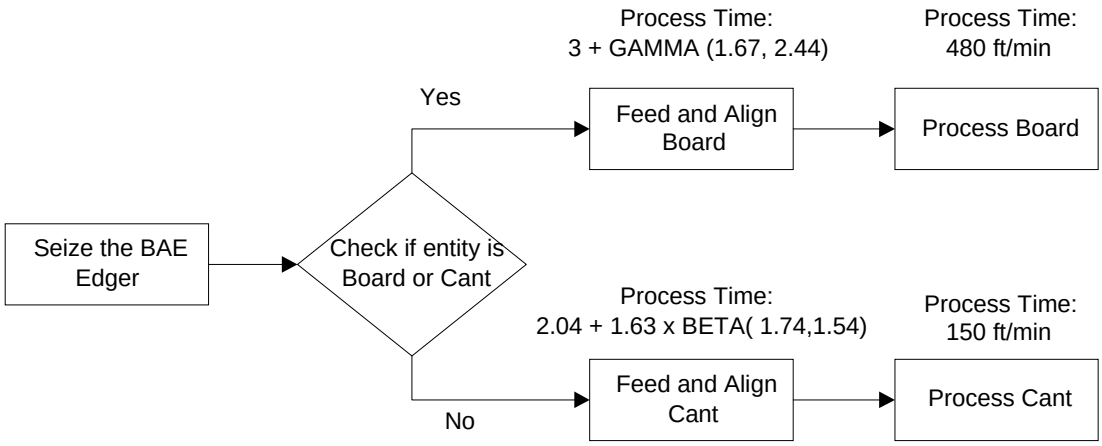

Figure 47: BAE Edger process time logic

The 3 scenarios compared consisted of the following:

1. Base Case as shown in Figure 47
2. Scenario 1 – variable process board and process cant times
3. Scenario 2 – no feed and align process time, variable process board and cant time

In scenario 1, the same process times for "Feed and Align" are kept within the simulation. OptQuest only changes the process board and process cant times. In scenario 2, it is assumed that there is no "Feed and Align" process times. This assumption was made on

the basis that a new BAE edger will most likely have a different time associated with the set up and alignment of boards and cants. Therefore in this scenario, the feed and align times are considered to be part of the total process time. Thus, OptQuest is set up to manipulate only the total process time.

In order to setup OptQuest to run with the sawmill model several steps are required by the user to enter in various inputs. The first input required is to define the control variables that are manipulated by the optimizer. Four control variables were selected:

1. BAE edger –Process Board Time
2. BAE edger – Process Cant Time
3. Trimmer lug loader conveyor – Speed
4. Waterfall conveyor – Speed

The two conveyors control the speed of boards entering the mill 2 trimmer. This process flow is shown in Figure 48.

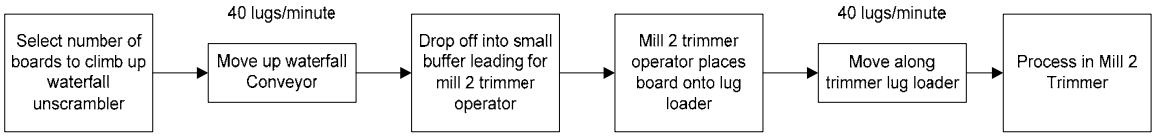

Figure 48: Mill 2 Trimmer process

Once the control variables are established, their range must be established. The minimum settings selected were the current simulation process times and conveyor speeds and conveyor speeds. The maximum settings were set to double the minimum. The step

value indicates the minimum incremental value the optimizer can select for changing the control variable. In the test case this was set at an integer value of 1.

Table 9: OptQuest control variable settings

Control Variable	Minimum	Maximum	Step Value
BAE Board Process Time (ft/min)	480	960	1
BAE Cant Process Time (ft/min)	150	300	1
Waterfall Conveyor Speed (lug/min)	40	80	1
Trimmer Conveyor Speed (lug/min)	40	80	1

The constraint settings must also be obtained from the user. OptQuest can handle two types of constraint settings: control variable constraints and overall process requirements. No control variable constraints were selected for the test. However, a process requirement was used which stipulated that the mill 2 trimmer operator utilization could not drop below 80%. This constraint was selected because in the scenario analysis, increases to trimmer lug conveyor speeds resulted in decreasing trimmer operator utilization as shown in Figure 46.

Finally, the user must select the run time requirements for the optimizer. The simulation/optimization can be set to run for:

- *x* number of simulations
- *x* number of minutes
- a future date
- *x* number of non-improving solutions

Further options allow for setting a fixed or variable number of replications and stopping when the 95% confidence interval half width is within *x* of the mean. For the test, the run requirements were set to 100 simulations with 30 replications.

7.6 OptQuest results

Results of the simulation/optimization run for both scenarios, as well as output from the base case in the scenario analysis are presented in

Table 10.

Table 10 : Output from the OptQuest scenarios

Variable	Base Case	Opt-Quest Scenario 1	Opt-Quest Scenario 2
Average Boards Out (# of boards)	13,147	16,708	17,996
BAE Board Process Time (ft/min)	480	935	487
BAE Cant Process Time (ft/min)	150	300	257
Trimmer Conveyor Speed (lugs/min)	40	70	78
Waterfall Conveyor Speed (lugs/min)	40	40	67
Mill 2 Trimmer Utilization (%)	98%	85%	94%

Results from the OptQuest analysis confirm those observations made by the manual scenario analysis. The BAE limits total boards out when the trimmer conveyor speeds are increased. This is particularly evident with the set up times required for loading boards and cants into the BAE. If the setup times are removed in scenario 2, the BAE feed speeds for boards must be increased by 7 ft/min, while the cant process time must be increased by 107 ft/min. This will ensure maximum board output, while still maintaining the mill 2 trimmer operator to be utilized.

8 Conclusion

The objective of this thesis was to provide the mill management team with information and recommendations on where productivity improvements could be made in their sawmill. To determine this information, a simulation model of the mill was developed. Simulation was selected to analyze this problem for a number of reasons. Simulation was able to deal with complex random elements that exist in a sawmill. The simulation model could quickly determine the effects of different manufacturing decisions without interrupting actual production of the mill. The use of animation integrated with the simulation software helped to convey the results of the model to the mill management and were able to see the impact of various process decisions on mill flow as pieces were routed to the various machine centers in the mill.

The simulation study was based on the framework outlined by Law (2003). In order to develop the model, data was collected pertaining to mill layout, the flow of material, log breakdown patterns, log parameters, machine process times and downtimes, conveyor parameters, and buffer capacities. A concept model was developed with the information collected. This initial structure was used to program the model using Arena 8.0 from Rockwell Automation. Probability distributions for machine process times were generated using the Input Analyzer software packaged with Arena. The model was considered to be valid by conducting a face validity test with the mill management team, as well comparing the actual mill output with the model output. Five different mill scenarios were analyzed to determine how process bottlenecks were affected by of

changing machine parameters. These scenarios were also compared to the model output when using the OptQuest simulation optimizer.

I discovered that when running only the Headrig line, or the canter line, the sawmill was constrained by these primary process centers. However, if both machine centers are used, the mill 2 trimmer becomes the sawmill bottleneck. If the mill 2 trimmer speed is increased from 40 feet per minute to 50 feet per minute, combined with a reduction in downtime, the bottleneck shifts from the mill 2 trimmer, to the BAE edger. Under these conditions, the average board output increased by 8.6% over the base case. If the speed of the mill 2 trimmer is increased to 80 feet per minute, machine downtime is decreased in half, and BAE processing speeds doubled, the average board output will increase by 31.5%. However, at these speeds an automated system must be implemented in order to feed boards into the trimmer. Further tests were conducted running the simulation model combined with the OptQuest Analyzer packaged with the Arena software. These two tests were used to gain further insight into the shift of the bottleneck from the mill 2 trimmer to the BAE. The OptQuest Analyzer was set to maximize board output, while changing BAE process times and mill 2 trimmer process times, while maintaining a trimmer utilization of over 80%. When there was no feed and align time associated with the BAE edger, the OptQuest Analyzer found a solution that would yield an average board output of 17,966 boards per shift. This is an increase of 36.6% over the initial base case output. When the set up times for the BAE edger were included, the average board output was 16,708 boards per shift. This is an increase of 27% over the initial base case. The mill management was presented with the findings from this thesis and decided to conduct improvements to the mill 2 trimmer area of the mill, as well as increasing the

feed speed of the lug loader to 50 ft/min. These changes resulted in an increase of 10% to mill output.

With the current low prices for lumber in North America, combined with the additional tax restrictions in place from the current Softwood Lumber Agreement, sawmills are under increased pressure to remain profitable. The results from the simulation model were able to provide the mill management with accurate information of where upgrades to the mill should be considered, and the potential improvement in mill productivity that could be expected. Although mill management felt that the mill 2 trimmer was a process bottleneck based on observations from their daily operations, the simulation model confirmed that this was indeed the case. More importantly, the model was able to show that the bottleneck would shift to the BAE if only improvements to the mill 2 trimmer were made. An improvement in one processing center will often create a problem in another. It is important to consider that any improvements to the sawmill must be balanced for the whole operation.

There were several limitations to the model. The model is not capable of accurately predicting specific details of the lumber outputs. While the model does report on basic dimensions, it is unable to provide specific information relating to grade, wane, and other characteristics impacting the price of lumber . The current breakdown logic for the Headrig and canter is unable to determine that complex information. Consequently, the model is unable to provide accurate information relating to profitability. The model was set to run with both the canter and Headrig continuously throughout the shift, even in the base case. In the actual mill this was not the case, as the canter was typically run

sporadically throughout the shift. This made it difficult to compare the outputs from model to the mill, and as a result, more weighting of the model validation was given to the face validation conducted with the mill management. The model is not designed with a user friendly interface. In order to run simulation tests, it requires someone knowledgeable with the Arena software, and the model itself, in order to set up the proper conditions for a simulation run.

There are a couple of areas for further research on this project. One area is to investigate the existing technology available for the sawmill to upgrade their mill 2 trimmer and BAE edger. Processing capabilities of possible machines can be implemented to the sawmill model to determine how they will affect mill flow, and what can be expected in terms of board output. Another area of further research is to add processing costs and product prices to the simulation model. With this information, the OptQuest Analyzer could be set up to determine what should be cut based on changing market prices for lumber produced. This would require redesigning the breakdown logic to cope with internal defects, and shape characteristics of both the log and lumber.

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