AN ABSTRACT OF THE THESIS OF

Olivia J. Pinon for the degree of Master of Science in Wood Science and Mechanical Engineering presented on May 26, 2005.

Title: Using Discrete-Event Simulation to Study the Influence of Log Yard Sorting on Sawmill Processing Efficiency of Small-Diameter Timber

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A sawmill is similar to other manufacturing enterprises when it comes to making decisions, scheduling production and meeting customer demands. In order to help sawmills achieve their goals, and because there is such a high degree of variability in the raw material used in this industry, computer simulation has proven to be a very valuable tool to help improve productivity and processing efficiency. Raw material variability is expected to be an increasing issue in coming years due to an increase in small-diameter timber on the market resulting from the thinning of overstocked forest stands. These changes are expected to result in a significant decrease in production for mills that are not equipped to process this type of material. As a means of analyzing the influence of these changes, this thesis details the development and use of a discrete-event computer simulation model of the Warm Springs Forest Products Industries sawmill in Warm Springs, OR. This research is part of a larger project in which other improvement scenarios were studied (Salichon 2005).

The simulation model was first used to identify some possible areas of improvement and to optimize the current overall process and production of the sawmill while operating with its current log distribution. The study identified a

number of opportunities for improvement. It was demonstrated that increasing the unscrambler maximum capacity up to 800 boards resulted in an increase in piece count production ranging from 2.6 to 5.3%. The influence of machines downtimes as well as the influence of having a second operator assisting at the horizontal resaw were also investigated.

Past studies have shown that log sorting is an essential condition to achieve high production in a sawmill. The simulation model was used to evaluate sorting strategies that would minimize the decrease in production resulting from introducing small-diameter timber (5 to 7 inches) into the log supply. Different small-diameter distributions were tried and different sorting solutions were tested for each of the log distributions. It was shown that the mill would suffer a decrease in piece count production ranging from 10.1 to 13.1% if their current two decks sort is retained. However, it was demonstrated that implementing a three decks sort would considerably reduce this drop in production to only 4.7 to 6.4%.

Simulation has been shown to be a very valuable tool that sawmills can use to investigate production and other log supply issues. While piece count production was sufficient for analyzing current mill efficiency changes, the introduction of smaller diameter logs will also reduce the board feet per piece ratio. Due to the loss of the trimmer data during the test run, no information can be provided about board footage and thus the results and statistics in this research were based on piece count only. However, future work could be done with log breakdown models like BOF or SAW3D to determine board footage. Future research could also focus on studying the influence of the trimmer's downtimes on the unscrambler queue and other machine utilization rates as well as testing mathematical algorithms that will search for other optimized sorting and feeding strategies.

Using Discrete-Event Simulation to Study the Influence of Log Yard Sorting on Sawmill Processing Efficiency of Small-Diameter Timber

by
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“The art of modeling is best learned through experience”

Randall Sadowski

Using Discrete-Event Simulation to Study the Influence of Log Yard Sorting on Sawmill Processing Efficiency of Small-Diameter Timber

1. INTRODUCTION

The expected increase in small-diameter timber on the market in the next few years resulting from the thinning of overstocked forest stands will be a utilization issue for mills that are not equipped to process this type of material. While it is possible that new mills might be built to specifically handle small-diameter timber, it is more likely that this type of material will flow to existing mills. Thus, a massive increase in small-diameter logs into the log supply of an existing sawmill may result in dramatic consequences if the sawmill hasn't been optimized to process this type of material. Although a decrease in production resulting from processing small-diameter logs can be expected, the consequences of processing these log sizes on machines' performance and the overall flow of the mill are unknown. As shown in past studies, log sorting is an essential condition to achieve high production in a sawmill. However, testing sorting solutions on a real log supply cannot be easily handled. Similarly, the influence of changes in log distributions on the overall sawmill performance cannot be precisely predicted.

Computer simulation is a valuable tool that can be used to analyze new strategies without disrupting an overall system. Previous sawmill simulation studies have already been conducted on small-diameter timber, but none have been conducted on an existing sawmill and its normal log supply. Computer simulation was thus used in this research to gain a better understanding of the behavior of an existing sawmill and to define log yard sorting strategies that will help increase the processing efficiency of small-diameter timber.

2. LITERATURE REVIEW

2.1 Small-diameter timber and its influence on sawmill production

Due to decades of successful fire suppression, overstocked stands of small-diameter and underutilized (SDU) material kept increasing in many forests. Those small trees and brushes now represent a substantial wildfire hazard. SDU are also responsible for insect infestation, a decrease in quality mix of species and disease problems. It is now necessary to thin those overstocked stands to improve forest health and decrease the risk of catastrophic wildfires (LeVan-Green and Livingston 2001a). Treatments will require removing an increasing number of trees with a mean diameter at breast height of 9 inches (mean small-end diameter of 7 inches), which are the main components of these overstocked stands (Wolfe and Moseley 2000; Wagner et al. 2002; Steward et al. 2004). However, the harvest cost for this type of material is high and the market for small-diameter material is limited. Therefore, it is essential to find value-added uses for this type of material (LeVan-Green and Livingston 2001a). Many projects are looking at potential value-added uses for small-diameter timber, such as dimension and non-dimension lumber, cut-stock (Lowell et al. 2000), structural roundwood, wood composites, wood fiber products, pulp chips, compost and mulch, energy or bio-fuel (Forest Products Laboratory 2000b; LeVan-Green and Livingston 2001a; LeVan-Green and Livingston 2001b; LeVan-Green and Livingston 2003).

From a sawmill's standpoint, an increase in small-diameter timber on the market might be an issue if the mill is not equipped to process this type of material. Headrigs can only process a limited number of logs per minute. Thus, if the logs being processed are too small, the machines downstream become underutilized and production volume decreases because not enough material flows through the mill. It then becomes essential for a sawmill to be able to process enough logs to maintain a proper production volume and thus generate a benefit (Barbour 1999). While it is possible that new mills might be built to specifically handle small-diameter timber, it is more likely that the material will flow to existing mills. Simulation, as in this research, can be used to help an existing sawmill, which is not a small-diameter timber sawmill, increase its processing efficiency in order to be able to handle small diameter timber.

2.2 Overview of simulation

Simulation is generally defined as any computer program or computer model representing a manufacturing system (e.g. a sawmill, machine shop, etc.) (Wiedenbeck and Araman 1995a). Simulation models can be classified according to different characteristics, depending on the kind of system they are representing. They can be static or dynamic, deterministic or stochastic, and continuous or discrete.

A static model is used when the passage of time doesn't play any natural role (Kelton et al. 2004). A dynamic model, on the other hand, has to be used if a system that changes over time is represented. Dynamic models are the most frequently used.

A model is said to be deterministic when it has no random input. However, most of the manufacturing systems that are studied contain random variables in one or many of their components. Thus, stochastic models that operate with some inputs being random need to be used to simulate these kinds of systems. Random inputs are usually represented by statistical distributions used to describe the probability that an event will happen at a certain time. It should be noted that stochastic models can produce uncertain output and thus, extra care must be used when interpreting the results provided by the model runs. Because results provided by such models are only an estimation of the expected performance of the system under consideration, multiple runs are necessary. Deterministic models, on the other hand, provide results that are exactly the same, as long as the inputs aren't changed.

Finally, a simulation model can either be continuous or discrete. In a continuous model, state variables change continuously over time. In a discrete model, though, state variables change only at a finite number of distinct points in time.

The system of interest in this thesis, a sawmill, evolves over time and possesses randomness in the way the material is processed as well as in its input and output. In addition, the state variables are changing only at specific time points, when events occur. For example, the number of boards produced by the sawmill changes only after a board reaches the sorter. Therefore, a sawmill has discrete, dynamic, and stochastic characteristics. The model being implemented is thus defined as a discrete-event simulation model.

The use of simulation as a tool for analyzing and investigating a manufacturing system has advantages and disadvantages. Computer simulation is a powerful tool for investigating entire manufacturing systems (Kline and Araman 1990) and for analyzing the effect of different alternatives, designs or new production methods on a system that can't be disrupted (Reeb and Leavengood 2003) or that cannot readily be physically handled. By designing a model of a real system, one can experiment with this model in order to gain a better understanding of its behavior, to evaluate various plans for using it (Pegden et al. 1995) and to study the influence of a change on the overall system performance as well as on important output variables (Kline et al. 1992; Wiedenbeck and Araman 1995a;

Wiedenbeck and Araman 1995b). This allows making sure that a costly change is worthwhile. Managers and engineers in general are really concerned about having an overall view of the system performance after a local change has been made, as a local change can have considerable and unpredictable consequences on the overall system performance (Law and Kelton 1991; Wagner and Ladd 1991). Changes in log input mix, equipment, and downtimes are the kinds of scenarios that simulation modeling can help look at (Adams 1984). Alternative management techniques can also be considered before being brought into practice (Kline and Araman 1990). Simulation modeling can also prove to be very useful in identifying and solving bottlenecks, as it allows the analyst to examine different ways of removing them (Wiedenbeck and Kline 1994). Another advantage to be considered is that simulation allows the time of the system's operation to be compressed or extended, making possible the simulation of months and even years of activity in just a few minutes of computer time (Wayne and Pooch 1980).

Simulation also offers the ability to model random behavior or variation (Reeb and Leavengood 2003), allowing the user to compare and experiment with numerous operating strategies. By modifying the input parameters, the behavior of a system can be tested under multiple situations and conditions as often as necessary (Wayne and Pooch 1980). For projects where simulation is used, project costs might be higher during the project design phase, but the overall cost is often less because implementation and operation can be less expensive when simulation is used (Figure 1).

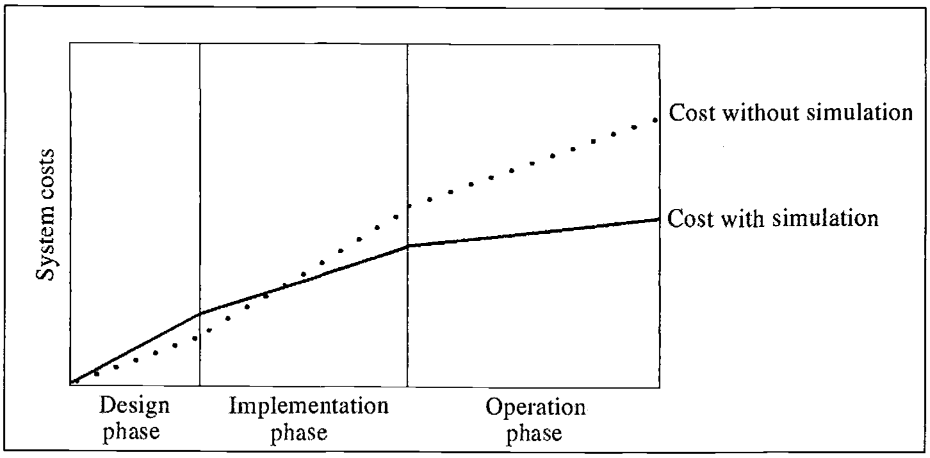


Figure 1. Comparison of cumulative system costs with and without simulation (Harrell et al. 2000).

The animation feature found in most of today's simulation software packages is another great characteristic of simulation and is also what makes simulation a powerful and effective industrial engineering tool (Wiedenbeck and Araman 1995a). The animation feature can prove to be very valuable during the model verification and validation steps that will be discussed later, as it helps in identifying problems which makes solving them faster, making model development easier and faster as well. Animation is also a very good communication and documentation tool and can assist managers in making decisions by illustrating why and under which circumstances a solution can be effective (Kline et al. 1992). Animation is also very beneficial for anybody who needs assistance in understanding a particular system (Kline and Araman 1990; Wiedenbeck and Araman 1995a).

As with all research tools, simulation modeling also has some drawbacks. One of them is the time it can take to model a real system, especially one that is large and complex. Depending on the system being studied, data might not be available or a large amount of data might need to be analyzed, increasing the time it takes to develop a model. This can be an issue in the case where a project has to be completed in a short period of time. Another possible problem might come from a lack of understanding of the results provided by the simulation model. It is important that the expectations, goals and assumptions under which the model is performing are well defined (Wiedenbeck and Araman 1995a). Therefore, the experience of the person modeling is also a factor to be taken into account. Because stochastic simulation models have some random inputs, they only provide estimates of the performance of the system, as their outputs are random as well. Thus, a number of independent runs need to be performed for each set of input parameters to be studied (Law and Kelton 1991). Finally, the analysis and the interpretation of the system might be very time consuming, resulting in an increase in model development time (Adkins and Pooch 1977).

It should be noted that using simulation is not always appropriate. In the case where the system to be modeled is not very detailed, it might be more appropriate to use another technique, as simulation has been more specially developed to study complex systems. Finally, designing a simulation model can be avoided in the case where it might be possible to experiment with the actual physical system (Banks and Gibson 1996; Kelton et al. 2004)

2.2.1 Modeling procedures

While there are no strict rules on how to perform a simulation study, the following set of steps is usually recommended to guide a model builder in a thorough simulation study (Figure 2). Similar figures and discussion steps can be found in other sources (Shannon 1975; Law and Kelton 1991). It should be noted that a simulation study is an iterative procedure, in which steps are refined and even sometimes redefined with each iteration.

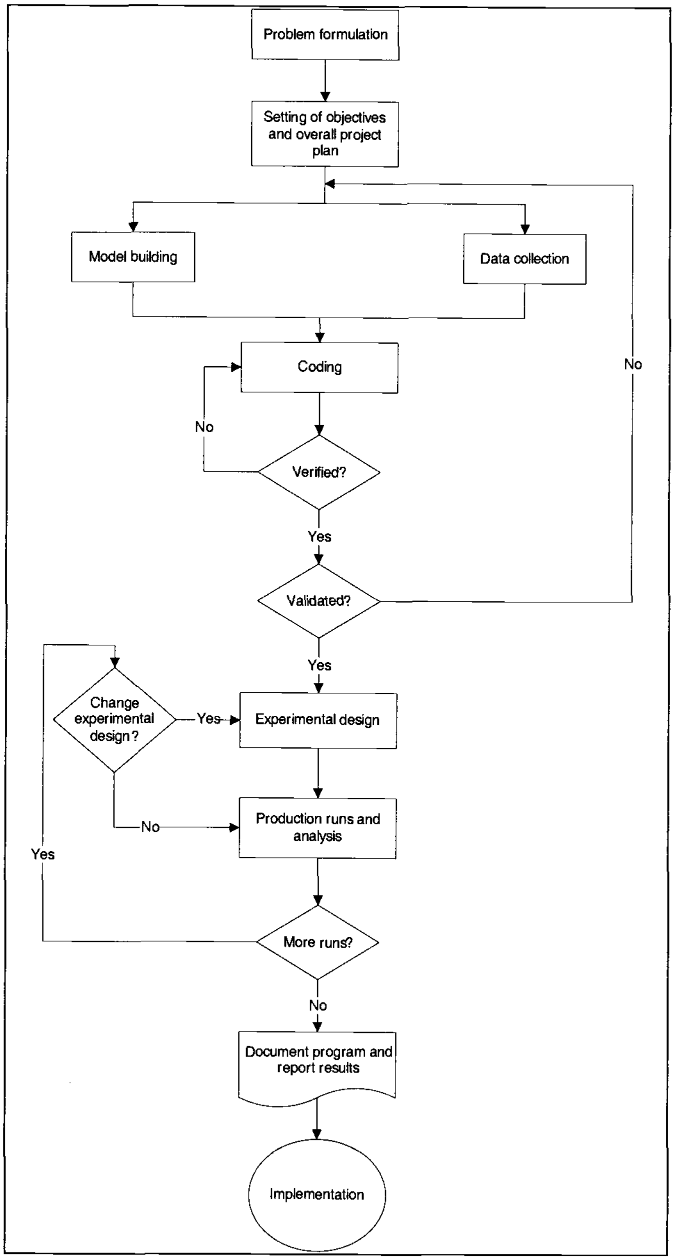


Figure 2. Procedures in conducting a simulation study (from Banks and Carson 1984).

The primary step involved in solving any kind of problem is to define and formulate the problem properly in order to make sure that the person who is in charge of solving it fully understands what the purpose and the ultimate intended use of the system to be modeled are going to be. A model can only answer the questions for which it has been developed (Banks and Gibson 1996). Once this is done, the objectives and the methodology that will be used to solve this problem must be set. The questions that the simulation model has to answer have to be clearly stated. In the same manner, an effort should be made to identify the constraints (deadlines, resource availability, etc.), as they could have a limiting effect on achieving the defined objectives. It is also very important to try to bound the system to be studied, knowing that those boundaries may eventually be expanded or contracted as the modeler learns more about the problem and system (Kelton et al. 2004). The level of detail with which the model will be built also needs to be determined but can be re-evaluated later on if there is a need to do so.

The next step concerns building the model. Building a model first consists of observing the real system and studying the various interactions that compose the system. Then, based on the observation of the real system, assumptions and hypotheses can be drawn (Wayne and Pooch 1980). The goal of model building is to provide a valid representation of the real system by transposing the real system into mathematical/logical relationships (Lin et al. 1995), and the real system is usually simplified based on assumptions that have been made (Banks and Carson 1984; Akbay 1996).

A step that is generally conducted in parallel with development of the model is data collection (Shannon 1975). Collecting data is the most time consuming stage in the simulation process but is also the phase rated as being the most difficult (Cochran et al. 1995). Therefore, it should be started as early as possible, usually together with the first stages of model building (Banks and Carson 1984). The kind of data to be collected depends on the objectives of the study. For example, Aune (Aune 1974) defined the data to be used in sawmill simulations as log population characteristics, process times, buffer capacities and product output characteristics. Adams (Adams 1984) used log characteristics, processing procedures, processing times and downtimes, conveyors capacities and speeds as well as the product routing information as key input parameters to the design simulator (DESIM) he developed to design and simulate hardwood sawmill systems. Wagner and Taylor (1983) used machines, conveyors, surge decks, lumber volume and lumber-grade yields from logs of different diameters, lengths, and grades as well as machine processing rates by log diameter, length, and species as data for their MSUSP simulator. Dogan (Dogan et al. 1997) described a simulation model of a hardwood sawmill that used seven types of data. Those were material characteristic distributions, processing times, setup times, downtimes, process flow probabilities, material divergence distributions and conveyor speeds and capacities. The required parameters needed for a sawmill simulation depends on the objective of the study being conducted and the questions that the simulation tries to answer.

The next step in simulation concerns the coding, or programming of the model. Today's simulation packages, such as Arena (Rockwell Software), provide the modeler with a visual environment for model building and experimenting. There is no need to be proficient in a programming language such as FORTAN or a simulation language such as SIMAN or SLAM anymore, but having an expertise in a programming language is always an advantage. Today's simulation software packages provide the user with a nice model development environment, which is usually a large workspace on which blocks or modules can be placed to represent the logic of the system and on which graphics can be added as well.

A verification step following coding is an essential one and has the purpose of making sure that the model behaves and executes as expected by the modeler. The verification process consists of identifying and correcting unintentional errors or bugs in the model. A good way to conduct model verification is by testing the model over and over during the development phase. Model animations are also extremely valuable in debugging and verifying the model.

Once the model has been verified, it needs to be validated. Validating a model implies proving that the model is an accurate representation of the real system. This step has the primary goal to make sure that the model behaves close enough to the real system in order to use the model as a substitute for the actual system and to be able to experiment with it. Another goal of validation is to make the managers or decisions makers confident about the results provided by the model so that they can make decisions based on those results.

Validation can be achieved by comparing the results from the model with the results historically produced by the actual system operating under the same conditions (Wayne and Pooch 1980; Law and Kelton 1991). For instance, the number of boards produced by the model can be compared to the number of boards that have been produced by the actual mill (Figure 3). This technique is called the correlated inspection approach (Law and Kelton 1991).

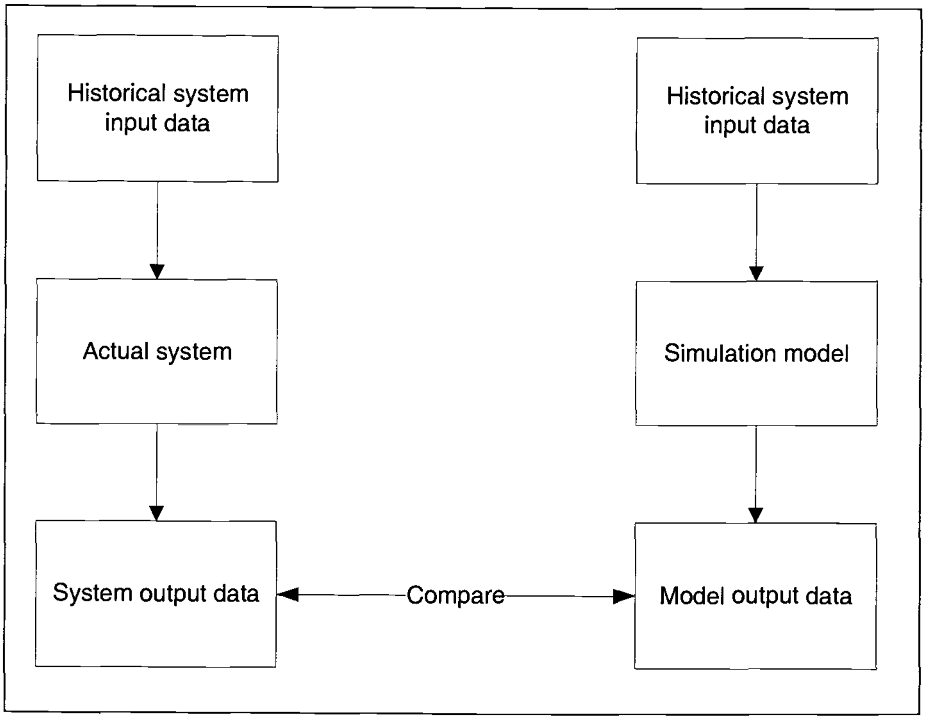


Figure 3. The correlated inspection approach (Law and Kelton 1991).

The results can also be shown to persons knowledgeable about sawmill operations who make sure that the model behaves the way it should (Lin et al. 1995; Wiedenbeck and Araman 1995b). In addition, sensitivity analysis can be used to assess model validity. A change in input variables can be made in order to see if the model performs or behaves as expected. Another method, called the post-model development procedure, can also be used. In this procedure, the first step is to make sure that the model accurately reflects the real system. Then, a change is made in both the real system, and the model and outputs from the altered model are compared with outputs provided by the modified system. If the two outputs are similar, then the model is considered accurate and is validated (Wagner and Taylor 1983). The validation process is an iterative process and is repeated until the model demonstrates an acceptable accuracy.

Once everybody agrees on the fact that the model is an accurate representation of the real system, experiments can be conducted and alternative scenarios studied. For each system design that is simulated, the initial conditions, the length of the simulation runs and the number of replications to be made of each run need to be determined (Law and Kelton 1991).

Then additional runs are made and statistical analyses are conducted on the generated output variables to estimate measures of performance for the system design or alternative scenarios being tested. Statistical analyses are done in order to gain some assurance and confidence that the estimated measures of performance are accurate enough. A statistical technique often used is the calculation of confidence intervals for those estimates.

The next step is to document the model in order for different modelers or users to be able to use the model and eventually modify it later on by understanding how it operates. It is also very important to document clearly and concisely all the assumptions that went into the model, as well as the results of all the analyses that have been performed.

Finally, the results of the simulation study are implemented. The success of the implementation phase depends entirely on the previous steps and on how well they have been completed.

With the exception of the implementation phase, all these steps were applied for the model developed in this project. Their applicability in the case of this project is described in the methodology section.

2.2.2 The different simulation pieces

As for all domains, simulation comes with its specific vocabulary and concepts that are very important and necessary to know in order to grasp how a model is built. The first term that needs to be defined represents the items that are moving through the system (Randhawa et al. 1994; Kelton et al. 2004). Those items are called entities and can be of different types. In the case of sawmill simulation, an entity can be a log, cant, board, slab, lumber or chips, for example. In a sawmill model, the first entity created is a log, which is bucked into segments. Then the segment is processed through the headrig, which then leads to the creation of different types of entites such as cants and slabs. The log entity is then disposed of and the newly created entities can start moving around in the system, before being disposed of later on when processed into boards or other entities.

Each entity has characteristics or properties attached to it that are called attributes. Attributes are tied to the entity during the whole time the entity is in the system. Examples of attributes are diameter, length, processing time, width and thickness. Many entities could have the same attribute, but the attribute would have a different value for each entity. For example, two logs (entities) can have "diameter" as an attribute, but for one of them the diameter (attribute) would be equal to 6 inches, while for the other one the diameter would be 10 inches.

Another essential term is a variable, also called a global variable. Variables are not linked to an entity like attributes, but they are related to the entire model. Variable values can also change during the simulation run. Variables are accessible by all entities and can be changed by an entity as well. An example of a variable would be the percentage of logs with 7 inch diameters that enter the system or the number of boards in the sorter.

Finally, one of the most important terms to understand is the event. An event represents anything that happens during the simulation that might change attributes or variables. Events can be categorized into three different types: the creation event (when log are created), the process event (when an entity is being processed) and the schedule event (when a machine goes down).

2.3 Discrete-event, stochastic simulation models used in the wood products industry

Computer simulations have been used to improve productivity and processing efficiency within many different sectors of the wood products industry. A lumber company is similar to other manufacturing enterprises when it comes to making decisions, scheduling production and meeting customer demand. In the case of a sawmill, for example, a manager has to pick the right logs to be processed and determine the appropriate sawing procedures in order to make sure that the final product satisfies customer requirements (Mendoza et al. 1991a). While different types of simulation models have been used in the wood products industry, this section will only discuss discrete-event, stochastic sawmill models.

Due to today's economic environment, there is a need for the wood products industry as a whole to improve and optimize its productivity as well as to enhance processing efficiency (Mendoza et al. 1991b). In order to help lumber companies achieve their goals, and because there is such a high variability in the raw material used in this industry, simulation has proven to be a very valuable tool when it comes to analyzing production and design alternatives (Randhawa et al. 2001). Thus, computer simulation has been used within various sectors of the wood products industry, including models that: simulate a double-arbor edger to demonstrate important concepts of sawmill simulation (Aune 1974); evaluate production parameters within planned or existing sawmill operations (Aune 1982); assist managers in making decisions in rough mills (Kline and Araman 1990; Kline et al. 1992); assist in designing and evaluating sawmills (Adams 1984; Hall and Jewett 1988); demonstrate the feasibility of utilizing short lumber in a crosscut-first rough mill (Wiedenbeck 1992); estimate profits from sawing - competitively bid timber (Wagner and Taylor 1983; Howard 1988) ; serve as a planning-tool in developing production schedules (Mendoza et al. 1991a; Mendoza et al. 1991b) ; help in the design and evaluation of log-to-dimension manufacturing systems (Lin et al. 1995) ; measure the effect of lumber length on equipment utilization and the volume and value of the rough parts produced for a rough mill (Wiedenbeck and Araman 1995b) ; determine sawtimber value and allocate sawlogs to sawmills (Wagner et al. 1996) ; study both crosscut-first and rip-first production systems (Gazo and Steele 1995) ; investigate the introduction and processing of small-diameter sawtimber (Wagner et al. 1998; Wagner et al. 2000; Steward et al. 2004) as well as its utilization opportunities in the furniture and cabinet industries (Wiedenbeck 1993) ; evaluate softwood sawmill performance and more specifically the effect of log size on the volume of lumber produced (Wagner and Ladd 1991) ; analyze equipment replacement in wood-products manufacturing (Carino et al. 1995; Dogan et al. 1997) and the addition of a third grader in a planer mill (Reeb 2003) ; and study the influence of sorting lumber by grade prior to rough mill processing (Steele and Gazo 1995). Research work done by graduate students on simulation projects applied to sawmills has recently increased as well, showing the interest of the wood products industry in the advantages provided by simulation (Ismihanoglu 2002; Szewczyk 2002; Poplawski 2003).

Mendoza et al. (1991) combined a simulation and optimization model in order to find and implement an optimal production schedule. The optimization model was used to determine a favorable log input combination to be processed that would meet lumber demand. In the simulation model, sawmill logic and material flow databases were included, enabling the model to be used for different purposes such as analyzing the log breakdown operation and sawing policies, forecasting production scenarios, designing, implementing and analyzing alternative production systems. They also emphasized the fact that simulation results provide significant and valuable information to the manager about the presence of potential bottlenecks, queue length or the determination of the lumber output mix.

Dogan et al. (1997) used Arena to develop a discrete-event simulation model of a hardwood sawmill to study the influence that replacing the trimmer had on productivity as well as on other areas in the material flow. Then they added a green chain area to the model and the complete model was thus used to determine the best grade mix of logs to cut in order to enhance the grade recovery and maximize profits. The sawmill being modeled was composed of two headrigs, a gang rip saw, an edger, a trimmer and a green chain. The key input parameters used in the sawmill model were the material characteristics distributions, processing times, setup times, downtimes, process flow probabilities, material divergence distributions and finally conveyor speeds and capacities. The validation step was conducted by comparing the model output with daily sawmill reports from the previous year. Results were checked by the mill manager and were considered valid if they fell within three percent. The change in productivity caused by the use of a new trimmer was investigated and it was concluded that the introduction of a new trimmer would increase production. The influences changing the trimmer had on the queue length and utilization rate of each machine were also studied and the results obtained showed that the utilization rate of the new trimmer was lower than for the previous one, indicating that the bottleneck occurring with the old trimmer was eliminated. Then, the sensitivity of the system output to the processing time of the trimmer was analyzed and provided the mill manager with an optimal speed for the trimmer station. Finally, a grade recovery study was performed in order to determine if sorting the log yard by grade would be advantageous in terms of grade recovery improvement. However, due to a lack of long-term data, no valid conclusions were drawn concerning the grade recovery study.

Wagner and Taylor (1983) developed a discrete-event simulation model of a southern pine sawmill to demonstrate sawmill modeling methodology and show how computer simulation can be used by sawmill managers to anticipate production and profit at their mill. The SPSM (southern pine sawmill model) model developed by Wagner and Taylor (1983) may also be used to analyze how a change in production rates, equipment, personnel, log quality, log costs, lumber grades, lumber prices, variable and fixed costs or material flow can affect the mill production output and profit. The model was developed using SLAM, a FORTRAN-based simulation language. Machine centers, conveyors, processing times, machine downtimes, log breakdown methods, log quality, log sizes, log costs, overhead costs and other parameters affecting the effectiveness of the overall system were included in the SPSM model. The model was validated using the post-model development procedure. They used the model to investigate the profitability of purchasing logs at a given bid price as well as overall sawmill performance and production levels resulting from processing those logs.

Wagner et al (1998) used a simulator (MSUSP) to investigate the potential for small-diameter sawtimber utilization by the current sawmill industry in western North America in order to determine whether the value of small-diameter sawtimber equaled or surpassed the costs of harvest and delivery to sawmills in that region. Typical random-length and stud sawmills were designed using the MSUSP simulator. Data such as machines, conveyors, surge decks, lumber volume and lumber-grade yields from logs of different diameters, lengths, and grades as well as machine processing rates by log diameter, length, and species were collected in order to design models as accurately as possible. Multiple runs of an 8-hour shift were then carried out by the MSUSP simulator with a different sawtimber dbh (diameter breast height) class being evaluated in each run. The logs had dbh's ranging from 6 to 18 inches at the random-length sawmill and from 6 to 14 inches at the stud mill. After each run, the profit/loss for three investment scenarios (25 percent ROI, 10 percent ROI and only variable costs covered) as well as the volume of sawtimber processed were recorded. Results suggested that the profit resulting from processing small-diameter sawtimber was not covering the expense of harvesting and delivering the logs for sawtimber less than 10 inches dbh and a 10 percent return on investment (ROI) capital. The authors also came to the conclusion that even an increase in processing speeds did not compensate for the low volume per piece obtained from small-diameter sawtimber.

Based on those conclusions, Wagner et al (2000) investigated the potential for a high-speed, small log sawmill and used the MSUSP simulator to compare that type of sawmill with the conventional stud mill described in their previous paper (Wagner et al. 1998). As before, a specific 1 inch increment sawtimber dbh class was assessed in each run, and after each run, the profit/loss for three investment scenarios (25 percent ROI, 10 percent ROI and only variable costs covered) as well as the volume of sawtimber processed were recorded. Results suggested that the profit resulting from processing small-diameter sawtimber was not covering the expense of harvesting and delivering the logs for sawtimber less than 9 inches dbh and a modest 10 percent return on investment (ROI) capital. However, for modern, high-speed, small-log sawmills, the breakeven value of sawtimber 6 inches dbh or larger covered the cost of harvest and delivery to this kind of mill. Thus, small-dbh sawtimber coming from ecological-restoration treatments were more likely to be profitable when processed at modern high-speed, small log sawmills.

Those two papers (Wagner et al. 1998; Wagner et al. 2000) differ from the research reported in this thesis in different ways. First, in those papers, only one specific dbh class was evaluated in each run, while in this thesis the input mix of logs processed in the mill is composed of a wide range of log diameters. Those papers did not assess production and flow constraints such as bottlenecks, whereas the research in this thesis is concerned about having an optimized flow throughout the mill that would be as smooth as possible. Finally, in this thesis, the goal is to improve flow and production in terms of number of boards produced but not in terms of revenue.

2.4 Log merchandising, bucking and log yard sorting

Due to the rise of customer's interest in certified forest products, certified wood industries now need to be able to trace forest products from timber harvest up to the final consumer (Jordan 1996). Traceability is defined as the ability to properly document the history of a product, from its origin up to its final destination. Besides being required by certification agencies, implementing traceability is also a tool to improve product quality (Wall 1995). Establishing the history of a product in the wood industry is a difficult task, due to the wide variety of material origins. Traceability can be better accomplished by sorting the log yard as well as by developing appropriate marking and reading techniques (Sorensen 1990; Chiorescu and Grönlund 2004a). Log yard sorting has been driven not only by the need to keep track of the products but also by the idea that better production and thus higher revenues come from a good knowledge of what is processed in the mill (Jäppinen 2000). This knowledge is acquired through identifying, measuring and controlling the material (Chiorescu et al. 2003). When you know what is in the yard, you are more likely to process it efficiently while meeting customers' requirements (Sunderman 2003).

Advantages of sorting the yard can be viewed differently in different countries, as customs and raw materials are different. In Europe and Eastern

Canada, log breakdown systems use fixed set saws to process logs efficiently. Thus, it is critical that the log mix feeding the mill has the appropriate characteristics (diameter, length, etc.), which implies that logs have been previously sorted (Jäppinen 2000; Dramm et al. 2002). Sorting logs is thus an essential condition to achieve high production in this type of mill. The idea behind sorting logs is to use the full potential of the sawlogs, in other words, to improve value recovery.

Achieving higher overall value for logs can also be performed through the use of log merchandisers (Figure 4). Merchandising consists of bucking a long log into shorter segments in order to maximize the value of the log. Logs are then allocated to their highest value use (Dramm et al. 2002). Log merchandizing can be categorized into three types: woods merchandising, single facility merchandising and multi-facility merchandising (Figure 5). Log merchandisers, when combined with log scanning and optimization technology, are thus valuable equipment to help in sorting the yard and in recovering higher value from a tree (Forest Products Laboratory 2000a). Initially used for long logs, merchandisers have been adapted to buck small diameter logs as well (Dramm et al. 2002).

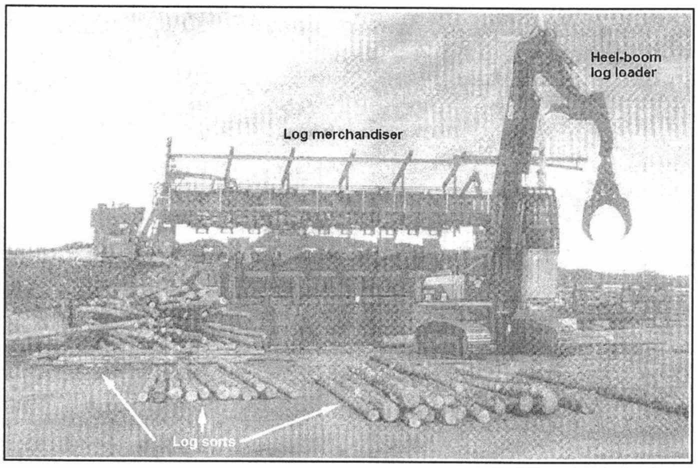


Figure 4. Log loader sorting sawlogs and stud bolts from a transverse log merchandiser (Dramm et al. 2002).

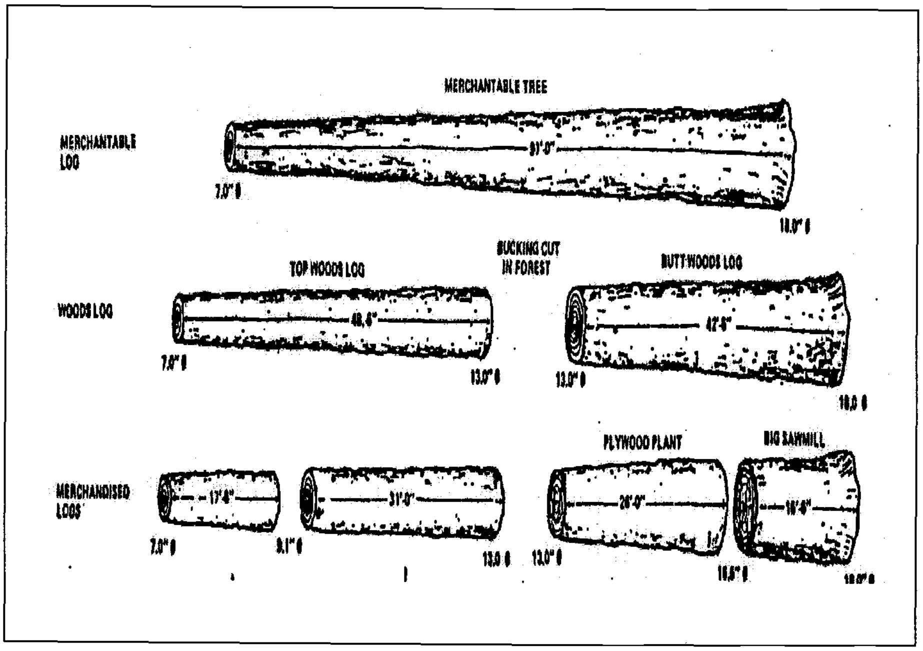


Figure 5. Multi-facility merchandising (Brown).

In order to increase the value recovery of logs, improvements can also be made directly when bucking stems at the point of harvest (Clark 2001; Boston and Murphy 2003). It was shown that improvements made on harvester measurement accuracy and performance could result in improvements in wood processing (Chiorescu and Grönlund 2001). Chiorescu and Grönlund (2001) also noticed that proper sorting of the logs depended on the accuracy with which diameters were measured by the harvester. In their paper, Noble et al. (2000) showed that implementing automated and optimized bucking systems in the mill yard helped increase the value of softwood stems. They also concluded that the determination of near-optimal bucking patterns on stems was better achieved by well-trained buckers (Noble et al. 2000).

Logs can be sorted by grade, diameter or species. Sawmills that are sorting their logs by diameter and species produce boards that have the right dimensions but show a wide discrepancy of grade. On the other hand, sawmills that are sorting logs by grade still won't produce 100% of their boards with the correct grade, since boards from the same log often have different grades (Oja et al. 2004). The main purpose of sorting logs in the yard is to be able to predict as well as possible what the final product will be in terms of grade and dimensions (Nordmark and Oja 2004). However, good sorting cannot be realized without the support of scanning technology. Technologies that have been used to estimate logs properties are ultrasonic measurements, measurements of longitudinal stress waves, gamma-ray measurements, two-axis X-ray scanners, one direction X-ray scanners, three-dimensional (3D) optical scanners, or even a combination of both one direction X-ray and 3D scanners (Oja et al. 2004). Most of the studies on log yard sorting and scanning technology have been conducted in the Swedish sawmilling industry as more than 95% of the larger Swedish sawmills are pre-sorting the logs, usually by small-end diameter (Jäppinen 2000).

Chiorescu et al. (2003) used data generated by 2-axis log scanners to achieve a traceability system between the log sorting station and the saw infeed. Data generated by scanning the logs at the log sorting station were stored in a database. Logs were then scanned at the saw infeed and data generated by the second scanning were linked to the ones originally stored in the database in order to establish a traceability system between the log yard and the saw intake. Their results showed that a 2-axis log scanner was not efficient enough to separate more than 34 percent of the logs and that large logs are easier to separate as they have more distinctive features that can be used to describe them. They also noticed that the 2-axis log scanner has a tendency to overestimate log diameter.

Chiorescu and Grönlund (2004) then attempted to use data generated by 3D log scanners combined with advanced recognition algorithms to develop a traceability system between the log sorting station and the saw infeed when working with debarked logs. Their results showed that their method, the fingerprint approach, was efficient in separating logs affected by climatic factors, handling damage and long storage periods. However, small logs were more difficult to separate than large logs because there are less laser beams hitting the log in the case of small diameter logs (Figures 6 and 7).

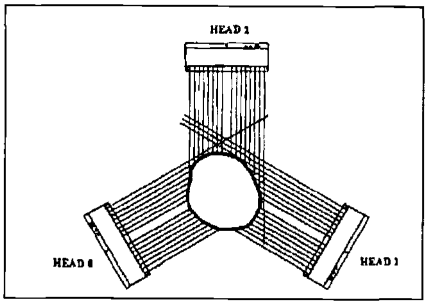


Figure 6. Schematic description of 3D scanner (Dashner 1993).

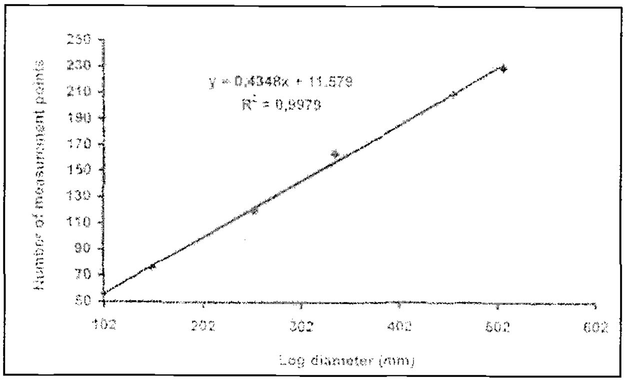


Figure 7. The 3D log scanner's inner relationship between the diameter of the log and the number of the measurement points/coordinates on the log mantle (Chiorescu and Grönlund 2004b).

Chiorescu and Grönlund (2004) finally investigated the possible use of data generated by 3D log scanners to develop a traceability system between the log sorting station and the saw infeed by taking into account the negative influence of measurement uncertainty due to bark thickness and missing bark. This study also used an original automated system for log marking/reading based on a radiofrequency identification (RFID) technique. Their results showed that the recognition rate radically decreases when there is bark and thus that bark was a real problem in terms of measurement accuracy.

Many studies were also conducted to compare different scanning technologies. Oja et al. (2004) compared four different combinations of three-dimensional (3D) and X-ray scanning that can be used to grade logs automatically. Their results showed that the highest accuracy was accomplished when using a combination of 3D scanning and one-dimensional X-ray scanning. It was also proven that using a combination of 3D and X-ray scanning notably increases the percentage of boards with the correct grade when logs have been sorted beforehand (31% without sorting and up to 66% with sorting).

Sorting logs in the yard allows the grade and dimension of the final product to be predicted. Nordmark and Oja (2004), by combining a sawing simulator with a 3D optical scanner and an X-ray log scanner, were able to predict the log values for any segment of a scanned stem. However, it was noticed that the prediction of the boards' value depended entirely on the ability to locate internal defects in the logs.

The literature review describes two main scanning features: external and internal. Currently, external scanning is used extensively in US softwood sawmills. Internal scanning would be more likely to be implemented in sawmills processing logs for grade, such as hardwood or large log softwood sawmills.

In this thesis, sorting of the log yard will be implemented by diameter classes and not by grade, the first reason being that the large majority of the segments being processed in the mill are not cut for grade, even if the final boards are graded. Then, recovery by grade wasn't tracked to validate the model. Finally the mill wouldn't be able to implement the many sorts resulting from sorting the log yard by grade because of the amount of time and space this would require. Therefore, the best solution among the ones that are going to be tested will be chosen based on recovery and not value.

3. OBJECTIVES AND HYPOTHESIS

3.1 Goal

The goal of this research was to determine methods to increase the efficient utilization of small-diameter timber in an existing sawmill, focusing on the log yard.

3.2 Hypothesis

Past studies have shown that log sorting was an essential condition to achieve high production in a sawmill. Therefore, the hypothesis is that if sorting of the log yard is properly implemented, an existing sawmill can minimize the impacts of an increase in the amount of small-diameter timber and thus, improve recovery and production.

3.3 Research objectives

This research work had two main objectives. The first objective was to develop a computer simulation model accurate enough that it could be used to investigate and optimize the overall process of the sawmill being modeled. The second objective was to determine some kind of log yard sorting and input log mix that would produce the best throughput and optimized flow when using increasing percentages of small diameter timber.

From the standpoint of the sawmill's management, the objective of this study was to have a reliable tool that would assist in making management decisions and pinpointing potential issues. The main idea was to help the mill personnel obtain the highest production possible with the resources available to them.

4. METHODOLOGY

This section of the thesis first describes Warm Springs Forest Products Industries and the sawmill that was modeled in this project and then, the different modeling steps and how they were applied in the simulation study.

4.1 Sawmill description

Warm Springs Forest Products Industries (WSFPI) was created in 1967 because of the desire of the members of the Confederated Tribes of the Warm Springs Reservation to exploit the Reservation's timber resources. During the following years, the mill kept growing and despite the changes and challenges facing the wood products industry, WSFPI overcame the difficulties and is now a major player in the timber products manufacturing industry (www.wsfpi.com).

Warm Springs Forest Products Industries produces framing lumber (2 inches by 4 inches to 2 by 12, 6 through 20 feet long dimensional lumber), industrial lumber (5/4 inches and 6/4 inches, random width 4 inches through 14 inches, random length 6 feet through 20 feet, shop and moulding grades, 5/4 inches and 6/4 inches vertical grain) and timbers (4 inches by 4 inches through 12 by 12 in lengths of 8 through 20 feet).

The Warm Springs Forest Products Industries' site includes a log yard, a sawmill with two headrigs (a large log headrig and a small log headrig referred to as the EDLF), seven dry kilns (two of which have double racks), a planer mill and finally a packaging and shipping department. As only the log yard and the sawmill are of interest in this thesis, the description that follows won't go beyond the sorting and sawmill operations.

4.1.1 Material input

The sawmill processes Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*) and ponderosa pine (*Pinus ponderosa*) lumber. For the purpose of this study, based on the mill's request, the material input was limited to Douglas-fir (*Pseudotsuga menziesii*) and the data collected only related to this species.

4.1.2 Material flow and the processes

In the log yard, logs are sorted into two different decks. The peewee decks include logs with small-end diameters ranging from 5 inches up to 17 inches, while the oversize deck includes logs with small-end diameters larger than 17 inches. However, only 1/3 of the logs delivered to the yard are scaled. Thus, it is very common to find some smaller diameter logs in the oversize deck and vice-versa. A crane, located between the big log infeed deck and the small log infeed deck (Figure 8), is primarily used to move the big diameter logs laying on the small log infeed deck back on the big log infeed deck. This is due to the fact that the headrig on the small log side, referred to as the EDLF (End Dogging Log Feeder), cannot process logs with diameters larger than 20 inches. On the other hand, the small diameter logs that might be on the big log infeed deck are usually not moved back to the small log infeed deck because those logs can be processed by the headrig on the big log side.

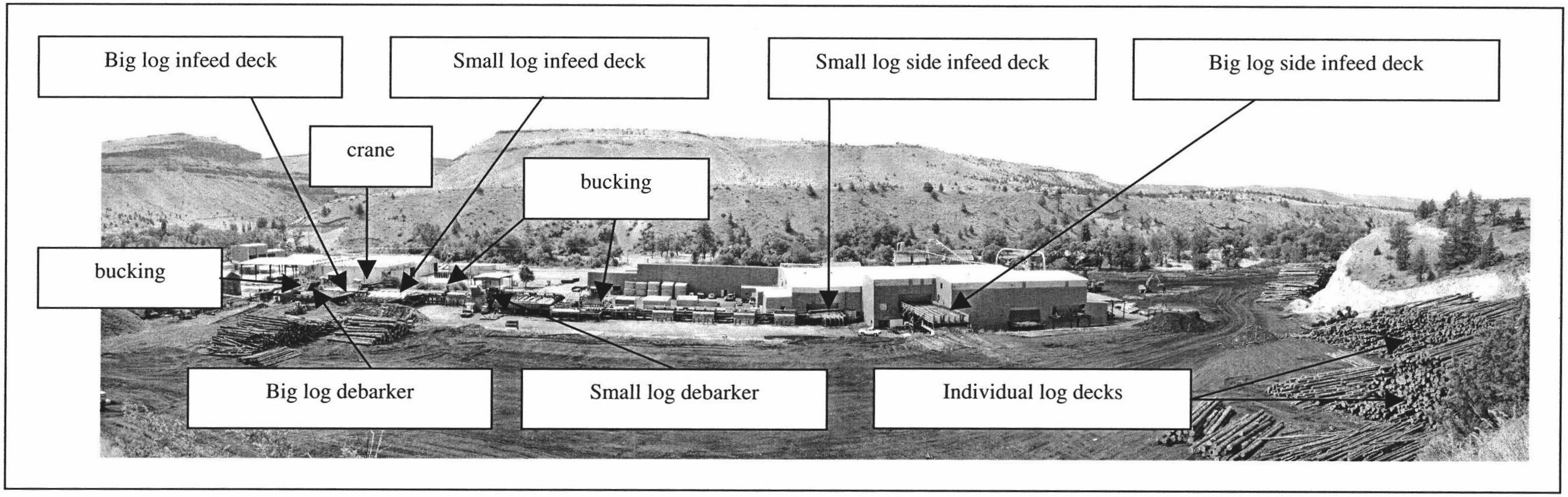


Figure 8. Panoramic view of the log yard and the mill.

Once the logs are placed on the appropriate infeed deck, they are debarked and then bucked. The debarking operation is essential because it removes bark from the chippable portion of log, prolongs the life of cutting tools, exposes wood surfaces for better breakdown decisions and finally reduces debris in the sawmill. A Nicholson A5 high-speed automatic debarker, located on the small log side, can debark logs with diameters up to 22 inches (Figure 9), while a Nicholson A1 debarker, located on the big log side, can debark logs with diameters up to 51 inches (Figure 10).

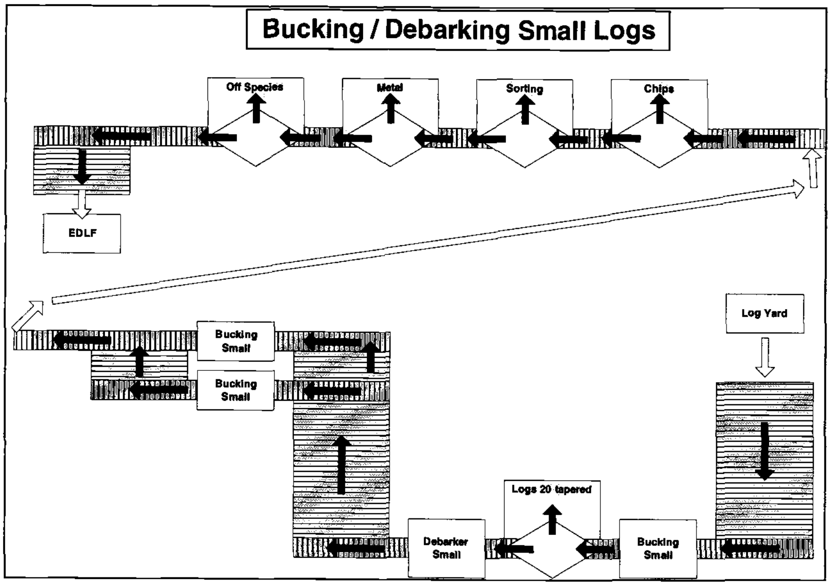


Figure 9. Debarking and bucking processes for the small diameter logs.

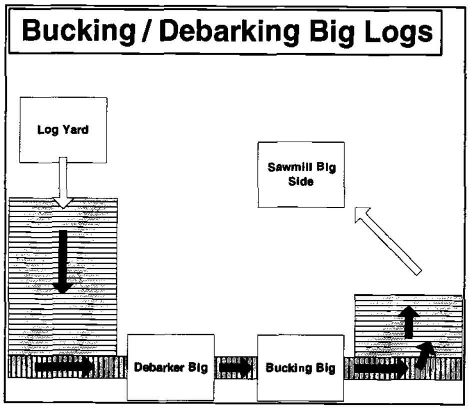


Figure 10. Debarking and bucking processes for the big diameter logs.

Then, the bucking operation is completed according to the guidelines described in Appendix A (Tables A- 3 and A- 4). The bucking solutions are variable due to the fact that every log is a unique case and the operator's primary concern is to minimize crook and sweep in order to maximize yields. During the bucking operation, logs are cut into segments. Once bucked, segments are conveyed to the small mill infeed deck for the small diameter logs or are moved by a letrostacker to the big mill infeed deck for the big diameter logs. If the small logs being bucked contain metal, are off-species or are simply too small to be processed by the EDLF, they fall into appropriate bins located between the bucking saw and the EDLF infeed deck. This prevents the downstream saws from being damaged by metal that might be present in some logs or the EDLF to be jammed because of logs that don't have the appropriate range of diameters.

It has to be noted that the material flow in this sawmill is fairly complicated due to the fact that this sawmill is a combination of two mills, a small log side and a big log side, that merge before the trimmer. The entire flow is shown in Figure 11.

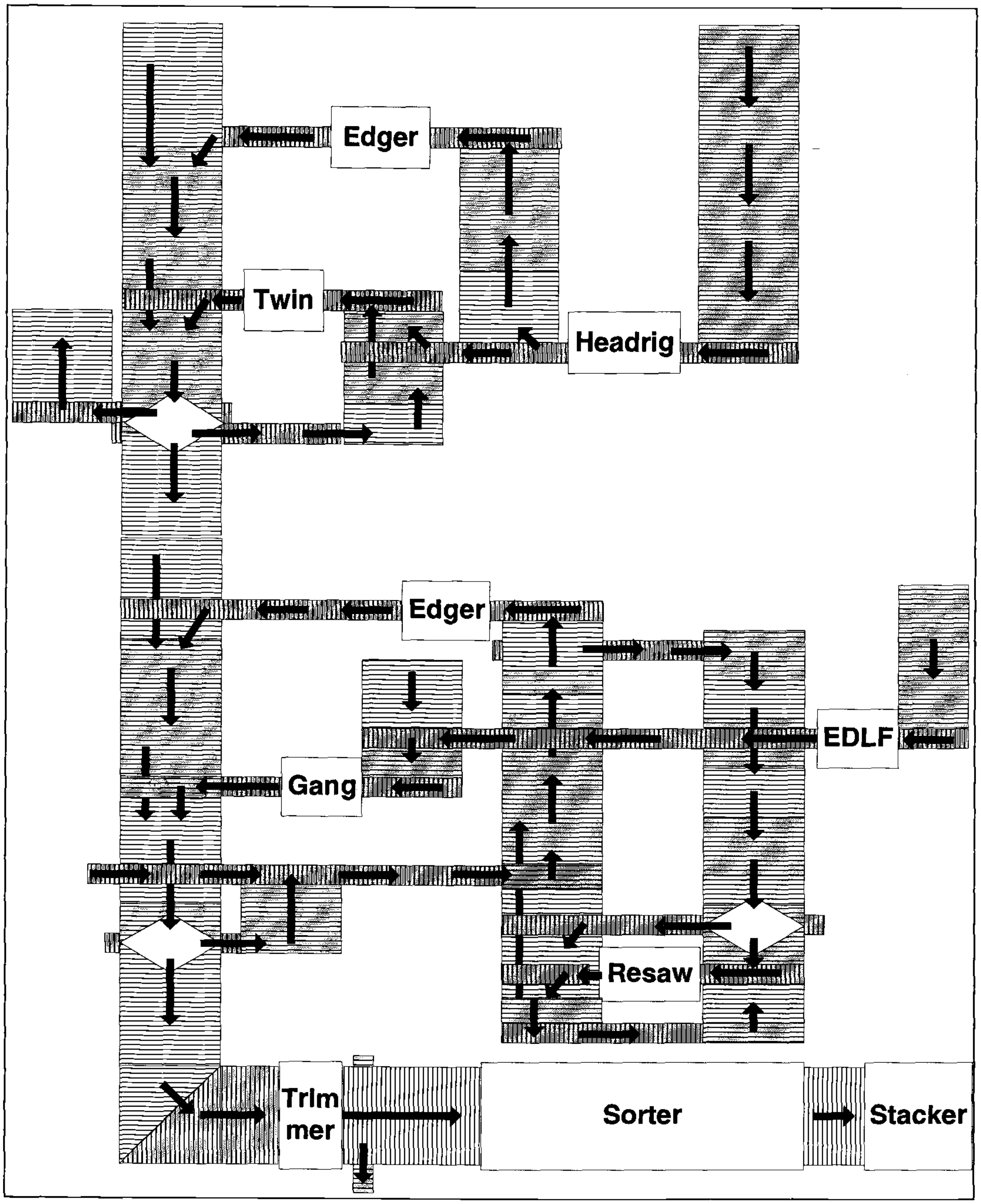


Figure 11. Diagram of the material flow in the mill.

Once on the infeed decks, segments are waiting to be processed. Segments with diameters ranging from 5 inches to 18 inches are processed by the EDLF (Figure 12), while segments with diameters larger than 18 inches are processed by the headrig. Segments are scanned before going through the headrigs. At each headrig, segments are broken-down into sideboards and cants. On the small log side, the scanning operation before the EDLF provides all the information necessary for an optimum breakdown (diameter, length, taper, sweep). Based on calculations, segments are oriented in an optimum position and then hold in this position while being transported in a straight line through the saws. The EDLF, which is a 6ft Mc Donough band-mill, can cut one or two sideboards from a segment, depending on its size and shape (Figure 13).

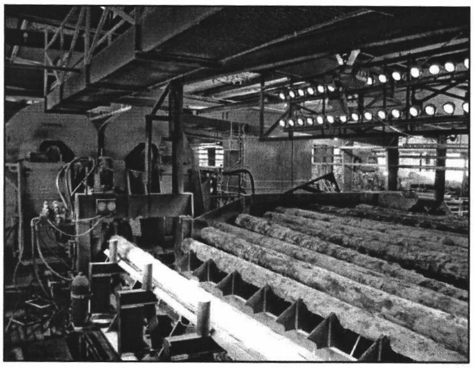


Figure 12. Segments going through the EDLF.

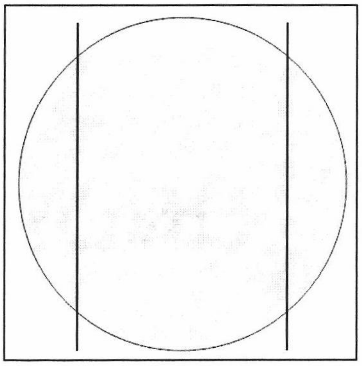


Figure 13. Example breakdown pattern at the EDLF.

The sideboards from the EDLF are then conveyed to the horizontal resaw or the board edger, depending on their thickness and shape. The cant is conveyed to the gang edger to be broken down into boards (Figure 14). The gang edger is a 12" Schurman double arbor gang edger (Figure 15).

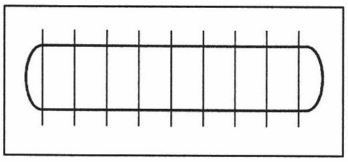


Figure 14. Example cant edging pattern.

Figure 15. Cants going through the gang.

The horizontal resaw, a 6ft Mc Donough band mill and the board edger, a USNR board-edger with 12 inch diameter saws, are used to recover lumber from slabs as shown in Figures 16 and 17. A scanner, located just before the board edger, scans the boards and decides if the boards need to be sent back to the horizontal resaw. Boards are sent back because they don't have the right thickness or have an insufficient face or excessive wane. The edging operation is very important as it removes wane from boards.

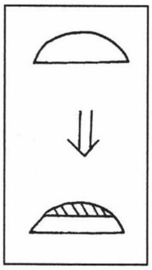


Figure 16. Sawing at the horizontal resaw.

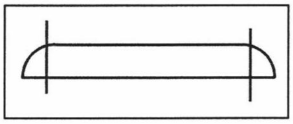


Figure 17. Board edging.

On the big log side, depending on the diameter, grain and shape of the segments, many sideboards can be produced and then conveyed to the combination edger. The cants that are 6 or 8 inches thick are also conveyed to the combination edger. Cants thicker than 8 inches are conveyed to the twin resaw. The combination edger is a McGehee combination-edger with 4 circular saws that can produce 3 boards. The twin-resaw, a 6ft Kockums Air Strain band-mill, can cut two boards off at a time. After the twin-resaw, a gate allows boards that need further processing to be sent back to the twin resaw. Boards that don't need to be resawn are sent down and merge with the boards coming from the board edger located in the small mill.

Then, boards from the two mills are conveyed to the unscrambler where an operator decides whether the boards can be processed by the trimmer, need to be sent back to the horizontal resaw or the board edger, or finally have to be dropped down to the chipper. Before reaching the trimmer (Figure 18), boards are scanned in order to get the maximum value out of each of them. The scanner also keeps track of the final dimensions of each board to sort them into the appropriate bin. The trimmer is used to remove defects and excessive wane from boards, but also to cross-cut long boards to saleable lengths or reduce odd-lengths to even lengths. After the trimmer, boards can be sent to the sorter or to the green chain if they need to be remanufactured. At the sorter, boards fall in the appropriate bin, depending on their dimensions. The sorter is a J-bar vertical sorter with 54 bins (Figure 19). Boards that are waiting at the green chain are then sent back into the mill by batches directly before the board edger. However, the operator does not always check the situation on the board edger conveyor before sending those boards back in the mill, and in the case where the conveyor is already almost full, the addition of these boards creates a bottleneck, which then becomes difficult to absorb.

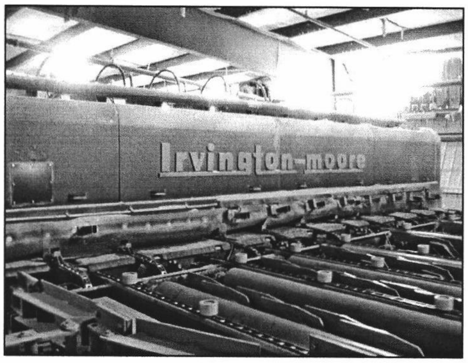


Figure 18. Trimmer.

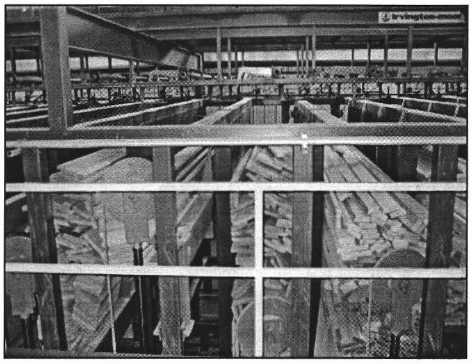


Figure 19. Sorter.

4.2 Data requirements and collection

The data used in the model developed for this project were collected during the summer of 2004 at the Warm Springs Forest Products Industries sawmill in Warm Springs, OR, as well as during a test run conducted in October, 2004. A detailed schematic of the material flow was made first (Figure 11) in order to get a good understanding of the flow of material through the mill and to get a precise idea of the type of data to be collected. The data collection was the most time-consuming step as not all the data were available but also because of the high variability that exists in wood processing. Information was gathered from production reports, machines print-outs or observations. A good knowledge of the process was also gained through discussions with the sawmill personnel and the different managers. The data that were collected included log characteristics in the log yard (length, diameter, species), bucking solutions, machines processing times by length and diameter, speeds and capacities of the different conveyors and surge decks, breakdown patterns of segments and cants according to their dimensions, downtimes and uptimes, schedules, and historical data concerning the production.

4.2.1 The log yard

As previously stated, only data concerning Douglas-fir were collected. For Douglas-fir, the log diameters ranged from 5 inches to 31 inches (Table A- 1), with an average length varying from 21 feet up to 34 feet. Those values were obtained based on log yard records from 12/31/03 to 6/30/04. Figure 20 shows the log diameter percentages that were in the yard during this period of time. Figure 21 shows the average length by diameter. Those data were used in the model to represent the input mix of material processed in the mill under normal conditions.

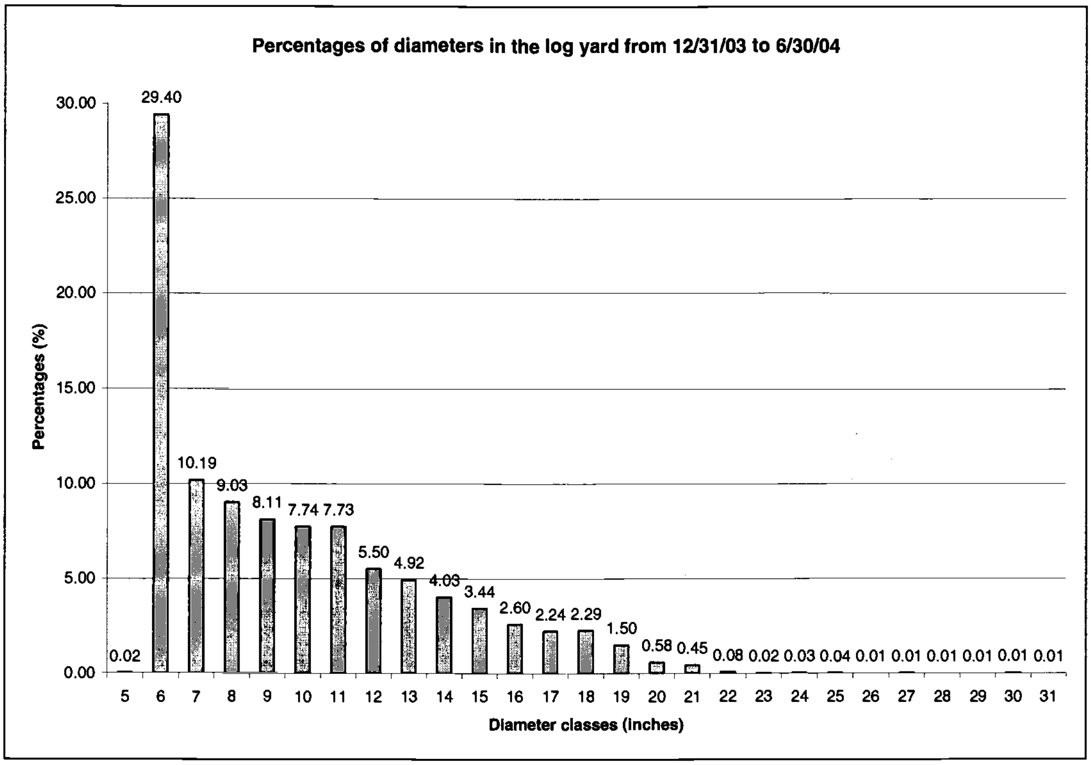


Figure 20. Percentages of diameters in the log yard from 12/31/03 to 6/30/04.

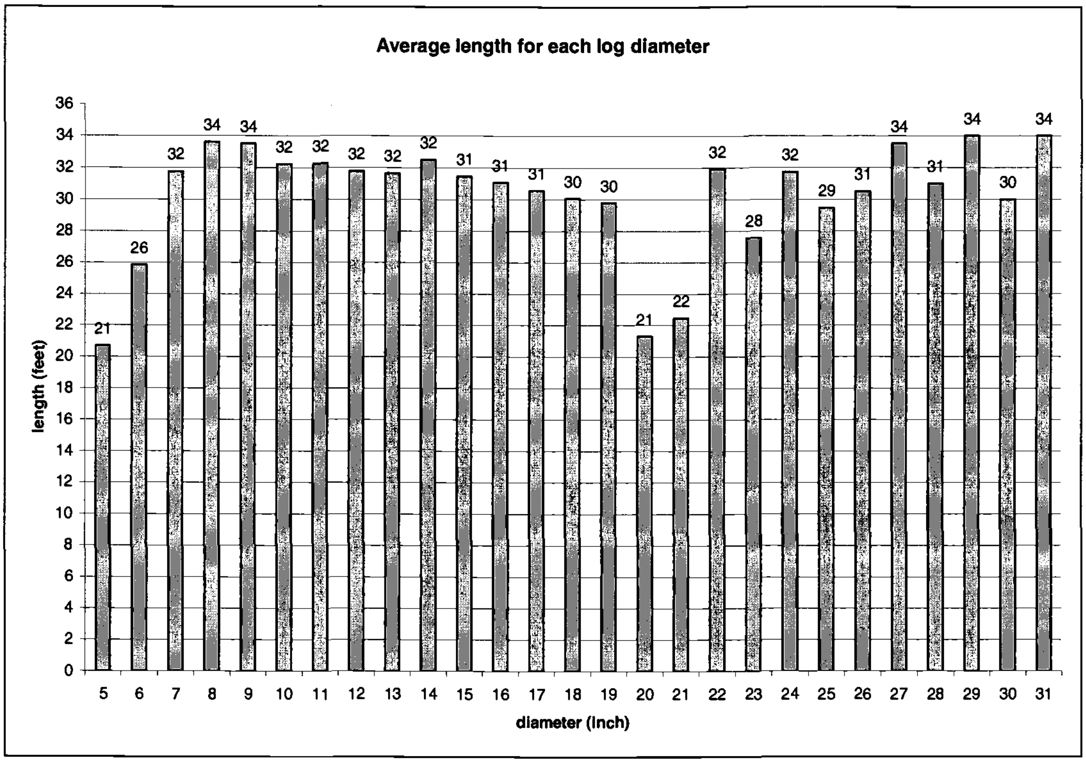


Figure 21. Average length for each diameter.

4.2.2 Bucking

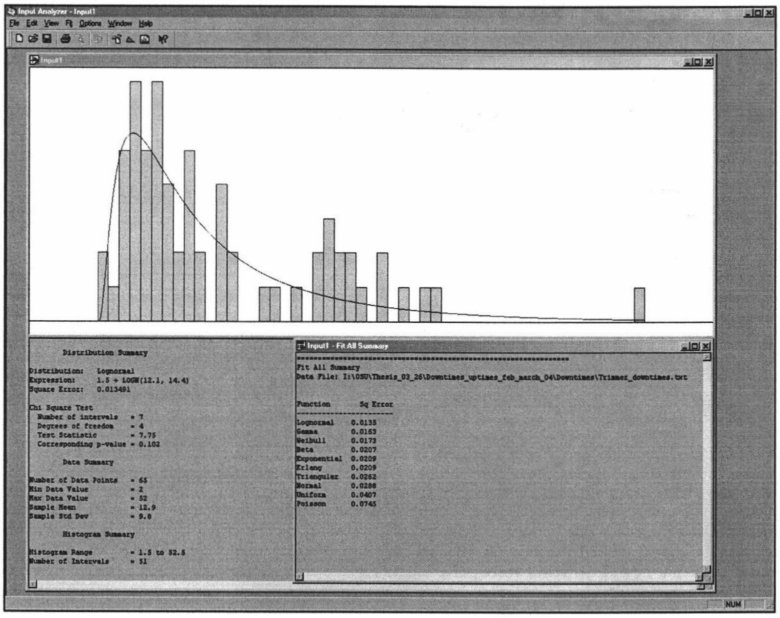
The bucking was modeled according to Tables A- 3 and A- 4. For each diameter class (1 inch increment), the average length was determined (**Table A- 2**) and the bucking guidelines were applied to those length averages.

4.2.3 Breakdown

The breakdown solutions for each side (Figures A- 1, A- 2 and A- 3) are based on the scanning solutions provided by the EDLF as well as theoretical calculations that were compared and adjusted with data collected on both sides. Only one breakdown solution per log diameter class was assumed at the EDLF. The EDLF scanning solutions are only reliable for the number of sideboards that might come out of a segment at the EDLF, as the cant breakdown suggested by the scanner is not always followed. Thus, the breakdown at the gang was determined by measuring cants upstream and by counting the number of boards coming out of the gang. Concerning the headrig, it was not possible to print any scanning solutions. The solutions were thus recorded manually during a few hours and breakdown percentages (Figures A- 2 and A- 3) were calculated based on those data. The breakdown solutions at the headrig depend on the quality and shape of the log being processed. Two logs that have the same diameter can be broken down differently. Thus, up to 5 breakdown solutions were considered in the model for the same diameter class. The breakdown at the twin resaw was also mostly based on calculations because cant size dictated how many times the pieces had to go back through the twin resaw.

4.2.4 Uptimes and downtimes

In order to model failures of the different machines, distributions of the downtimes and uptimes were needed. Data from February and March, 2004, were recorded on a daily basis by the mill personnel for each machine. Different statistical packages were tested in order to obtain distributions and it finally appeared that the input analyzer provided in the Arena simulation package provided the distributions that fitted the data the best. The Input Analyzer is a valuable tool that fits a distribution to the data collected and estimates the distribution parameters and calculates p-values for two goodness-of-fit tests, the Chi Squared and Kolmogorov-Smirnov tests (Figure 22). Corresponding p-values less than about 0.05 indicate the distribution is not a very good fit. The Input Analyzer also provides the user with a summary of all the distributions ranked with respect to how well they fit the data.



```
        Distribution Summary

Distribution:   Lognormal
Expression:     1.5 + LOGN(12.1, 14.4)
Square Error:   0.013491

Chi Square Test
  Number of intervals     = 7
  Degrees of freedom      = 4
  Test Statistic          = 7.75
  Corresponding p-value   = 0.102

        Data Summary

Number of Data Points     = 65
Min Data Value            = 2
Max Data Value            = 52
Sample Mean               = 12.9
Sample Std Dev            = 9.8

        Histogram Summary

Histogram Range           = 1.5 to 52.5
Number of Intervals       = 51
```

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============================================================
Fit All Summary
Data File: I:\OSU\Thesis_03_26\Downtimes_uptimes_feb_march_04\Downtimes\Trimmer_downtimes.txt


Function        Sq Error
-----------------------
Lognormal      0.0135
Gamma          0.0163
Weibull        0.0173
Beta           0.0207
Exponential    0.0209
Erlang         0.0209
Triangular     0.0262
Normal         0.0288
Uniform        0.0407
Poisson        0.0745
```

Figure 22. Arena Input Analyzer.

The distributions are summarized in Table A- 5. It has to be noted that downtimes are only recorded when a machine stops and are also very approximate. In the case of a bottleneck at the unscrambler, the entire process is usually slowed down instead of being stopped. However, those slow downs are not recorded and thus, cannot be modeled.

4.2.5 Machine processing times

Machine processing times vary according to the length and diameter or width of the material flowing through the machine. Processing times displayed in Appendix A (Tables A- 6 to A- 12) do not take into account the time required to scan and properly position the entity on the conveyor. A person knowledgeable about the machines, except for the headrig, provided all the processing times. The fact that some segments were cut for grade at the headrig and that each segment was unique made the data collection difficult. The processing times at the headrig were recorded manually for each diameter category, and processing time distributions were determined based on the few data collected.

4.2.6 Speed and capacities

Speeds and capacities of each machine center were determined through observations. Capacities are approximate as they are dependent on the size of the material on the conveyor. Boards also tend to pile up, making it difficult to determine the maximum number of boards that can lay on each conveyor. When a queue reaches its maximum capacity, the upstream machine stops until the number of entities waiting drops below the limit. Thus, if the queue at the horizontal resaw exceeds 200 entities, the EDLF stops. All the machines, in the mill as well as in the model are thus related. Conveyors/surge areas capacities were modeled as shown in Figure 23.

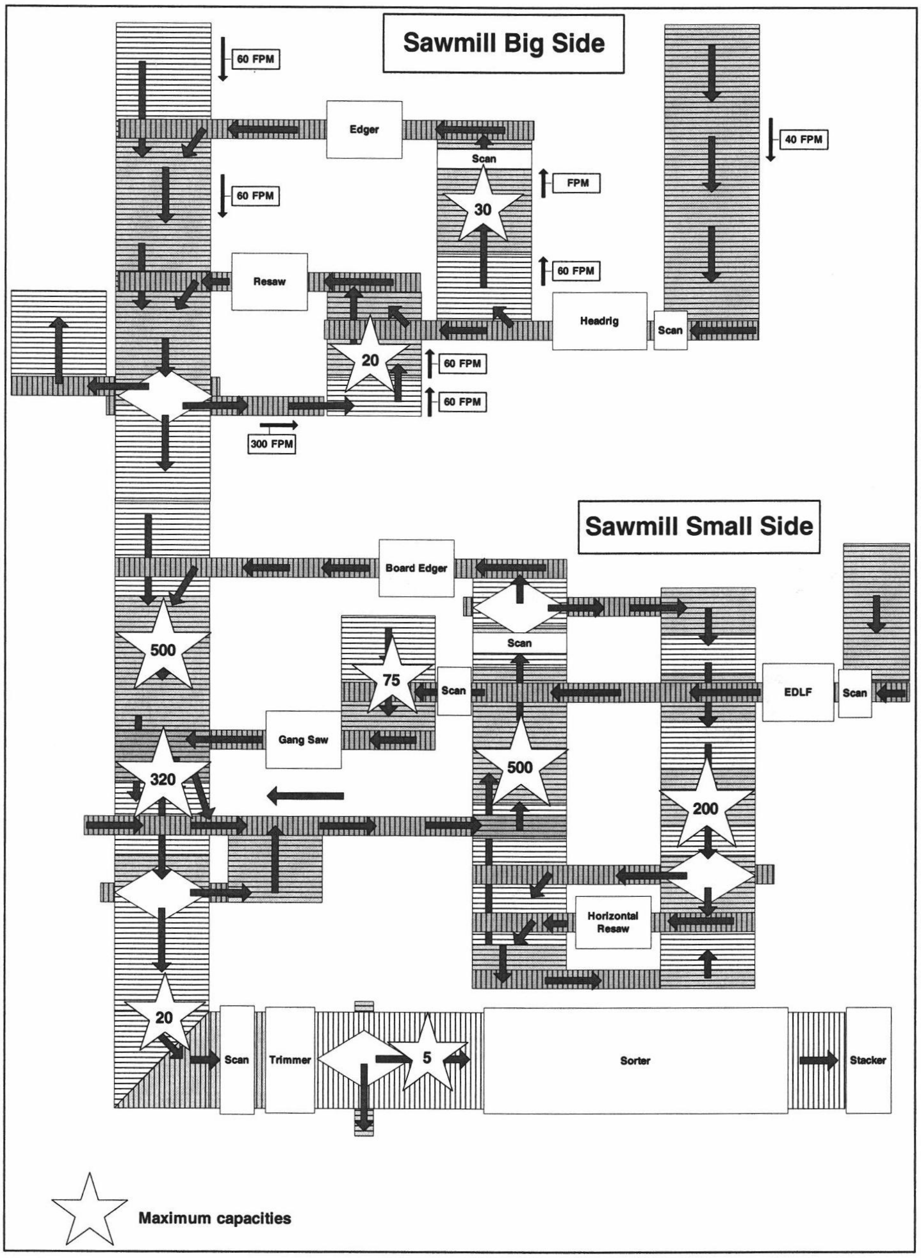


Figure 23. Approximate capacities for conveyors/surge areas (indicated by stars with numbers).

4.2.7 Schedule

The schedule in the mill has been defined as follows. The shift starts at 6am and ends at 2:00pm for the EDLF and at 2:30pm for the rest of the machines.

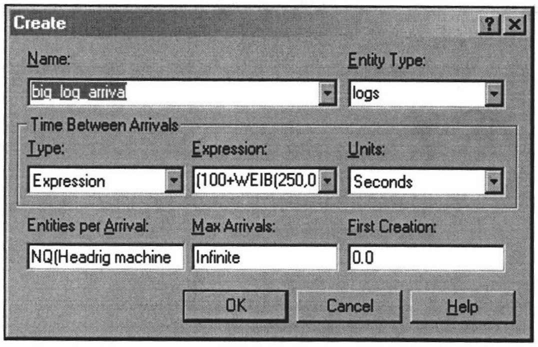
There are two 15-minute breaks, one at 8:00am and one at 12:30pm, for all of the machines. The lunch break starts at 10:00am and ends at 10:30am, except for the horizontal resaw, gang, board edger and unscrambler that resume working at 10:10am in order to process the boards or cants that are waiting in the queues.

4.3 Model development using Arena

Model development was conducted during the data collection step. The level of detail of the model increased with a greater understanding of the many constraints and high variability of the material flow. The level of detail in the model was also adapted in order to be able to fulfill the objectives of the project.

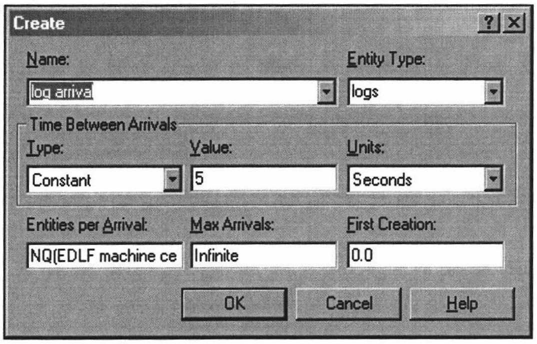
4.3.1 Entity creation

In Arena, entities are created using a Create Module. In the model, two Create Modules were used (Figures 24 and 25), representing the two infeeds.



Name: big_log_arriva
Entity Type: logs
Time Between Arrivals
Type: Expression
Expression: (100+WEIB(250,0
Units: Seconds
Entities per Arrival: NQ(Headrig machine
Max Arrivals: Infinite
First Creation: 0.0

Figure 24. Create Module for the big mill.



Name: log arriva
Entity Type: logs
Time Between Arrivals
Type: Constant
Value: 5
Units: Seconds
Entities per Arrival: NQ(EDLF machine ce
Max Arrivals: Infinite
First Creation: 0.0

Figure 25. Create Module for the small mill.

The Create Module allows the modeler to define the type of entity, its interarrival time, as well as the number of entities per arrival. The entities created at the beginning of the model are logs. The interarrival time expression has been chosen to be short enough to keep the infeed decks full for both mills. The allowable capacity for each headrig queue was set to 200 entities. In order to model this constraint, a Boolean expression NQ(Headrig machine center.Queue)<=200 for the Headrig and NQ(EDLF machine center.Queue)<=200 for the EDLF was set for the number of entities per arrival, where NQ equals the number of entities in the queue. When the number of entities in the queue is less than or equal to 200, the Boolean expression is true and returns a 1 allowing an entity to be created and added in the queue. Similarly, when the queue reaches 201 entities, the expression becomes false and returns 0, stopping the addition of new entities in the queue.

4.3.2 Bucking modeling and attributes assignment

Once created, entities flow to a Decide Module (Figures 26 and 27). The Decide Module splits entities into different diameter categories by assigning percentages to variables (nb_5, nb_6, etc.). The percentages assigned to the variables depend on the range of log diameters found in the log yard.

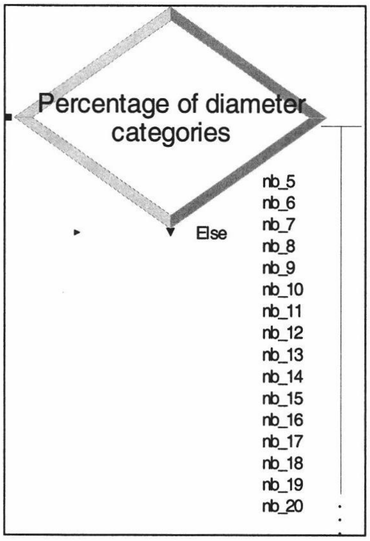
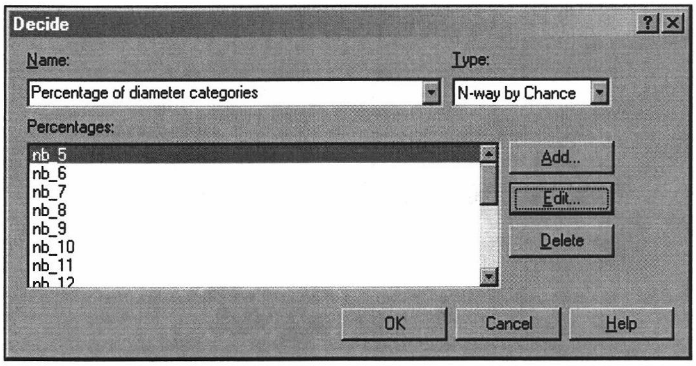


Figure 26. Decide Module.



Name: Percentage of diameter categories

Type: N-way by Chance

Percentages:
nb_5
nb_6
nb_7
nb_8
nb_9
nb_10
nb_11
nb_12

Figure 27. Decide Module characteristics.

Using variables makes changing the values assigned to these variables easier as the changes are made in only one place (the Variable Spreadsheet), even if values are used in several different places. Defining variables is also very valuable when using the Process Analyzer (described in the Experimentation and Analysis section).

The bucking operation consists of cutting a log into two segments. This operation is modeled in Arena using a Separate Module (Figures 28 and 29). This module is used to copy an incoming entity into multiple entities. The number of entities to be duplicated is entered in # of Duplicates.

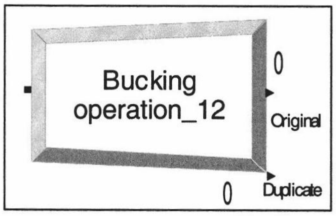
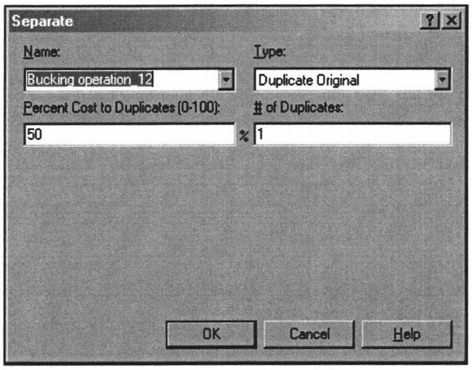


Figure 28. Separate Module.



Name: Bucking operation_12

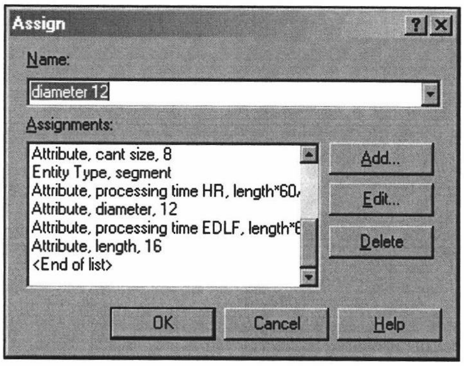
Type: Duplicate Original

Percent Cost to Duplicates (0-100): 50 %

# of Duplicates: 1

Figure 29. Separate Module characteristics.

After being duplicated, entities are assigned attributes (processing times, entity type, length, diameter, cant size, number of sideboards, etc.) through the Assign Module (Figure 30).



Name:
diameter 12

Assignments:
Attribute, cant size, 8
Entity Type, segment
Attribute, processing time HR, length*60,
Attribute, diameter, 12
Attribute, processing time EDLF, length*6
Attribute, length, 16
<End of list>

Figure 30. Assign Module.

The modeling of the bucking operation was large and complex due to the numerous diameter categories. It was thus decided to use submodels (Figure 31).

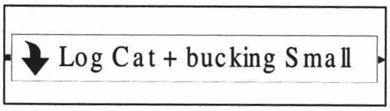
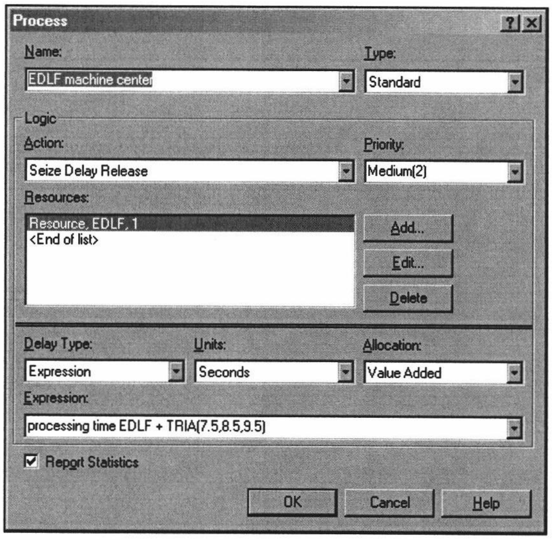


Figure 31. Submodel.

Each submodel has its own workspace on the screen and is connected to other modules of the model. The use of submodels also makes the verification and debugging step easier as it clarifies the logic of the model. Two submodels were created, one for bucking at the small diameter side and one for the bucking at the big diameter side.

4.3.3 Machine centers

Each machine center (EDLF, gang, horizontal resaw, board-edger, etc.) is modeled using a Process Module (Figure 32). A Process Module represents the machine, including the resource, its queue and the entity delay time (processing time in this case). In the case of the EDLF, the processing time is composed of two expressions. The first one, “processing time EDLF” represents the time it takes for an entity to go through the saws. Another expression (TRIA(7.5,8.5,9.5)) has been added to the previous one to take into account the time necessary for the scanning and proper positioning of the entity on the conveyor. The expression "processing time EDLF" is an attribute and has been defined in the previously described Assign Module for each entity, based on log length and diameter.

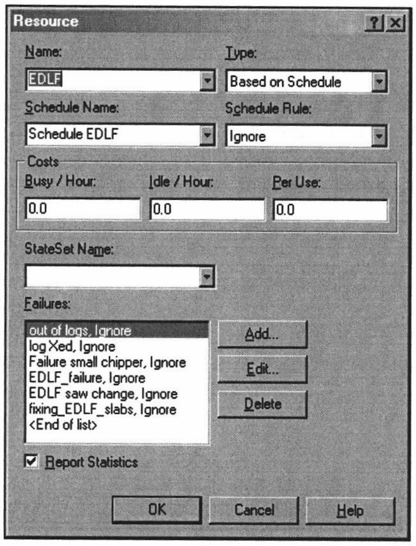


Name: EDLF machine center
Type: Standard
Logic
Action: Seize Delay Release
Priority: Medium(2)
Resources:
Resource, EDLF, 1
<End of list>
Delay Type: Expression
Units: Seconds
Allocation: Value Added
Expression: processing time EDLF + TRIA(7.5,8.5,9.5)
☑ Report Statistics

Figure 32. Process Module for the EDLF.

4.3.4 Resources

Each resource defined in a Process Module has characteristics that can be determined in the Resource Module (Figure 33). Characteristics defined are the resource capacity, which can be fixed or based on a schedule, and the failures that will stop the resource. In the case of the EDLF, its capacity is based on the schedule that has been previously described. The EDLF is also subject to different kinds of failures (out of logs, logs crossed, failure of the small chipper, etc…) that are defined in the Failure Module.



Name: EDLF

Type: Based on Schedule

Schedule Name: Schedule EDLF

Schedule Rule: Ignore

Costs

Busy / Hour: 0.0

Idle / Hour: 0.0

Per Use: 0.0

StateSet Name:

Failures:

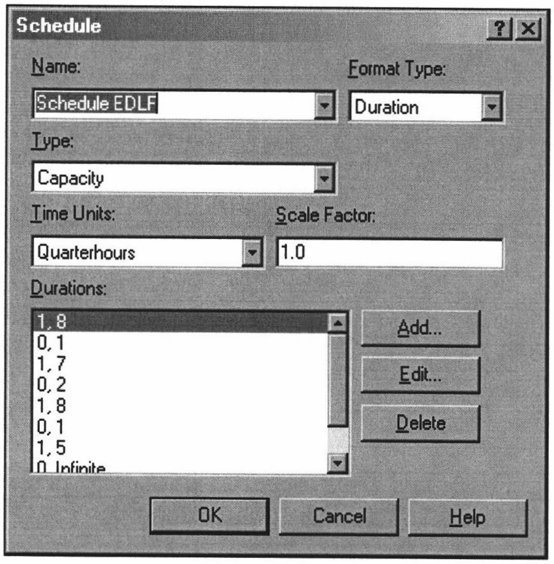
- out of logs, Ignore
- log Xed, Ignore
- Failure small chipper, Ignore
- EDLF_failure, Ignore
- EDLF saw change, Ignore
- fixing_EDLF_slabs, Ignore
- <End of list>

☑ Report Statistics

Figure 33. EDLF Resource Module.

4.3.5 Schedule

A schedule was defined for each machine (except the trimmer and sorter that are modeled to run all the time) using the Schedule Data Module (Figure 34). This module allows the modeler to define the pairs (capacity, duration) that will make up the schedule. In the case of the EDLF, the time unit has been set to quarter-hours. Thus, the first pair (1,8) means that the EDLF capacity is set to 1 (machine available) for 8 times 15 minutes (2 hours). The next pair (0,1) means that the machine is unavailable (capacity set to 0) for 1 times 15 minutes. As many pairs as required can be added to model the entire schedule.

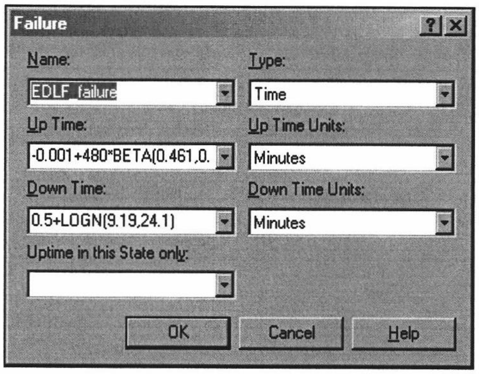


Name: Schedule EDLF
Format Type: Duration
Type: Capacity
Time Units: Quarterhours
Scale Factor: 1.0
Durations:
1, 8
0, 1
1, 7
0, 2
1, 8
0, 1
1, 5
0, Infinite

Figure 34. Schedule Data Module.

4.3.6 Failures

As previously explained, each resource is subject to failures. Failures cause the resources to be temporarily unavailable and are defined by uptime and downtime distributions. The origin of the distributions that can be found in Figure 35 is explained in the data requirements and collection section of this thesis (section 4.2.4).



Name: EDLF_failure
Type: Time
Up Time: -0.001+480*BETA(0.461,0.
Up Time Units: Minutes
Down Time: 0.5+LOGN(9.19,24.1)
Down Time Units: Minutes
Uptime in this State only:

Figure 35. Failure Module.

4.3.7 Material flow and breakdown modeling

The direction that each entity must take is often modeled using Decide Modules. The direction that an entity can take can be dictated by a percentage, like in Figure 36 where a board can go to the horizontal resaw or the board edger, or by a condition, like in Figure 37 where a cant goes to the combination edger if the condition is true or the twin resaw if it is false.

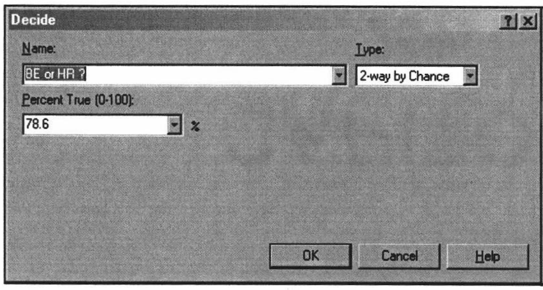

Decide
Name: BE or HR ?
Type: 2-way by Chance
Percent True (0-100): 78.6 %

Figure 36. Decide Module using a percentage.

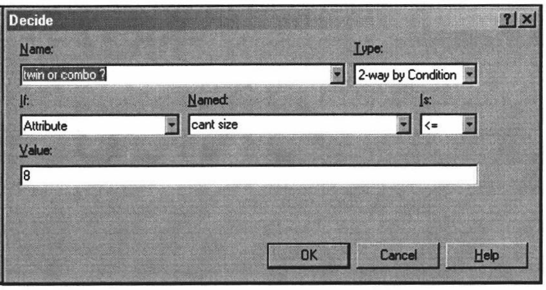
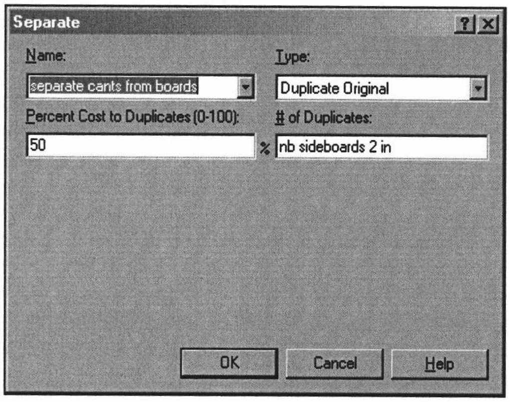

Decide
Name: twin or combo ?
Type: 2-way by Condition
If: Attribute
Named: cant size
Is: <=
Value: 8

Figure 37. Decide Module using a condition.

The breakdown of segments into sideboards and cants (Figure 38) as well as the breakdown of cants into boards (Figure 39) were modeled using Separate Modules. The duplicate entity has exactly the same attributes as the original entity. The function of the Separate Module has been explained in section 4.3.2 but in this case, attributes were used to define the number of duplicates.



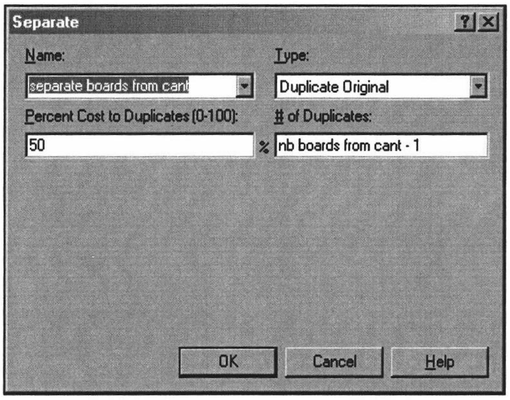
Name: separate cants from boards

Type: Duplicate Original

Percent Cost to Duplicates (0-100): 50 %

# of Duplicates: nb sideboards 2 in

Figure 38. Breakdown of segments into boards and cants.



Name: separate boards from cant

Type: Duplicate Original

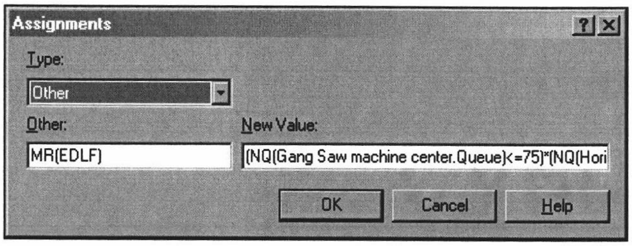
Percent Cost to Duplicates (0-100): 50 %

# of Duplicates: nb boards from cant - 1

Figure 39. Breakdown of cants into boards.

4.3.8 Capacities

It has been previously explained that conveyors and surge decks have certain capacities that, if exceeded, stop the preceding machine(s). This fact has been modeled using Boolean expressions that set the preceding resource capacity (MR) to 0 (machine unavailable) if the queue limit is exceeded on a machine downstream. For example, in Figure 40, an expression NQ(Gang Saw machine center.queue)<=75 returns 1 if the number of entities in the queue is less than or equal to 75 or 0 if the number of entities in the queue is higher than 75, setting MR(EDLF) (resource capacity of the EDLF) to 1 (available) or 0 (unavailable).



Type: Other

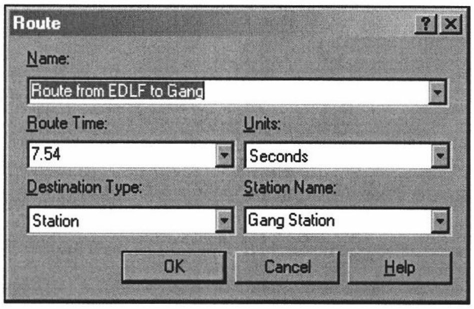
Other: MR(EDLF)

New Value: (NQ(Gang Saw machine center.Queue)<=75)*(NQ(Hori

Figure 40. Setting queue capacities.

4.3.9 Routing entities

Conveyors stop often and randomly so it was decided to model the conveyors with route and station modules and to allocate a distribution or an average time for the route time. The Route Module in Figure 41 modeled the time needed by an entity to go from the EDLF to the gang. Other Route Modules were used between other machine centers. Using Route and Station Modules are also necessary to create the animation of the material flow.



Route

Name: Route from EDLF to Gang

Route Time: 7.54

Units: Seconds

Destination Type: Station

Station Name: Gang Station

Figure 41. Route Module.

4.3.10 Operators

Human factors, such as the performance of an operator, are very difficult to model, because an operator may not have the same efficiency throughout a shift and there are differences between operators. It was decided to model the operator at the unscrambler with a Process module and to allocate a distribution for the processing time. The unscrambler is the key position in the mill as the entire flow and production depend on how well the operator at this location is doing. By modifying the distribution, one can thus easily estimate the impact on the production of a trained operator versus a less efficient operator.

4.4 Model verification and validation

4.4.1 Verification

The verification step was accomplished by testing the model each time a modification was made. Thus, bugs and unintentional errors were corrected throughout the development phase. Several features and tools have shown to be extremely valuable to verify the model. The flow of material in the model was checked by using the animation feature (Figure 43), while the schedule and failures were checked with plots representing machines' capacities over time (Figure 42).

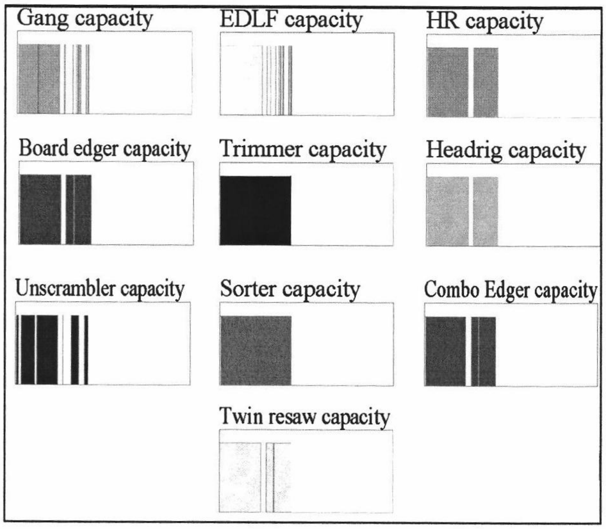


Figure 42. Plots of the machines' capacities over 9 minutes and 44 seconds.

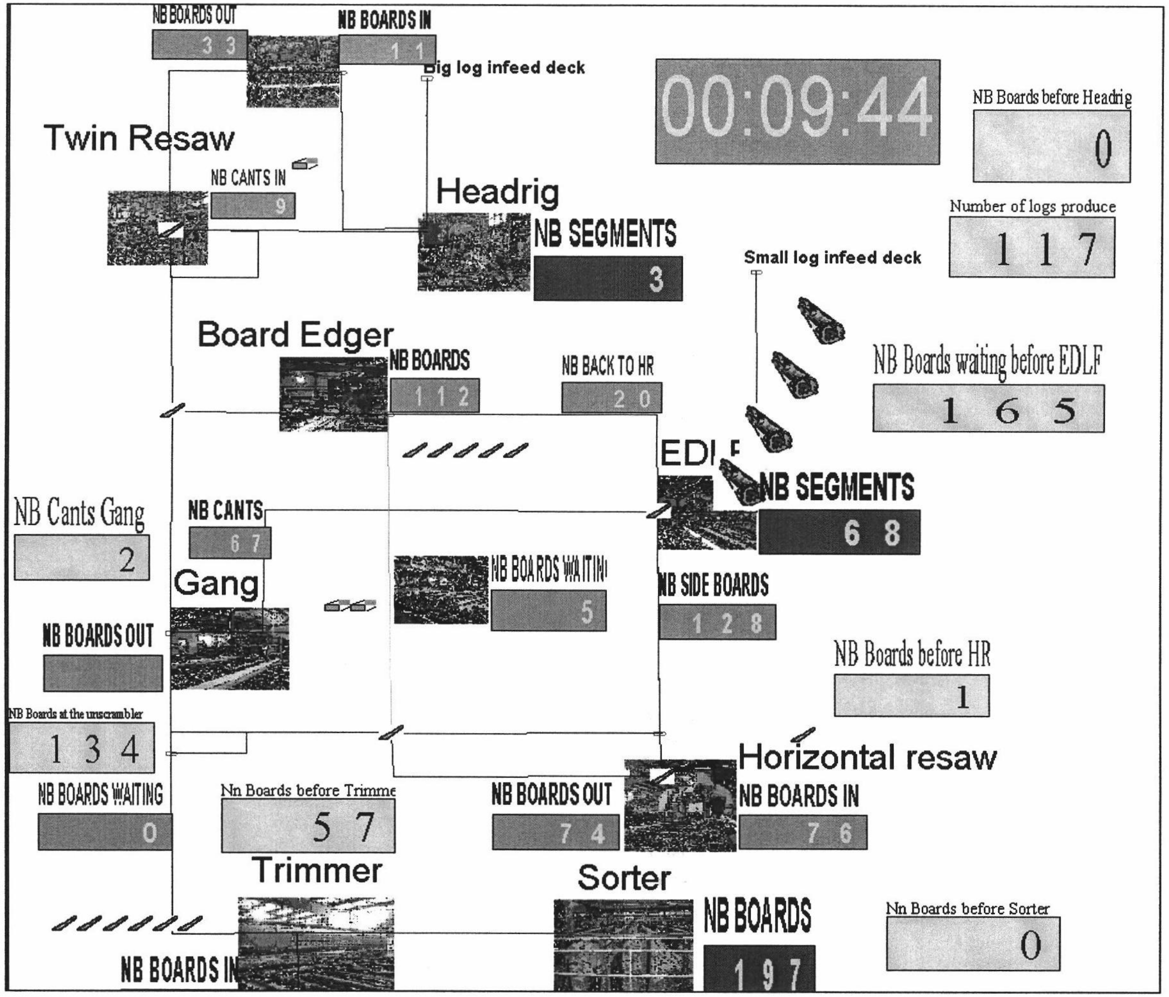
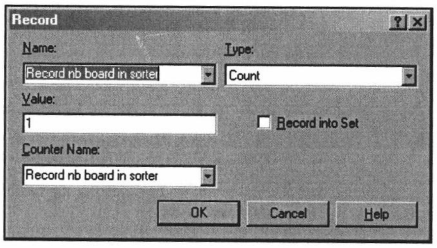


Figure 43. Animation of the model.

Arena modules such as Record and ReadWrite modules were also used. Record modules have been used to tally entities after different processes, such as tallying the number of boards at the sorter (Figure 44). ReadWrite modules were used after both headrigs to write the diameters of the segments going through these two machines in two different text files (Figure 45). The Input Analyzer was then used with each text file in order to determine diameter distributions for each headrig.



Name: Record nb board in sorter

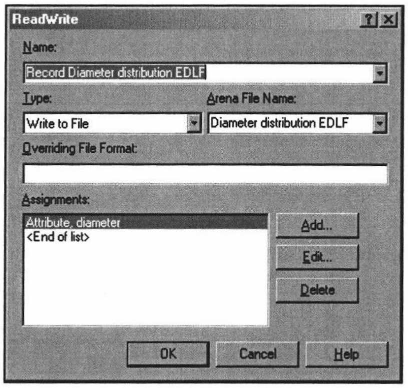
Type: Count

Value: 1

☐ Record into Set

Counter Name: Record nb board in sorter

Figure 44. Record Module.



Name: Record Diameter distribution EDLF

Type: Write to File

Arena File Name: Diameter distribution EDLF

Overriding File Format:

Assignments:
Attribute, diameter
<End of list>

Figure 45. ReadWrite Module.

4.4.2 Validation

Validation is an essential step in the development of a computer model. Validation of the model was achieved by first comparing the results of the model with historical production data. A test run was then conducted and the model output was compared with the test run output. Finally, the model was shown to people knowledgeable about sawmill operations and simulation.

4.4.2.1.Comparison with historical data

The model was validated by first comparing the results from the model with and without downtimes, with results historically produced by the real mill operating under the same conditions. In other words, the same number of segments was processed by the model as the real mill and the model output was then compared with the number of boards that were produced by the real mill.

a) Without downtimes

Two days for which the input and output were known were selected and compared with the model. Although the number of segments that went through each headrig was known, the diameter distribution was not. Likewise, no information concerning downtimes was available for those two days. The comparison between the model and those two days was thus just valid in terms of piece count as no downtimes were simulated in this model. Results are shown in Tables 1 and 2.

Table 1. Comparison of the model (with no downtimes) output with the production of the 14th of July 2004 (after one model replication).

	Real mill	Model	difference
Nb of segments that went through the headrig	324	322	0.62%
Nb of segments that went through the EDLF	1744	1744	0%
Nb of cants produced	NA	1744	
Sideboards coming from EDLF	NA	3214	
Boards produced by the gang	NA	7718	
Nb of boards in the sorter	**15320**	**16079**	**4.95%**
Reman boards	762	496	
Total reman + sorter	**16082**	**16575**	**3.06%**

Table 2. Comparison of the model (with no downtimes) output with the production of the 15th of July 2004 (after one model replication).

	Real mill	Model	difference
Nb of segments that went through the headrig	343	338	1.48%
Nb of segments that went through the EDLF	1650	1650	0%
Nb of cants produced	NA	1650	
Sideboards coming from EDLF	NA	3041	
Boards produced by the gang	NA	7294	
Nb of boards in the sorter	**15646**	**15760**	**0.73%**
Reman boards	740	496	
Total reman + sorter	**16386**	**16256**	**0.80%**

As shown in these two tables, the piece count provided by the model was very close to the actual production of the sawmill for each day. The differences between the model and the actual mill can be explained by the high variability of the process, but also by the fact that the input mix generated in the model was certainly different from the real input mix and there may have been some downtimes.

b) With downtimes

Then, a model taking into account downtimes was run and its output was once again compared with the historical production data of February and March, 2004. Those two months were chosen because they represent the period of time for which data concerning downtimes were made available. As was previously explained, the data concerning the downtimes were not very accurate; thus, the distributions used to fit those data were very approximate. To account for the high variability of the downtimes and the lack of accuracy of the data available, a large number of replications (500) were run and model averages were then compared with averages of historical data done over a long period of time. The model was thus run with the diameter distributions shown in Figures 46 and 47. The segments result from the bucking operation.

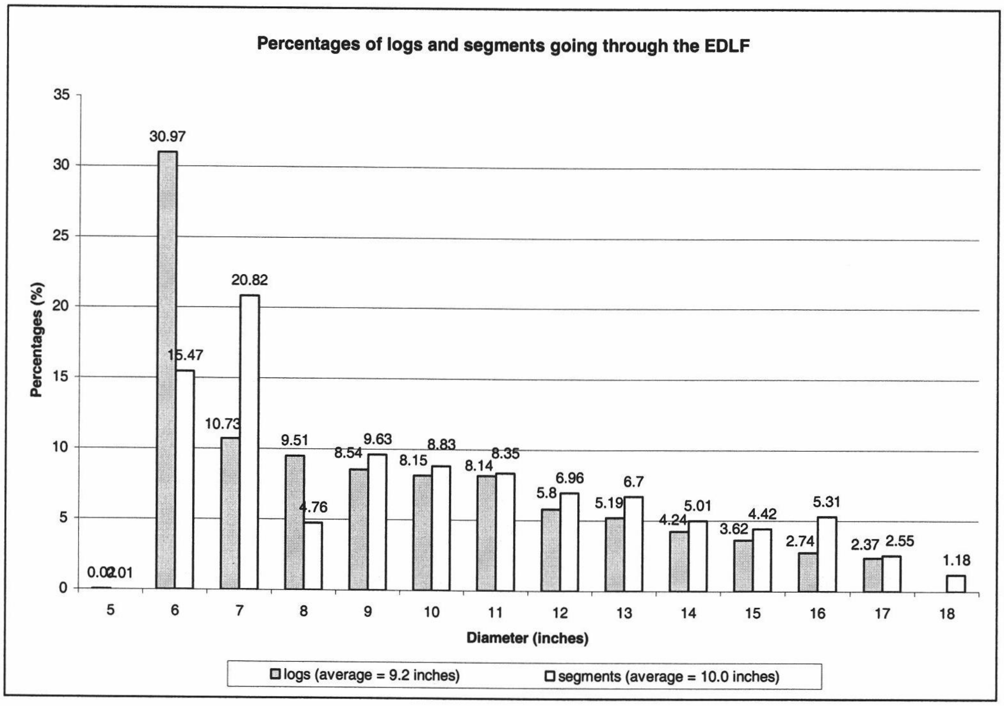


Figure 46. Percentages of logs and then segments going through the EDLF.

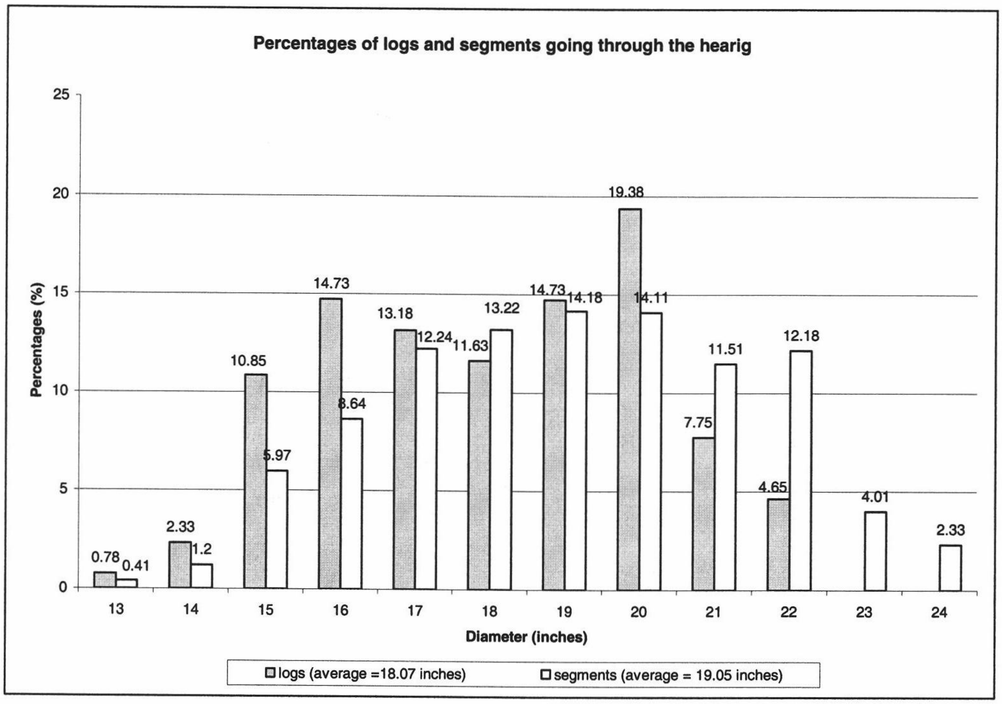


Figure 47. Percentages of logs and segments going through the headrig.

Both model input and output were compared with historical data. The number of segments that went through both headrigs in the model was compared with the number of segments processed by both headrigs in the real mill between January, 2004 and August, 2004. When considering all the Douglas-fir segments that went through the EDLF between January, 2004 and August, 2004, an average of 2026 segments a day was recorded. When not considering the two lowest days (487 and 808 segments), an average of 2065 segments a day was recorded. Then, when considering only the days for which the average segment diameter was close to what is processed in the model (9.5 inches < diameter average < 10.5 inches), an average of 2002 segments a day was recorded. Results are summarized in Table 3 and compared with the model.

Table 3. Comparison of the average, maximum and minimum number of segments that is processed by the EDLF.

	Average	**Max**	**Min**	**Difference in averages (%)**
All segments (real mill)	2026	3005	487	5.37
Model (500 replications)	2141	2668	1131	
All segments without the 2 lowest days (real mill)	2065	3005	1362	3.55
Model (500 replications)	2141	2668	1131	
Segments with same average diameter (real mill)	2002	2260	1440	6.49
Model (500 replications)	2141	2668	1131	

When considering only the days for which the average segment diameter is close to what is processed in the model by the headrig (18.7 inches < diameter average < 19.3 inches), an average of 311 segments a day was recorded. Results are summarized in Table 4 and compared with the model.

Table 4. Comparison of the average, maximum and minimum number of segments that is processed by the headrig.

	Average	**Max**	**Min**	**Difference in average (%)**
Segments (real mill)	311	381	244	9.10
Model (500 replications)	342	377	232	

In Tables 3 and 4, the differences in average were less than 10%, which was considered reasonable enough.

Tables 5, 6 and 7 summarize the results obtained after running the model for 500 replications.

Table 5. Number of segments processed and number of boards produced after 500 replications with downtimes.

Nb segments through EDLF	**Nb segments through headrig**	**Nb boards in green chain**	**Nb Boards in sorter**
2141	342	576	18641

Table 6. Machine utilization after 500 replications with downtimes.

Machines	**Machine utilization average (%)**	**95% CI Half-width**
Board edger	82.8	0.76
Combo edger	9.4	0.05
EDLF	72.3	0.76
Gang saw	66.5	0.71
Headrig	92.1	0.42
Horizontal resaw	49.1	0.51
Sorter	60.9	0.47
Unscrambler	73.4	0.57
Trimmer	62.8	0.49
Twin resaw	13.4	0.08

Table 7. Average number of entities in queue after 500 replications with downtimes.

Machines	**Average**	**95% CI Half-width**	**Maximum Capacity**	**Av./capacity (%)**
Board edger	214.7	9.37	500	**42.95**
Combo edger	1.8	0.13	30	6.03
Gang saw	41.4	1.02	75	**55.23**
Horizontal resaw	21.6	2.25	200	10.80
Sorter	0.5	0.04	5	10.20
Surge Area	32.0	2.50	500	6.4
Trimmer	9.0	0.42	20	45.05
Twin resaw	0.5	0.03	20	2.40
Unscrambler	133.3	4.75	320	**41.66**

Machine utilization (Figure 48) could not be compared with historical data, as the mill does not record this type of information. However, these numbers appeared to be realistic. The utilization rates for the combination edger and the twin resaw are low due to the fact that those two machines are processing material that is coming from the headrig only. Because the headrig is slow in processing segments, those machines are underutilized as shown in Table 6. Considering the average number of entities waiting in queues, the model clearly shows that the queues at the gang edger, board edger and unscrambler are the most important ones (Figure 49). No accurate comparison can be done, as the number of boards in queues is difficult to keep track of in the real process. However, those numbers represent well what was observed during the data collection phase.

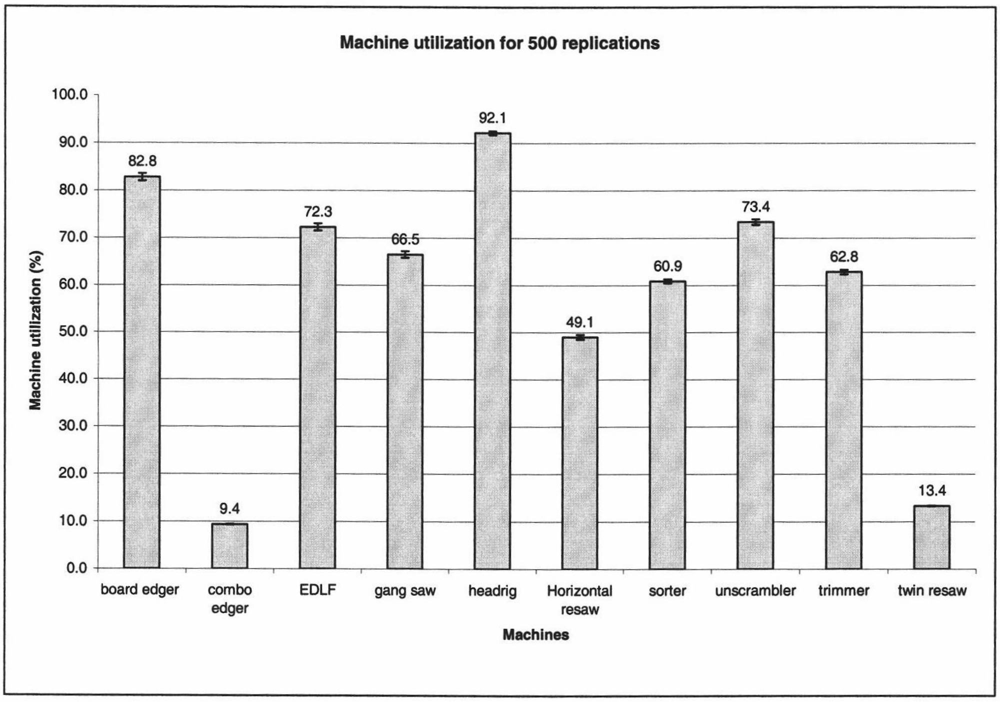


Figure 48. Machine utilization for 500 replications.

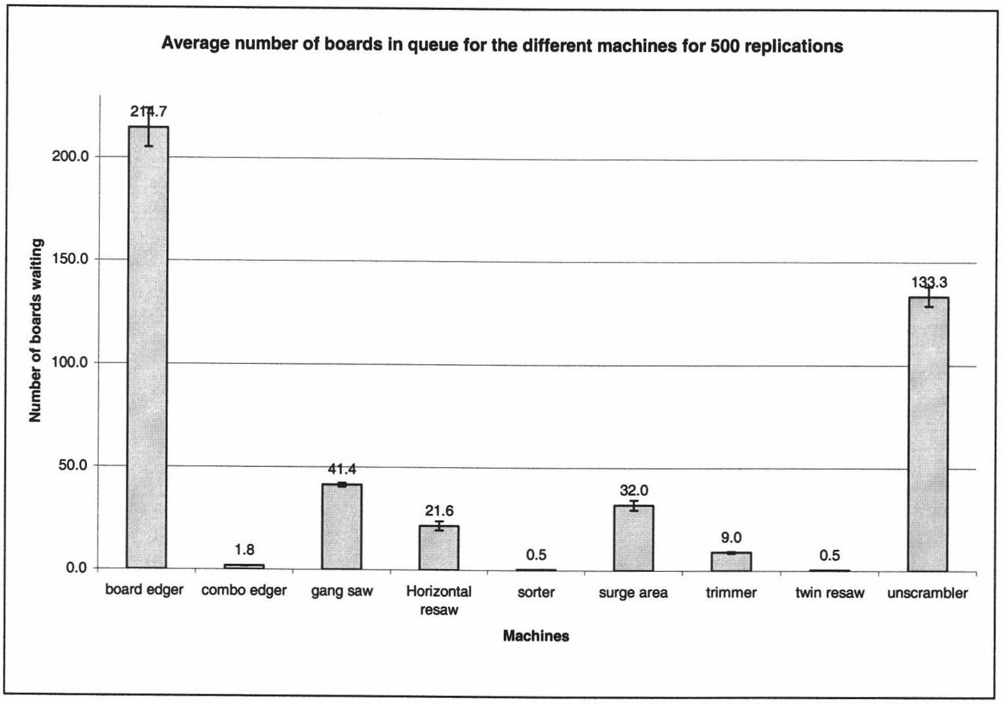


Figure 49. Average number of boards waiting in queue for each of the machine after 500 replications.

The average of boards produced in February and March, 2004, (Table 8) was then compared with the model output (Table 9).

Table 8. Production (number of boards in sorter) for February and March, 2004 (historical data).

	Production February 2004	Production March 2004	2 months combined
Total	361059	376943	738002
Average per day	18052.95	17133.77	17571.48

Table 9. Comparing the output provided by the historical data and the model (after 500 replications).

Historical data for Feb/Mar 2004						
Average production per day	Max	Min	Standard dev.	95% C.I Half-width	95% CI low bound	95% CI high bound
17571.48	22360	11928	2127.04	643.28	16928.20	18214.75
Model (500 replications)						
Average production per day	Max	Min	Standard dev.	95% C.I Half-width	95% CI low bound	95% CI high bound
18600	21800	10200	1640	144	18456	18744

Table 9 shows that there is a statistically significant difference between the output from the model and the output from the historical data. This difference is mainly due to the lack of accuracy of the downtimes data as well as the approximation of the breakdown for big diameter segments. However, the model overestimates the production by only 5.52%, which was considered reasonable.

4.4.2.2.Test run

The model was also validated by conducting a sawmill test run. The test run was conducted in order to trace each board in the mill and thus to check the breakdown theory with the real breakdown that was taking place at the headrigs, gang saw and twin resaw. Two hundred segments at the EDLF and forty segments at the headrig were scaled and a number was assigned to each of them before being processed. This number, as well as a letter assigned to each machine center, was written on each board processed by a machine. The marking for each board (number and letter(s)) were then recorded manually and videotaped at the trimmer. The same number of segments and the same diameter distributions that were processed during the test run were used in the model to compare the model output with the real sawmill output. The difference in the log diameters given by the scalers and the EDLF scanner was also recorded. A 0.831 inch average difference was recorded between the small-end diameter measured by the scalers and the small-end diameter given by the EDLF scanner, while a 0.626 inch average difference was recorded between the small-end diameter measured by the scalers and the effective diameter given by the EDLF scanner. Due to the loss of the trimmer data during the test run (the data from the trimmer couldn't be saved), no information can be provided about board footage. Thus, all the results and statistics are based on piece count only. A comparison of the model output with the test run output is displayed in Table 10.

Table 10. Comparison of the model (with no downtimes) output with the production of the test run (for 100 replications of the model).

	Test run	Model (averages after 100 replications)	Difference
Nb of segments that went through the headrig	40	39.4	1.5%
Nb of sideboards produced by the Headrig	222	162	27.03%
Nb of Boards produced by the Combo edger	466	459.63	1.37%
Nb of segments that went through the EDLF	200	200	0%
Nb of cants produced	200	200	0%
Sideboards coming from EDLF	390	383.10	1.77%
Boards produced by the gang	1031	835	19.01%
Nb of boards in the sorter	**2118**	**1802.17**	**18.75%**
Boards at green chain	74	74.59	0.8%

The results provided by the test run were a little different from a regular day production. A test run is supposed to mimic what happens during a real shift. However, the overall process during the test run went about two times slower than usual to give people time to mark the boards. It was also noticed that a large number of boards that went through the trimmer should have actually been sent to the trash, which might explain the reason for the 18.75% difference in the number of boards in the sorter for the real mill compared to the model. The presence of most of the mill managers in the mill during the test run may also have influenced the work of the operators, notably at the headrig. An 18.75% difference may seem large but was considered close enough after considering all the factors that influenced the process and production during this test run.

4.4.2.3.Discussion with knowledgeable people

Finally, the last validation method consisted of showing the model and the results to people knowledgeable about sawmill operations and simulation. The attributes and assumptions that were used in the model as well as an animation of the model were shown and explained to the sawmill's managers. The differences between the model and the real mill were discussed and declared acceptable by the sawmill's management team.

There are differences between the model and the real mill that can be explained by the high variability inherent in wood processing and more particularly by the lack of information available concerning the processing of the segments on the big log side. In the second part of this research, the model will be used to look at trends resulting from changes rather than to precisely quantify the influence of a change. The degree of accuracy of the model was thus considered sufficient and the model was declared valid.

4.4.2.4. Determination of the number of replications to be made

In order to be confident in the output provided by the model, the number of replications for which the model has to be run needed to be determined. Increasing the number of replications has the effect of reducing the half width of the confidence interval. The confidence interval gives a point estimate of the expected average. As the number of replications increases, the confidence interval shrinks. In order to determine the number of replications that would provide a reasonably small confidence interval, the model was run for a number of replications varying from 50 up to 1200. Results for the minimum and maximum across replications, 95% confidence interval low and high bounds and 95% confidence interval half-width are summarized in Table 11. Figure 50 shows the number of boards in the sorter as well as the associated 95% confidence interval for each number of replications.

Table 11. Minimum and maximum across replications, 95% CI low and high bounds and 95% CI half-width for different numbers of replications.

Number of replications	**Min across replications**	**Max across replications**	**95% CI low bound**	**95% CI high bound**	**95%CI Half-width**
50	13290	21080	18140	19120	493.5
100	13290	21470	18410	19050	321.1
150	13290	21470	18590	19080	248.9
200	10210	21470	18520	18990	237.5
250	10210	21470	18510	18940	210.9
300	10210	21490	18490	18870	187.3
400	10210	21490	18500	18830	161.1
500	**10210**	**21770**	**18500**	**18790**	**144.1**
600	8586	21770	18480	18750	135.2
700	8586	22000	18520	18760	124.3
800	8586	22300	18530	18760	115.5
900	8586	22300	18550	18760	108.4
1000	8586	22300	18540	18750	103.7
1200	8586	22300	18540	18730	94.52

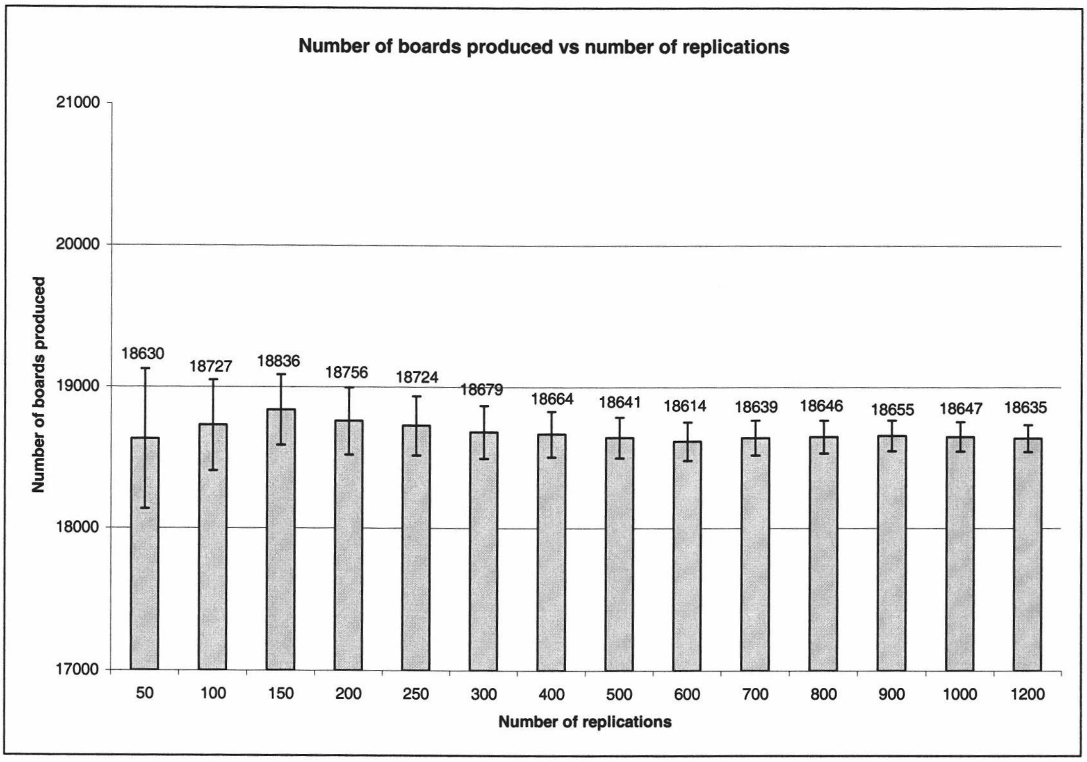


Figure 50. Number of boards in sorter by number of replications.

Vertical lines indicate 95% confidence intervals on expected number of boards in the sorter for each number of replications. A number of 500 replications was determined to be reasonable both in terms of precision and computation time.

4.5 Experimentation and analysis

4.5.1 PART I: Study of some scenarios of interest

Once validated, the model was used to investigate some scenarios of interest for the mill. A study was conducted on the unscrambler located before the trimmer (Figure 51). The unscrambler is used to singulate the boards before they are trimmed. It is a key location in the sawmill as it dictates the production rate but can also become a bottleneck fast. Its influence and more especially the influence of its queue capacity on the overall process and production were thus investigated.

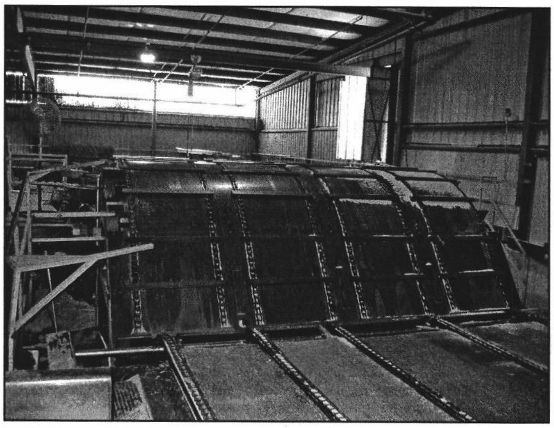


Figure 51. Unscrambler located before the trimmer.

Other scenarios studied in this thesis are the influence of downtimes on the production as well as the influence of having a second operator to improve the decision making and handling at the horizontal resaw (simulated by decreasing the percentages of boards being sent to the horizontal resaw from the EDLF).

4.5.2 PART II: Log yard sorting strategies

The Warm Springs Forest Products Industries sawmill is not a small-diameter log mill. Thus, an increase of the number of small-diameter logs on the market may have dramatic consequences on the mill production, both in terms of piece count and volume. The model was thus used to investigate some log yard sorting strategies that would minimize the decrease in production resulting from processing a larger number of small diameter logs. After discussion with the sawmill's managers, it was established that in the future, the mill was expecting logs with diameters of 5 to 7 inches to represent 25% of the total volume of the logs in the yard. Based on this consideration, three different diameter distributions were used as input in the model. Because the exact proportions of 5, 6 and 7 inches logs were unknown, two different diameter distributions resulting from introducing small-diameter timber were used. The third distribution used represented the actual log distribution. Those three distributions are defined as current, intermediate and smallest distributions and are described in Appendix C. Figures 52 and 53 compare the three distributions in terms of volume and pieces. For each distribution, different log yard strategies were implemented in order to compensate for the decrease in production induced by the increase of small-diameter logs being processed at the EDLF.

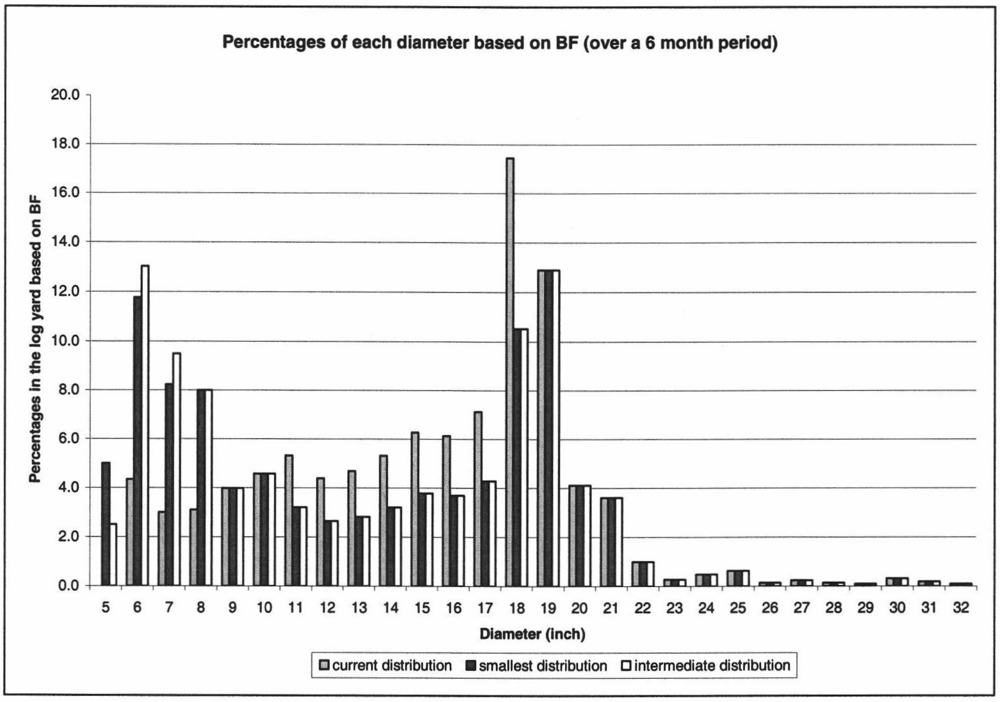


Figure 52. Percentages of each diameter based on BF for the 3 distributions over a 6 month period.

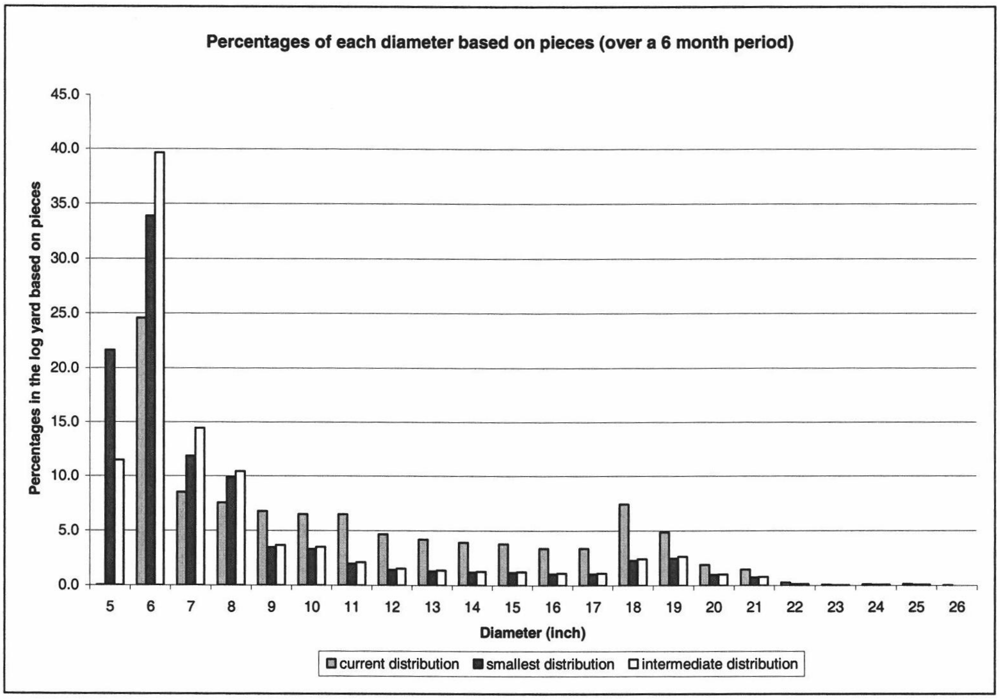


Figure 53. Percentages of each diameter based on pieces for the 3 distributions over a 6 month period.

5. RESULTS AND DISCUSSION

The discussion will be broken in two parts. The first part will cover the study of current mill improvement scenarios of interest, while the second part will discuss some log yard sorting strategies. However, due to the loss of the trimmer data during the test run, no information can be provided about board footage. Thus, all the results and statistics are based on piece count only.

5.1 PART I: Study of current improvement scenarios of interest

The model was first used to investigate some mill improvement scenarios of interest while using the current log distribution. Based on previous observations and discussions with the mill's management, the following points of interest were studied: the influence of downtimes on material flow, the consequence of increasing the average diameter of the segments being processed at the headrigs, the influence of the unscrambler conveyor capacity on material flow and production and finally the influence of the percentage of boards being sent to the horizontal resaw from the EDLF.

5.1.1 Influence of downtimes on material flow and production

In order to evaluate the consequences of machine downtimes on production, two scenarios were run and compared. The first one represents the mill with the current downtimes, while the second one doesn't include any downtimes. Five hundred replications were done for each model. The number of segments processed by both headrigs, the number of boards in the sorter as well as the machine utilization rates and queues were recorded for both scenarios.

As expected, Figure 54 and Table 12 show that the machine utilization rates are higher without downtimes than with downtimes. The utilization rates for the combination edger and the twin resaw are low because those two machines are processing material that is only coming from the headrig. The headrig is slow in processing segments, so those machines are underutilized. Very few downtimes were recorded for the combination edger and the twin resaw, which explains the very small difference in machine utilization rates between the scenarios with and without downtimes for those two machines. However, the utilization rates don't reach 100% for any of the machines, even though they approach it (headrig, board edger). This is due to the fact that even if no downtimes are included, machines can nevertheless stop because the queue of a machine downstream reaches its maximum capacity. When looking more closely at Figure 55 and Table 13, it can be seen that the average number of entities in the board edger queue is very high. On average, the board edger queue is at 84.2% of its maximum capacity, which means that the limit of this queue is exceeded quite often during the day. When the board edger queue exceeds its maximum capacity, the horizontal resaw has to stop. This is the reason for the fairly low utilization rate of the horizontal resaw and the average number of entities waiting at this machine. On average, the horizontal resaw queue is at 49.2% of its maximum capacity, which once again indicates that this queue reaches its limit quite often during the day. When this happens, the EDLF has to stop, resulting in a utilization rate for the EDLF of 90.2% even when no downtimes are included. The fairly low utilization rate of the gang is the direct consequence of the EDLF utilization rate. When the EDLF stops, it doesn't produce any cants, resulting in the gang being idle.

When considering the scenario with downtimes, it can be seen that the queues at the board edger, gang edger and unscrambler are the most important ones (Figure 55). Those machines may thus be considered as potential bottlenecks.

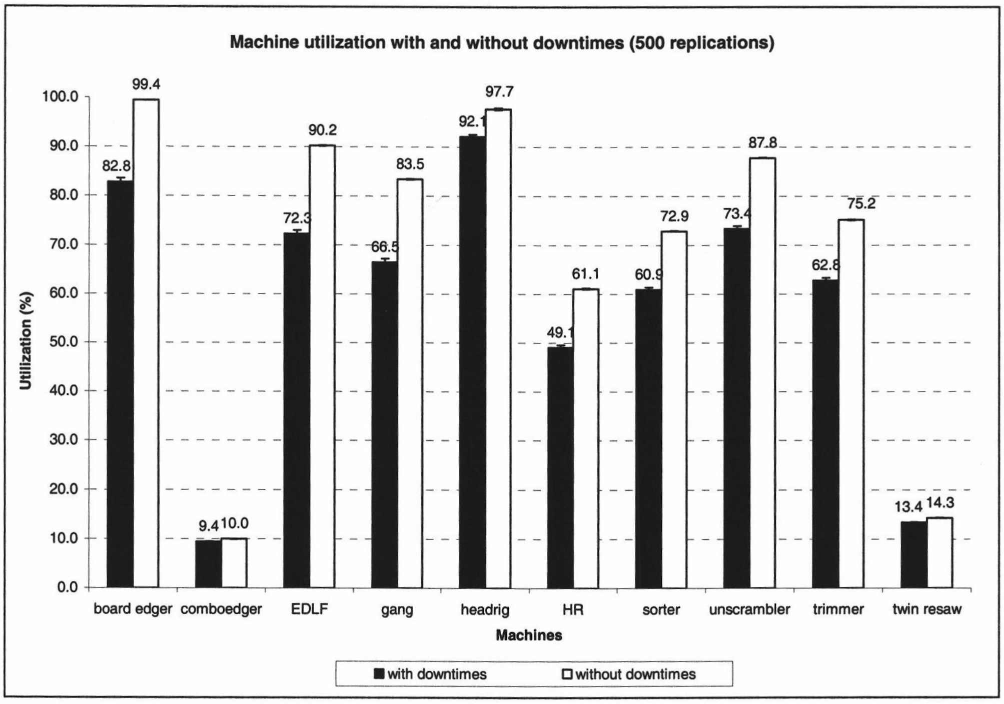


Figure 54. Machine utilization rates with and without downtimes (500 replications).

Table 12. Utilization rates with and without downtimes (500 replications).

	Average (%)	95% CI Half-width
Model with downtimes		
Board edger	82.8	0.76
Combo edger	9.4	0.05
EDLF	72.3	0.76
Gang saw	66.5	0.71
Headrig	92.1	0.42
Horizontal resaw	49.1	0.51
Sorter	60.9	0.47
Unscrambler	73.4	0.57
Trimmer	62.8	0.49
Twin resaw	13.4	0.08
Model without downtimes		
Board edger	99.4	0.01
Combo edger	10.0	0.03
EDLF	90.2	0.08
Gang saw	83.5	0.08
Headrig	97.7	0.19
Horizontal resaw	61.1	0.09
Sorter	72.9	0.05
Unscrambler	73.4	0.06
Trimmer	75.2	0.06
Twin resaw	14.3	0.05

CI: Confidence Interval

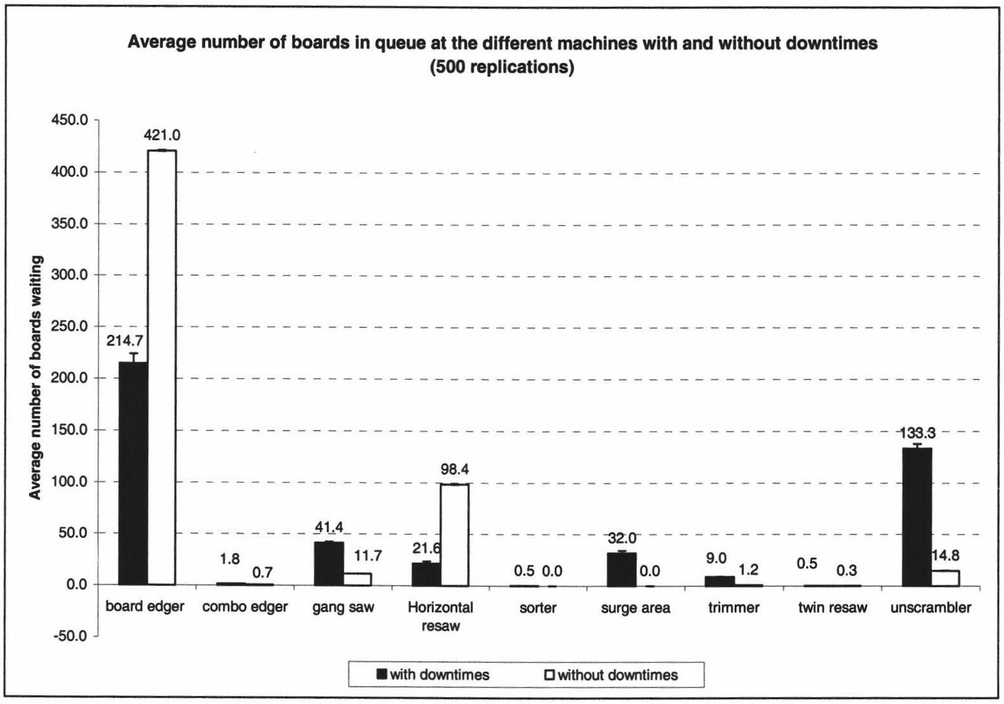


Figure 55. Average number of entities in queue at the different machines with and without downtimes (500 replications).

Table 13. Average number of entities in queue (500 replications).

	Average	**95% CI Half-width**	**Capacity**	**Av./capacity (%)**
Model with downtimes				
Board edger	214.7	9.37	500	**42.95**
Combo edger	1.8	0.13	30	6.03
Gang saw	41.4	1.02	75	**55.23**
Horizontal resaw	21.6	2.25	200	10.80
Sorter	0.5	0.04	5	10.20
Surge Area	32.0	2.50	500	6.4
Trimmer	9.0	0.42	20	45.05
Twin resaw	0.5	0.03	20	2.40
Unscrambler	133.3	4.75	320	**41.66**
Model without downtimes				
Board edger	421.0	0.57	500	**84.2**
Combo edger	0.7	0.01	30	2.33
Gang saw	11.7	0.11	75	15.6
Horizontal resaw	98.4	0.41	200	**49.2**
Sorter	0.0	0.00	5	0
Surge Area	0.0	0.00	500	0
Trimmer	1.2	0.00	20	6
Twin resaw	0.3	0.01	20	1.5
Unscrambler	14.8	0.16	320	4.62

When downtimes are not included in the model, the two headrigs are used more and can thus process a higher number of segments. The EDLF processes 24.9 % more segments while the headrig processes 5.8% more (Figure 56). Because more segments are being processed when no downtimes are included, the number of boards produced increases by 16.5%, as shown in Figure 57.

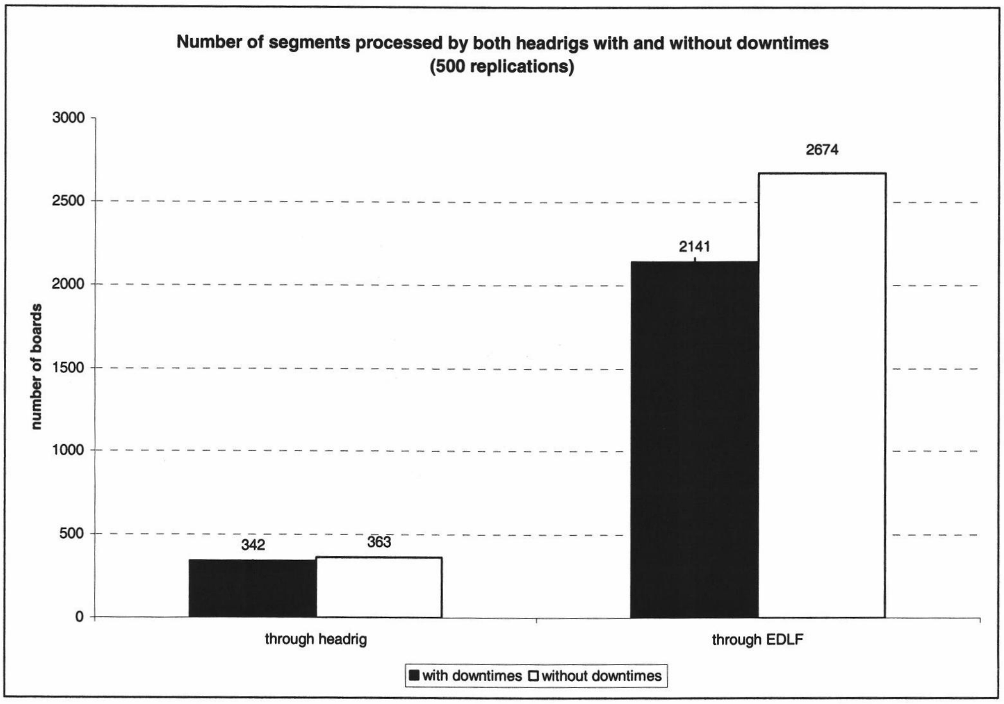


Figure 56. Number of segments processed by both headrigs with and without downtimes (500 replications).

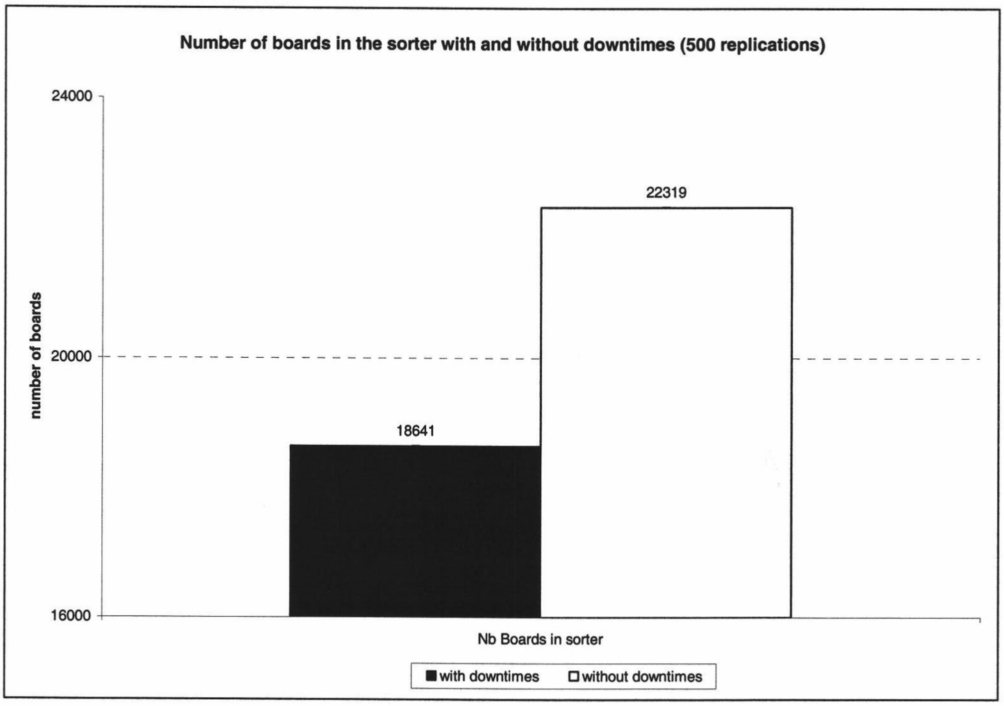


Figure 57. Number of boards in the sorter with and without downtimes (500 replications).

A paired t-test was conducted and showed that the difference in production between the two scenarios was statistically significant. Results of the paired t-test are displayed in Table 14.

Table 14. Paired-T-test Means Comparison: Comparison of the number of boards in sorter with and without downtimes for 500 replications.

Identifier	Est. mean difference	Standard deviation	95% C.I. Half-width	Min. value	Max. value	Number of obs.
Without downtimes	3678	1650	145	21700	22800	500
With downtimes				10200	21800	500
-> Means are not equal at 0.05 level						

5.1.2 Consequence of an increase in the average diameter of the segments being processed at the headrigs

In order to identify possible bottlenecks, the influences of having a large number of boards flowing in the mill on the machine utilization rates, queues and production were investigated. Two different mixes were chosen as input. The first one, called the regular day mix, represents the log distribution currently available in the log yard. The second mix, called the Optquest mix, was determined using Optquest. Optquest is the built-in optimizer provided with Arena and was used to determine the input mix that would generate the maximum number of boards in the sorter. The average log diameters for the two different mixes are summarized in Table 15. A detailed description of both distributions can be found in Appendix D.

Table 15. Average log diameter going to the EDLF and headrig for the two different mixes.

	Regular mix	Optquest mix
Average log diameter at EDLF (inches)	9.20	14.28
Average log diameter at headrig (inches)	18.07	20.55

The Optquest mix is not a realistic mix in the sense that the sawmill doesn't have enough big logs to be able to run that kind of distribution. However, this mix was used as an input in the model to study the consequences of having a large number of boards flowing in the mill. The number of segments processed by both headrigs is shown in Figure 58. In the case of the Optquest mix, the numbers of segments processed by the EDLF and the headrig are lower than in the case of the regular mix. The EDLF is processing 22% less segments when using the Optquest mix, while the headrig is processing 12.9% less segments. This is a result of the fact that, because the segments are bigger, they take more time to process and prevent the headrigs from running more segments. However, because the segments have a larger average diameter in the case of the Optquest mix, more boards are produced out of those segments, resulting in an increase of 7.8% in the production (Figure 59).

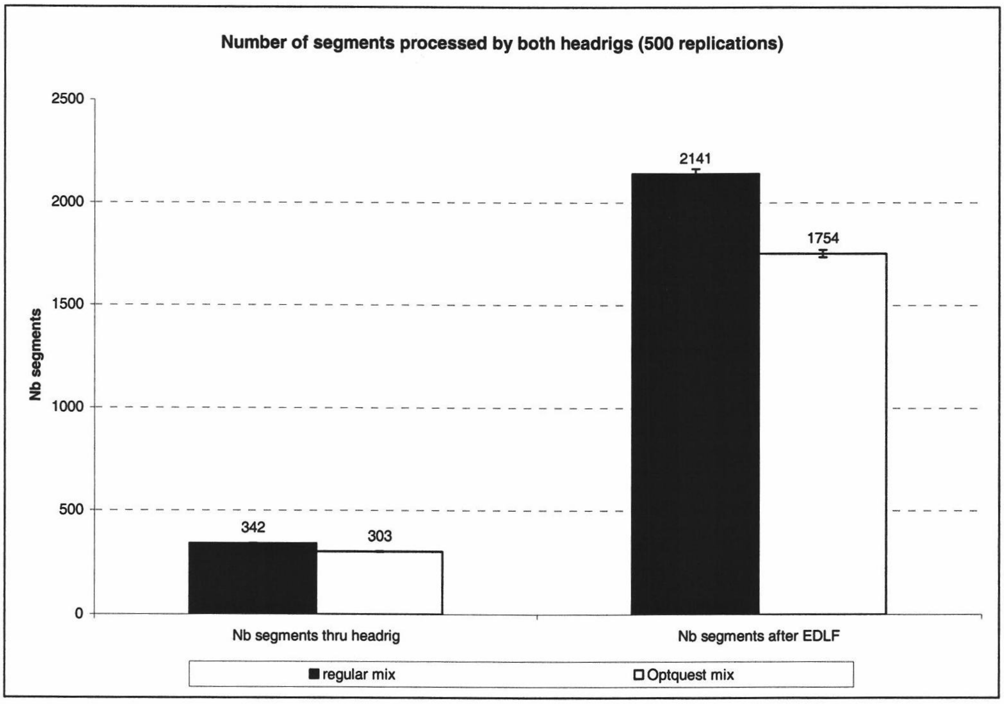


Figure 58. Number of segments processed by both headrigs (500 replications).

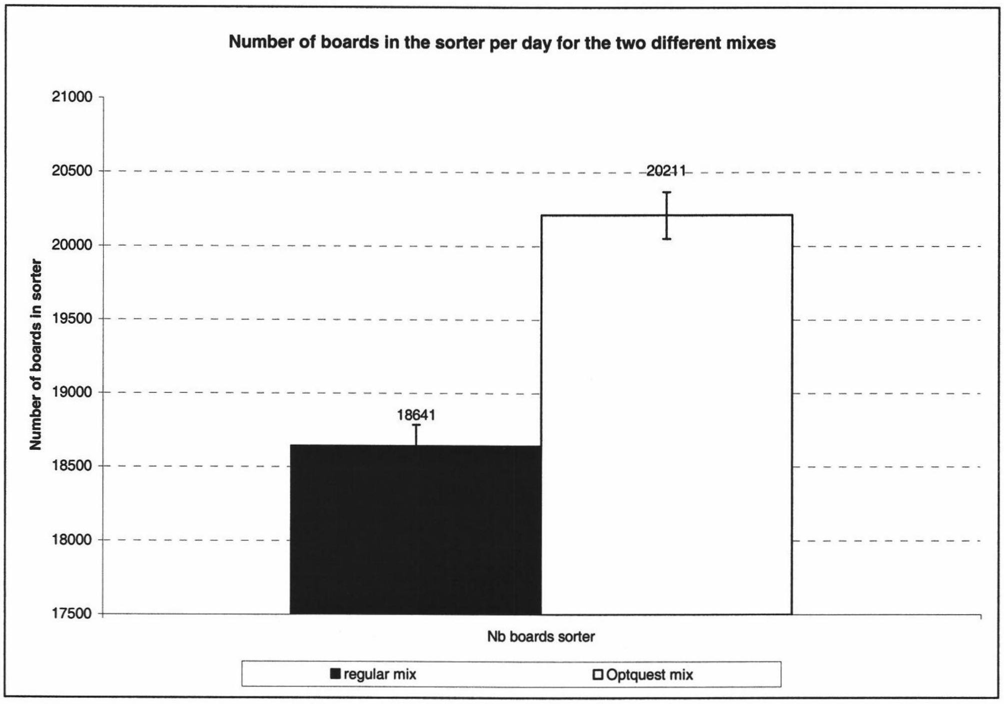


Figure 59. Number of boards produced in the sorter per day for the two different mixes (500 replications).

Many conclusions can be drawn from the utilization rates displayed in Figure 60 and Table 16. The utilization rate of the headrig doesn't change much between the two mixes. Thus, the headrig seems to be the limiting factor on the big log side, which is what is expected in a mill that works properly. The decrease in the utilization rates of the EDLF and the gang edger in the case of the Optquest mix, on the other hand, was not anticipated. The reason for the drop in utilization rates of those two machines can be explained by observing the average number of entities waiting in queues (Figure 61 and Table 17). The average number of entities waiting in the unscrambler queue when using the Optquest mix is high. On average, the unscrambler queue is at 82.5% of its maximum capacity when using the Optquest mix, which means that the limit of this queue is often exceeded. When the unscrambler capacity is reached, the gang edger has to stop, resulting in a low utilization rate for this machine (54.3% with the Optquest mix compared to 66.5% with the regular mix). The queue in front of the gang edger increases as well due to the fact that this machine has to stop often because of the overflow occurring at the unscrambler. This results in having an average number of cants in front of the gang equivalent to 68.7% of the maximum capacity of the gang queue. Once again, this means that the limit of the gang queue is often exceeded during the day. Having the gang queue reach its maximum capacity causes the EDLF to stop, causing the drop in the EDLF utilization rates observed when comparing the two mixes (72.3% with the regular mix compared with 59.1% with the Optquest mix).

Based on those observations, the unscrambler conveyor capacity seems to be the origin of the cascading effect that influences the gang edger and EDLF. The influence of the unscrambler conveyor capacity on the mill flow and production is investigated in section 5.1.3.

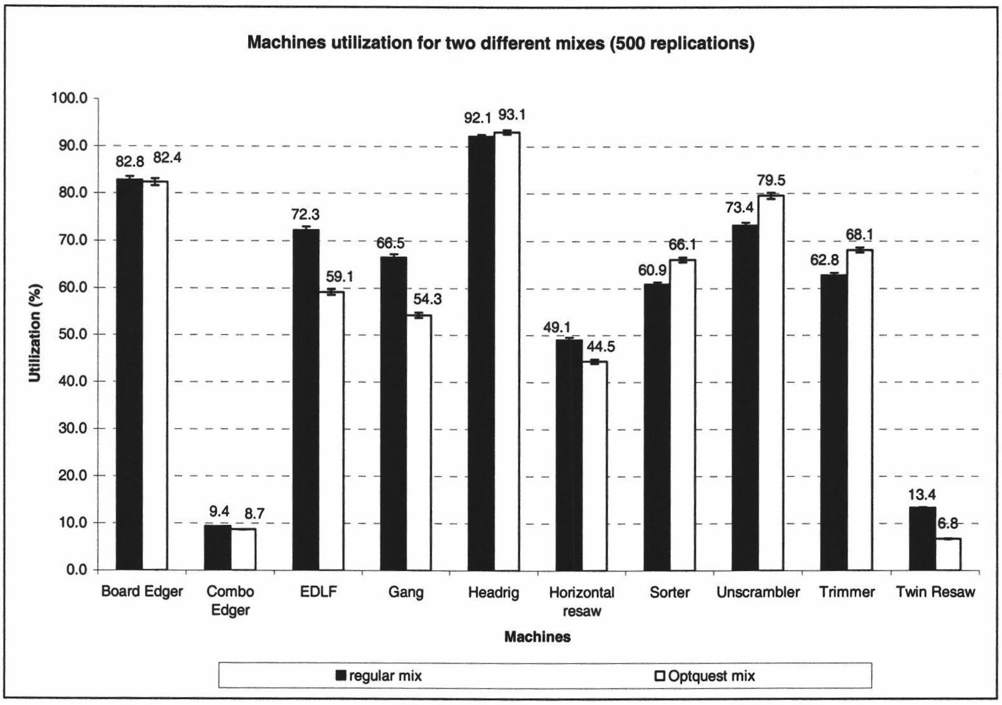


Figure 60. Machine utilization rates for two different mixes (500 replications).

Table 16. Machine utilization rates and 95% confidence interval half-width for two different mixes (500 replications).

	Average (%)	**95% CI Half-width**
With regular mix		
Board edger	82.8	0.76
Combo edger	9.4	0.05
EDLF	72.3	0.76
Gang saw	66.5	0.71
Headrig	92.1	0.42
Horizontal resaw	49.1	0.51
Sorter	60.9	0.47
Unscrambler	73.4	0.57
Trimmer	62.8	0.49
Twin resaw	13.4	0.08
With Optquest mix		
Board edger	82.4	0.73
Combo edger	8.7	0.05
EDLF	59.1	0.61
Gang saw	54.3	0.57
Headrig	93.1	0.46
Horizontal resaw	44.5	0.45
Sorter	66.1	0.51
Unscrambler	79.5	0.62
Trimmer	68.1	0.53
Twin resaw	6.8	0.06

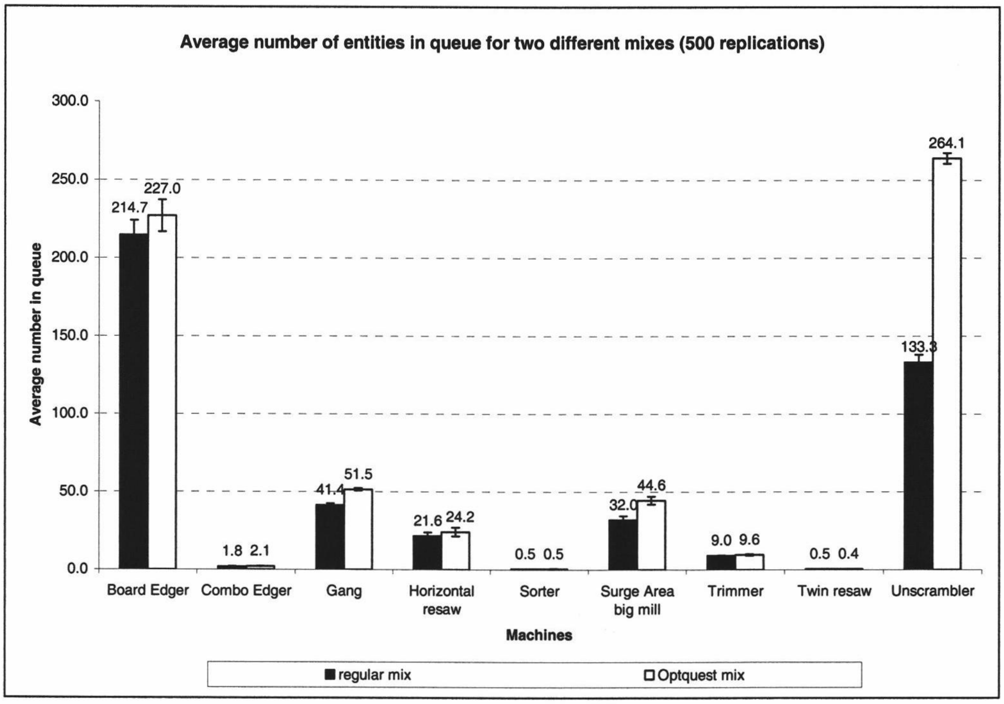


Figure 61. Average number of entities in queue for two different mixes (500 replications).

Table 17. Average number of entities in queue for two different mixes (500 replications).

	Average	95% CI Half- width	Capacity	Av./capacity (%)
With regular mix				
Board edger	214.7	9.37	500	**42.95**
Combo edger	1.8	0.13	30	6.03
Gang saw	41.4	1.02	75	**55.23**
Horizontal resaw	21.6	2.25	200	10.80
Sorter	0.5	0.04	5	10.20
Surge Area	32.0	2.50	500	6.4
Trimmer	9.0	0.42	20	45.05
Twin resaw	0.5	0.03	20	2.40
Unscrambler	133.3	4.75	320	**41.66**
With optquest mix				
Board edger	227.0	10.28	500	**45.47**
Combo edger	2.1	0.13	30	7
Gang saw	51.5	0.88	75	**68.67**
Horizontal resaw	24.2	2.80	200	12.1
Sorter	0.5	0.04	5	10
Surge Area	44.6	2.60	500	8.92
Trimmer	9.6	0.41	20	48
Twin resaw	0.4	0.03	20	2
Unscrambler	264.1	3.46	320	**82.53**

5.1.3 Influence of the unscrambler conveyor capacity on the material flow and production

The influence of the unscrambler conveyor capacity using the regular log mix was previously described in section 5.1.2. To investigate this further, the unscrambler conveyor capacity was increased. Machine utilization rates as well as the average number of entities waiting to be processed by each machine were recorded for unscrambler conveyor capacities ranging from 200 entities up to 1200 entities.

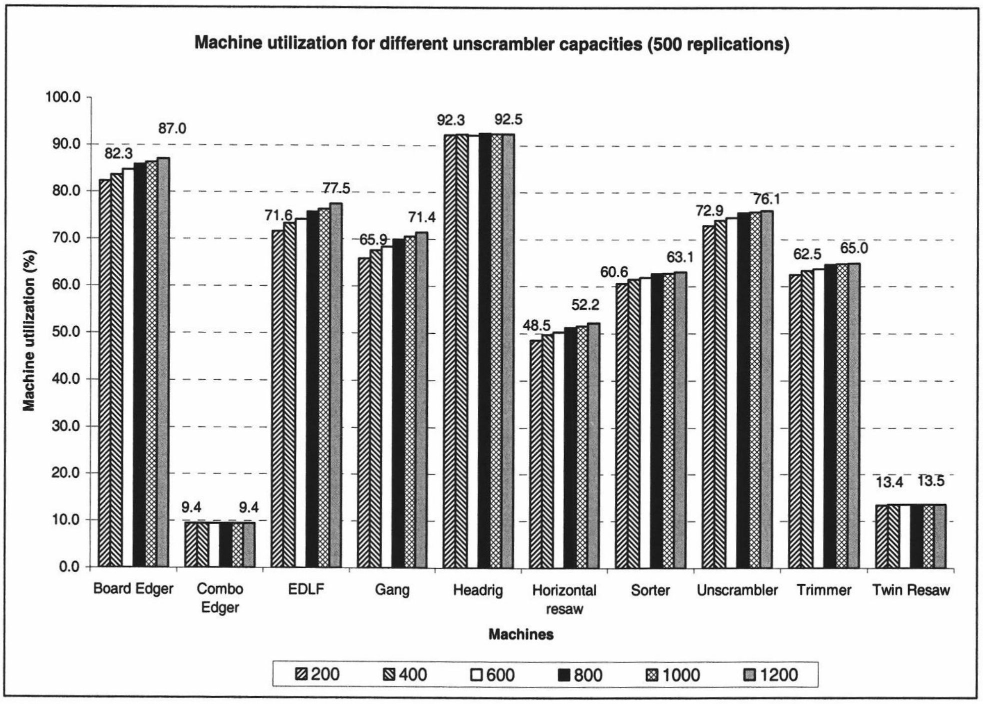


Figure 62. Machine utilization rates for unscrambler maximum capacities ranging from 200 up to 1200 entities.

From Figure 62, it can be seen that the utilization rates of the machines located in the big log side don't increase with an increase of the unscrambler conveyor maximum capacity. The combination edger and the twin resaw can only be affected by the queue at the surge area. However, as shown in Figure 63, this queue represents only 7.1% of its maximum capacity when the unscrambler conveyor capacity is set to 200. Increasing the unscrambler conveyor capacity thus has no influence on the utilization rates of those machines as they were already working at their maximum rates when the unscrambler conveyor capacity was set to 200. However, the utilization rates of the machines located on the small log side increase when the maximum capacity increases. When considering the average number of entities waiting in the different machine queues (Figure 63), it can be seen that an increase in the capacity of the unscrambler conveyor results in a decrease in the number of cants waiting at the gang. Because the queue in front of the gang is smaller, the EDLF doesn't have to stop because of an overflow at the gang queue. Thus, the utilization rate of the EDLF increases, resulting in a higher number of segments being processed as the unscrambler's maximum capacity increases (Figure 64). Then, as more segments are processed by the EDLF, the production increases as well (Figure 65). As shown in Figure 65, increasing the unscrambler capacity leads to statistically significant increases in production ranging, from 2.6 to 5.3% (Table 18). However, queues larger than 800 produced no statistically significant improvement in production (Tables B- 7 to B- 12).

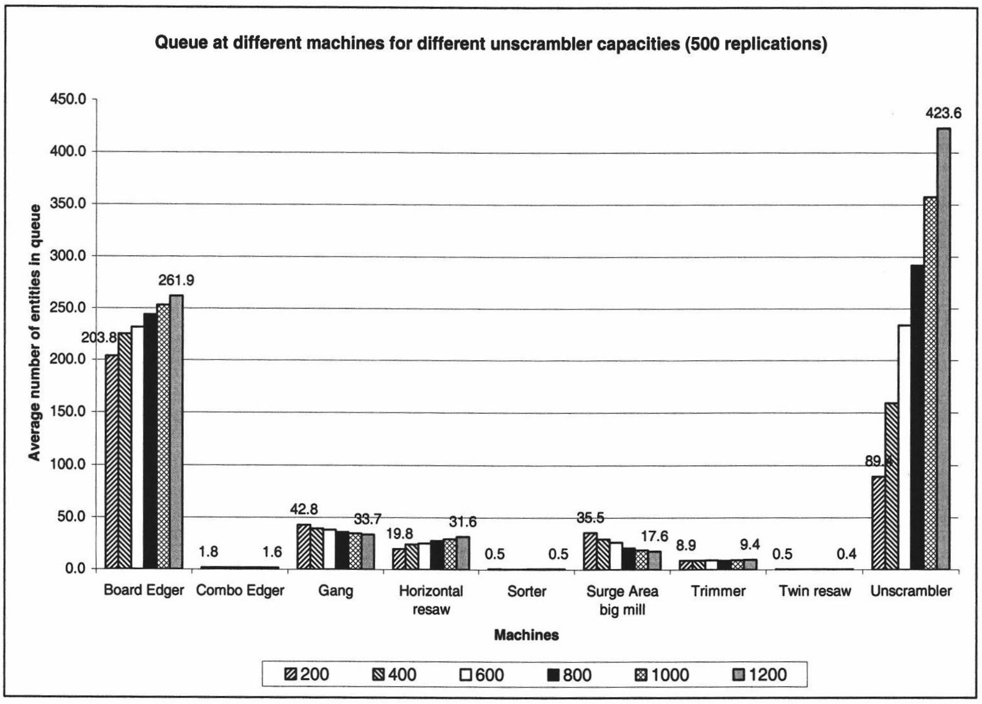


Figure 63. Average number of entities waiting in queues for different unscrambler conveyor capacities (500 replications).

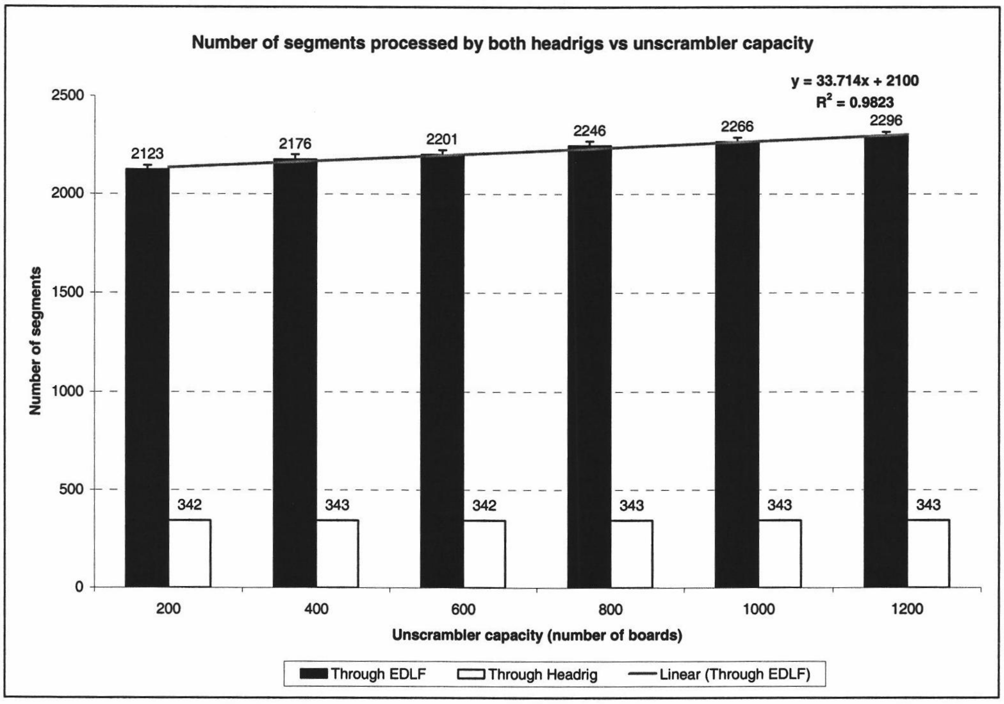


Figure 64. Number of segments processed by both headrigs vs unscrambler maximum capacity (500 replications).

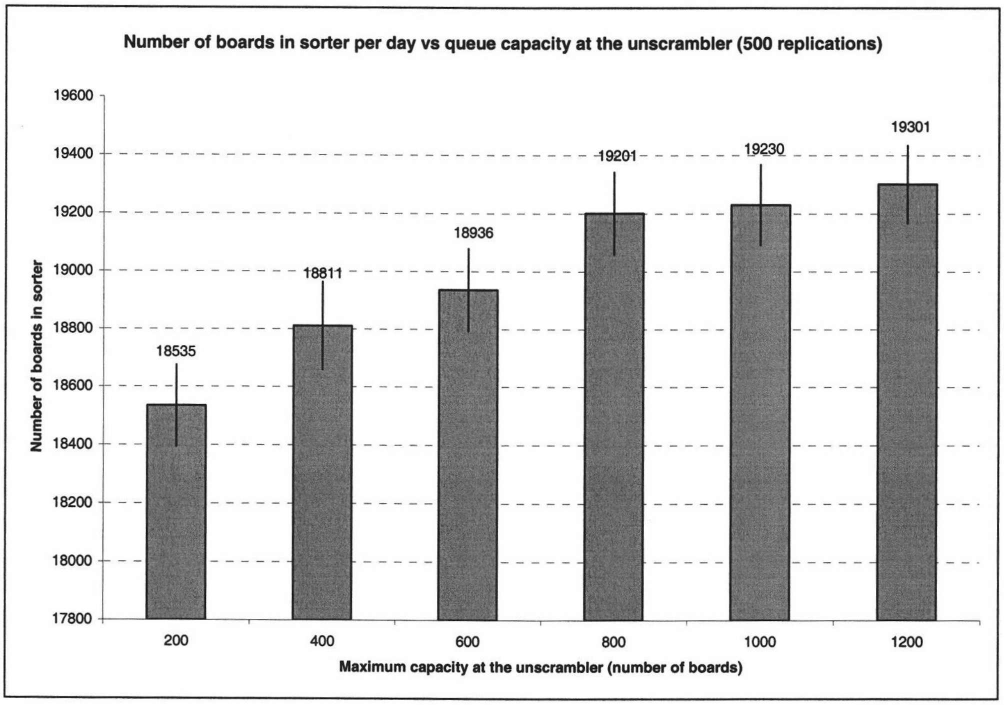


Figure 65. Number of boards produced in the sorter per day vs unscrambler maximum capacity (500 replications).

Table 18. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day with the unscrambler capacity ranging from 200 up to 1200 entities.

Boards in the sorter per day with a change of the unscrambler capacity				
Unscrambler maximum capacities	min across replications	max across replications	95% Confidence Interval	95% CI Half-width
200	12000	21870	18390 – 18680	140.50
300	11090	21820	18410 – 18720	152.40
400	10250	21670	18670 – 18950	142.50
500	12910	21700	18670 – 18950	141.50
600	12160	21830	18800 – 19070	138.60
700	12530	21830	18960 – 19220	132.90
800	13530	22380	19070 – 19330	128.30
900	13560	22320	19000 – 19260	132.40
1000	13830	22150	19100 – 19360	129.00
1100	12630	22150	19010 – 19300	144.2
1200	11080	22150	19170 – 19430	131.9

These results show that the unscrambler is the limiting factor on the small log side. However, it has also been demonstrated that increasing the unscrambler conveyor capacity resulted in better utilization of the gang edger and EDLF, resulting in an increase in the production. Finally, as observed previously, the headrig is the limiting factor on the big log side of the mill.

5.1.4 Influence of the percentage of boards being sent to the horizontal resaw from the EDLF

The horizontal resaw can be operated by one or two operators. However, in the case where only one operator runs the machine, this person doesn't really have time to look at the oncoming boards and make a decision on the direction that those boards should take. As a result, many boards are being processed by the horizontal resaw when they should have been sent directly to the board edger. The influence of having a second operator assisting at the horizontal resaw was thus studied using the regular log mix described in section 5.1.2 and was simulated by changing the percentages of boards being sent to the horizontal resaw from the

EDLF. Machine utilization rates as well as the average number of entities waiting to be processed by each machine were recorded for percentages of boards being sent to the horizontal resaw varying from 20% to 100%.

Figure 66 shows a drop in the utilization rate of the board edger, gang edger, EDLF, unscrambler, trimmer and sorter for percentages of boards being sent to the horizontal resaw above 90%. The percentages of boards sent to the horizontal resaw don't seem to have a significant influence on the utilization rates of the machines in the mill, when those percentages remain below 80%. Figure 66 also shows that, as expected, the utilization rate of the horizontal resaw increases as more boards are conveyed directly to this machine.

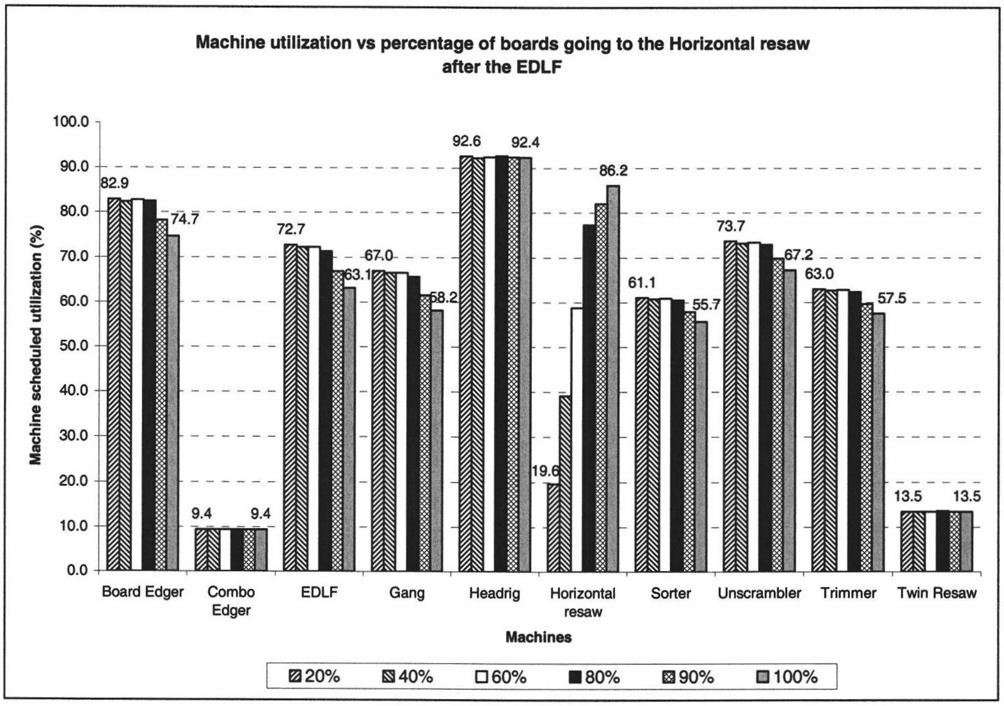


Figure 66. Machine utilization rates vs percentage of boards being sent to the horizontal resaw (500 replications).

The drop in machine utilization rates for percentages above 90% is due to the high average number of entities waiting in the horizontal resaw queue. As shown in Figure 67, for percentages equal to 90 and 100%, the average number of entities waiting represents 53.3 and 64.5% of the horizontal resaw conveyor maximum capacity. Each time during the shift that the horizontal resaw conveyor exceeds its limit, the EDLF has to stop. This also has consequences on the gang edger. Figure 67 clearly shows that the average number of cants waiting in front of the gang edger decreases when the horizontal resaw percentage increases due to the fact that the EDLF has to stop more often as the percentage of boards being sent to the horizontal resaw increases. The same reasoning can be applied to explain the decrease in the queue in front of the board edger for high percentages of boards sent to the horizontal resaw.

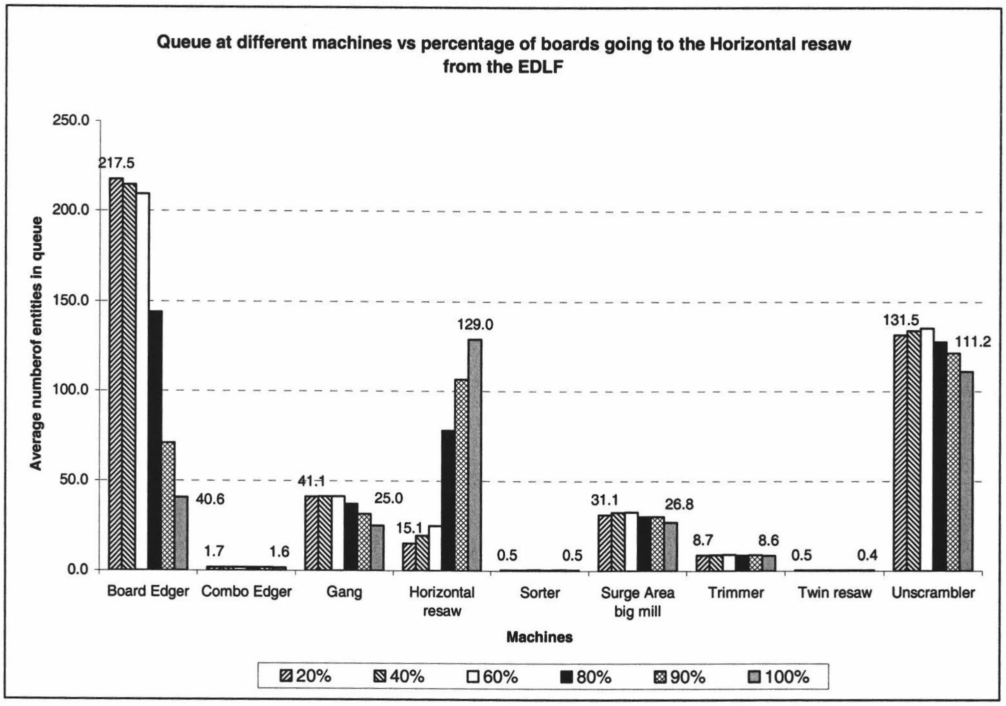


Figure 67. Average number of entities waiting in queues for different percentages of boards being sent to the horizontal resaw from the EDLF (for 500 replications).

Stopping the EDLF due to an overflow of the horizontal resaw conveyor has the consequence of decreasing the number of segments processed (Figure 68), thus decreasing production (Figure 69). Finally, Figure 69 shows that as long as the percentage of boards sent directly to the horizontal remains below 80%, there isn't any significant difference in terms of production. As it is pretty unlikely that 90 or 100% of the boards coming from the EDLF will be sent directly to the horizontal resaw, the presence of a second operator doesn't seem to be essential for the production. Nevertheless, a second operator assisting at this machine could allow the first operator to make better decisions. However, this couldn't be modeled.

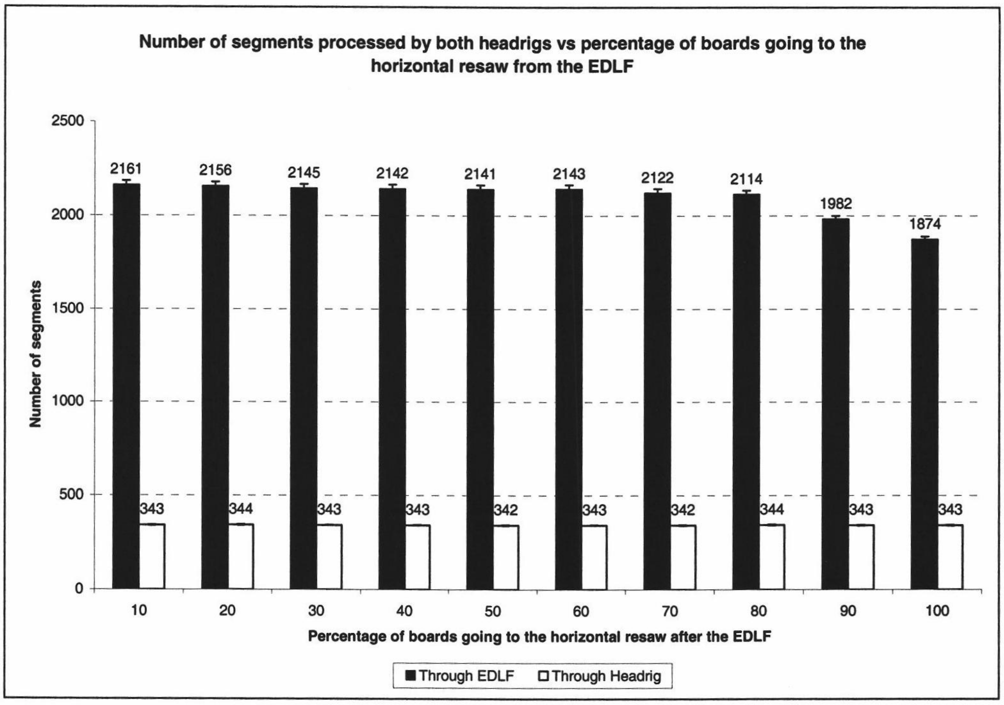


Figure 68. Number of segments processed by both headrigs for different percentages of boards being sent to the horizontal resaw from the EDLF (500 replications).

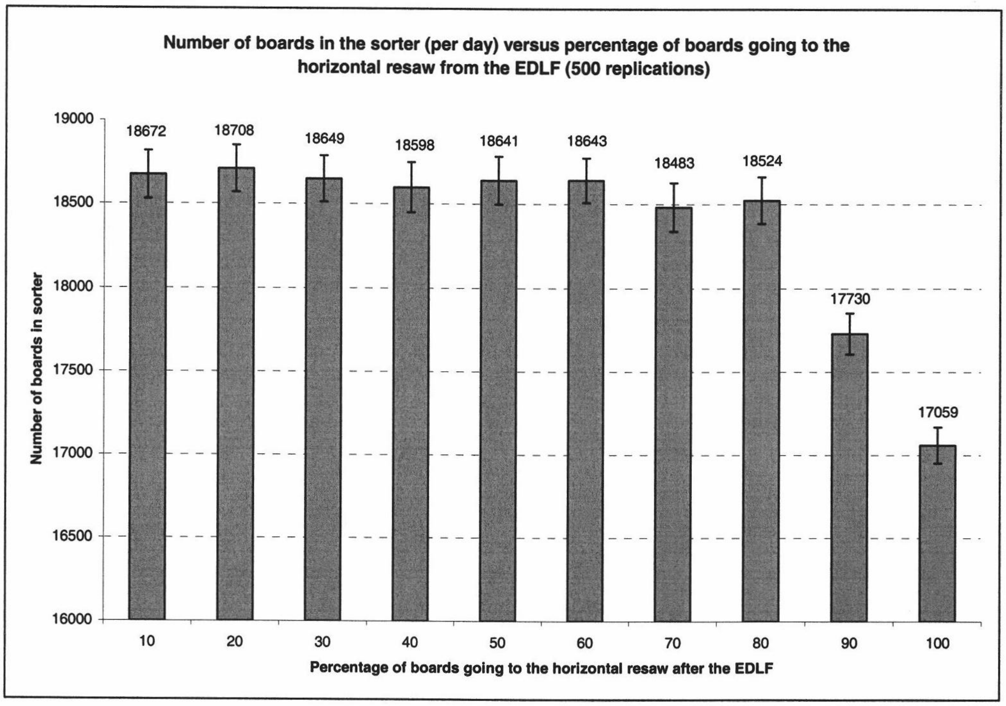


Figure 69. Number of boards in the sorter per day for different percentages of boards being sent to the horizontal resaw from the EDLF (500 replications).

5.2 PART II: Log yard sorting strategies

To investigate some log yard sorting strategies that would minimize the decrease in production resulting from processing a larger number of small-diameter logs, three distributions were created (current, smallest and intermediate distributions). For each distribution (Tables C- 1, C- 2 and C- 3), the model was used to implement and test the different sorting strategies.

Those strategies are defined in Tables 19 and 20. Because downtimes are not uniform during the day, it was decided to schedule each sorting solution on two days (except for the 2 deck sort), instead of having certain decks feeding the mill in the morning and other ones in the afternoon. On the first day, the smallest logs are processed at the EDLF while the largest ones are processed at the headrig in order to compensate as much as possible for the decrease in production induced by processing small logs. However, the decrease cannot be totally compensated. The idea is then, on the second day, to process logs from decks that will significantly increase the production, so that, on average over the two days, production stays as close as possible to what it was when using the current log distribution. Detailed descriptions of each deck for each distribution can be found in Appendix C, Tables C- 4 to C- 19 for the current distribution, Tables C- 20 to C- 36 for the intermediate distribution and Tables C- 37 to C- 53 for the smallest distribution. The number of logs processed for each diameter class as well as the number of boards in the sorter were recorded. The production for each sorting strategy associated with each distribution was compared with the current mill production.

Table 19. The different sorting strategies implemented for the current and intermediate distributions.

Current distribution	**Description of the decks**	**Processed by**	**Scheduled on**
2 decks	5 to 17 inches	EDLF	1 day
	18 inches and above	Headrig	
3 decks day 1	5 to 9 inches	EDLF	2 days
	18 inches and above	Headrig	
3 decks day 2	10 to 17 inches	EDLF	
	18 inches and above	Headrig	
3 decks modified day 1	5 to 11 inches	EDLF	2 days
	18 inches and above	Headrig	
3 decks modified day 2	12 to 17 inches	EDLF	
	18 inches and above	Headrig	
4 decks day 1	5 to 9 inches	EDLF	2 days
	21 inches and above	Headrig	
4 decks day 2	10 to 15 inches	EDLF	
	16 to 20 inches	Headrig	
Intermediate distribution	**Description of the decks**	**Processed by**	**Scheduled on**
2 decks	5 to 17 inches	EDLF	1 day
	18 inches and above	Headrig	
3 decks day 1	5 to 9 inches	EDLF	2 days
	18 inches and above	Headrig	
3 decks day 2	10 to 17 inches	EDLF	
	18 inches and above	Headrig	
4 decks day 1	5 to 7 inches	EDLF	2 days
	21 inches and above	Headrig	
4 decks day 2	8 to 17 inches	EDLF	
	18 to 20 inches	Headrig	
4 decks modified day 1	5 to 9 inches	EDLF	2 days
	21 inches and above	Headrig	
4 decks modified day 2	10 to 15 inches	EDLF	
	16 to 20 inches	Headrig	

Table 20. The different sorting strategies implemented for the smallest distribution.

Smallest distribution	Description of the decks	Processed by	Scheduled on
2 decks	5 to 17 inches 18 inches and above	EDLF Headrig	1 day
3 decks day 1	5 to 9 inches 18 inches and above	EDLF Headrig	2 days
3 decks day 2	10 to 17 inches 18 inches and above	EDLF Headrig	
4 decks day 1	5 to 7 inches 21 inches and above	EDLF Headrig	2 days
4 decks day 2	8 to 17 inches 18 to 20 inches	EDLF Headrig	
4 decks modified day 1	5 to 9 inches 21 inches and above	EDLF Headrig	2 days
4 decks modified day 2	10 to 15 inches 16 to 20 inches	EDLF Headrig	

5.2.1 Current distribution

Different sorting strategies were implemented using the current log distribution. The current sorting of the yard is done with two different decks. From the results displayed in Table 21, it can be seen that the different sorting solutions implemented don't result in a significant increase in production. Thus, no particular recommendations can be given for this log distribution as the 2 deck sorting already produced the highest output.

Table 21. Production comparison for different sorting strategies using the current log distribution.

With unscrambler capacity = 320 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from the current production (=18868 boards)
2 decks	18868	18868	0%
3 decks day 1	16944	18515.5	-1.9%
3 decks day 2	20087		
3 decks mod day 1	17668	18917	+0.3%
3 decks mod day 2	20166		
4 decks day 1	17020	18357.5	-2.7%
4 decks day 2	19695		

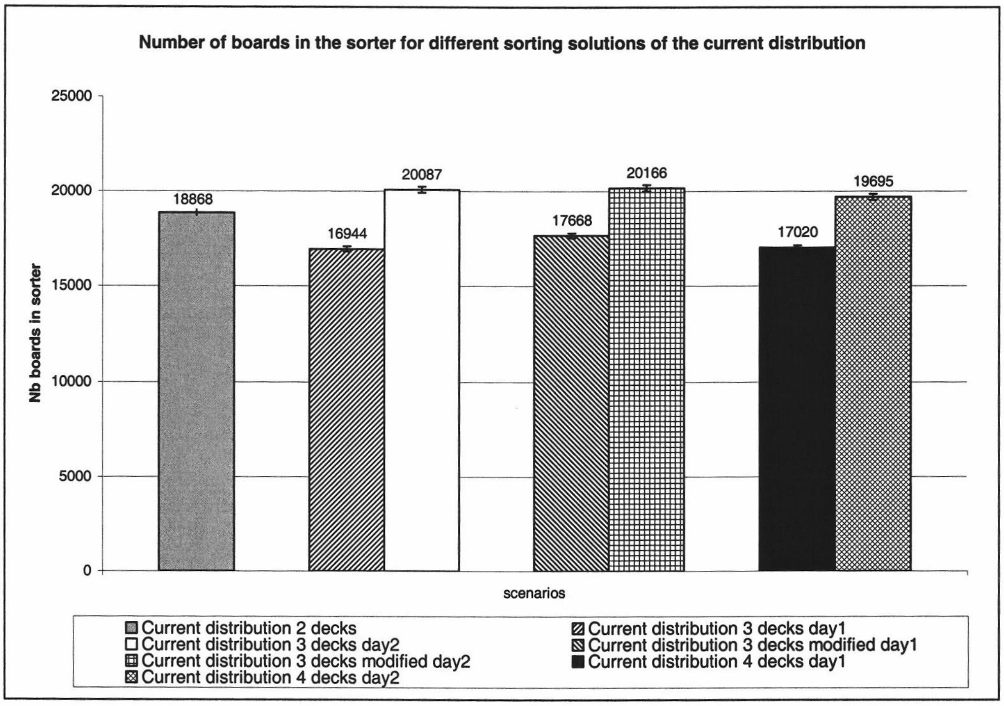


Figure 70. Number of boards in the sorter per day for different sorting solutions of the current log distribution.

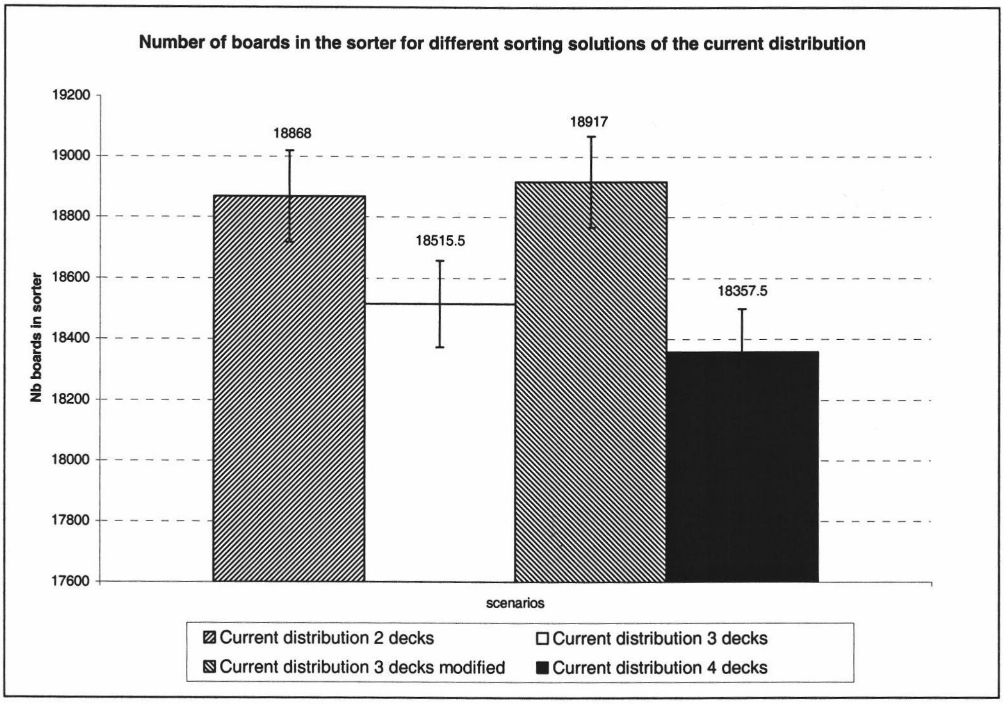


Figure 71. Number of boards in the sorter per day for different sorting solutions of the current log distribution (production over 2 days has been averaged).

As expected, the number of boards produced by the small log side when using the small-diameter decks (5 to 9 inch deck and 5 to 11 inch deck) is lower than when using decks with log diameters ranging from 10 to 17 inch (3 decks, day 2) or 12 to 17 inch (3 decks modified, day 2) because fewer boards are being recovered out of small-diameter logs. Figure 72 also shows that the big log side is not influenced by the dimensions of the material being processed on the small log side, which is expected as no boards from the small side flow to the big side. Finally, the change in diameter of the material being processed at the headrig (for a 4 deck sort on day 1 and 2 as well as for a 4 modified deck sort on day 1 and 2) doesn't seem to result in a significant variation of the number boards in the sorter coming from the big log side.

It is very important, when implementing log yard sorting, to closely monitor what is in the yard and make sure that the different decks are appropriately supplied in order to realize the desired sort. Table 22 summarizes the approximate number of logs necessary per day in order to implement in the real log yard the sorting solutions tested in the model. Using this table, the people in charge of the log yard could evaluate the need in material for each log diameter over a certain period of time and purchase the appropriate logs.

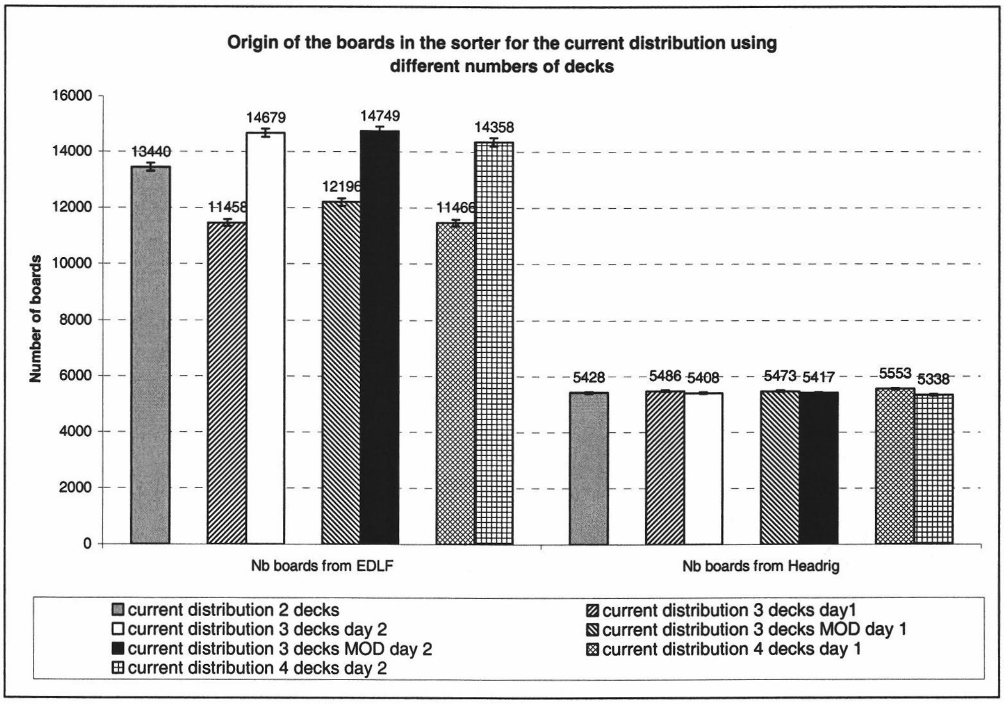


Figure 72. Origin of the boards produced when using the current log distribution under different sorting solutions.

Table 22. Number of logs necessary per day for each sorting solution of the current log distribution.

Number of logs necessary per day for each sorting strategy of the current distribution							
diameter	2 decks	3 decks		3 decks modified		4 decks	
	Day 1	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
5	0	0	0	0	0	0	0
6	311	578	0	447	0	577	0
7	108	201	0	155	0	200	0
8	96	178	0	137	0	177	0
9	86	159	0	123	0	159	0
10	82	0	165	118	0	0	211
11	82	0	165	117	0	0	210
12	59	0	119	0	175	0	151
13	53	0	107	0	158	0	136
14	48	0	100	0	148	0	128
15	48	0	97	0	143	0	124
16	42	0	86	0	126	0	28
17	43	0	86	0	126	0	28
18	75	76	75	76	75	0	62
19	49	50	49	50	49	0	41
20	19	19	19	19	19	0	16
21	15	15	15	15	15	99	0
22	7	7	7	7	7	49	0

5.2.1.1 Influence of increasing the unscrambler conveyor capacity

From the study of the influence of the unscrambler capacity on the overall production, it is known that increasing the unscrambler limit results in an increase in production. Thus, the same sorting strategies were implemented in the model with the unscrambler capacity set to 1200. Results displayed in Table 23 and Figure 73 show that the highest increase in production (3.8%) occurs when using a 3 deck sort over 2 days.

Table 23. Production comparison for different sorting strategies using the current log distribution and the unscrambler capacity set to 1200.

With unscrambler capacity = 1200 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from the current production (=18868 boards)
2 decks	19540	19540	+3.6%
3 decks day 1	17648	19082.5	+1.1%
3 decks day 2	20517		
3 decks mod day 1	18397	19578.5	**+3.8%**
3 decks mod day 2	20760		
4 decks day 1	17815	19069	+1.1%
4 decks day 2	20323		

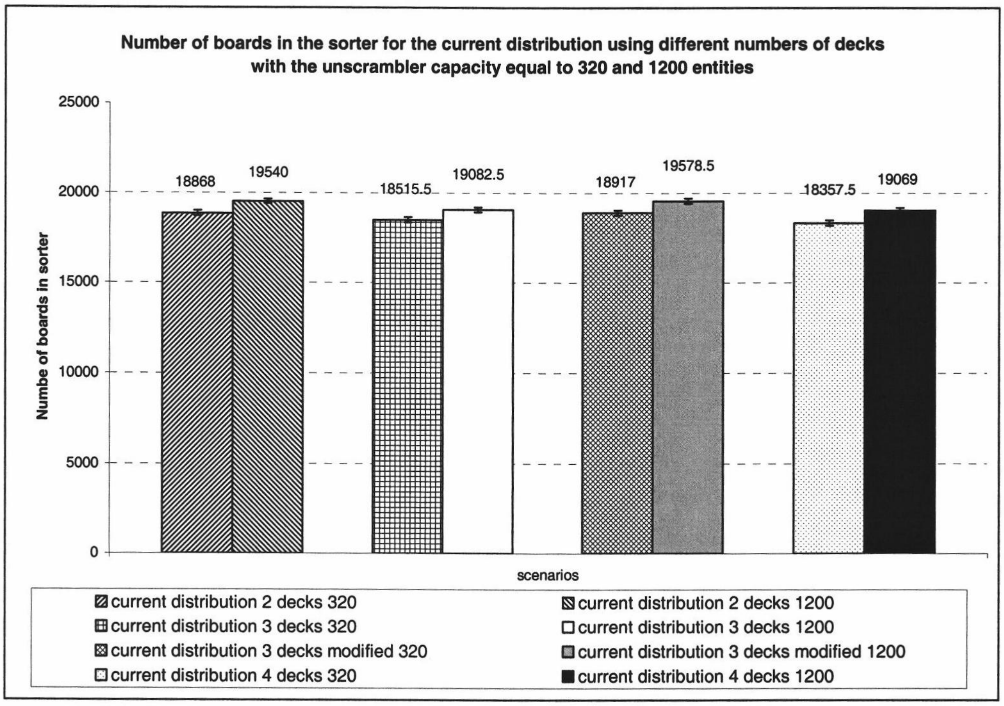


Figure 73. Number of boards in the sorter per day when using different numbers of decks for the current log distribution with the unscrambler capacity equal to 320 and 1200 entities.

5.2.2 Smallest distribution

Different sorting strategies were implemented using the smallest log distribution. Figure 74 shows that using the 3 or 4 deck sort on day 2 results in overflowing the queues at both the board edger and unscrambler. The consequence of overflowing the unscrambler queue is the low utilization rates of both the gang edger and EDLF as shown in Figure 75. The utilization rates of the board edger, horizontal resaw, unscrambler and trimmer are higher on day 2 than on day 1 because bigger material is processed at both the big-side and small-side headrigs, resulting in more boards flowing in the mill.

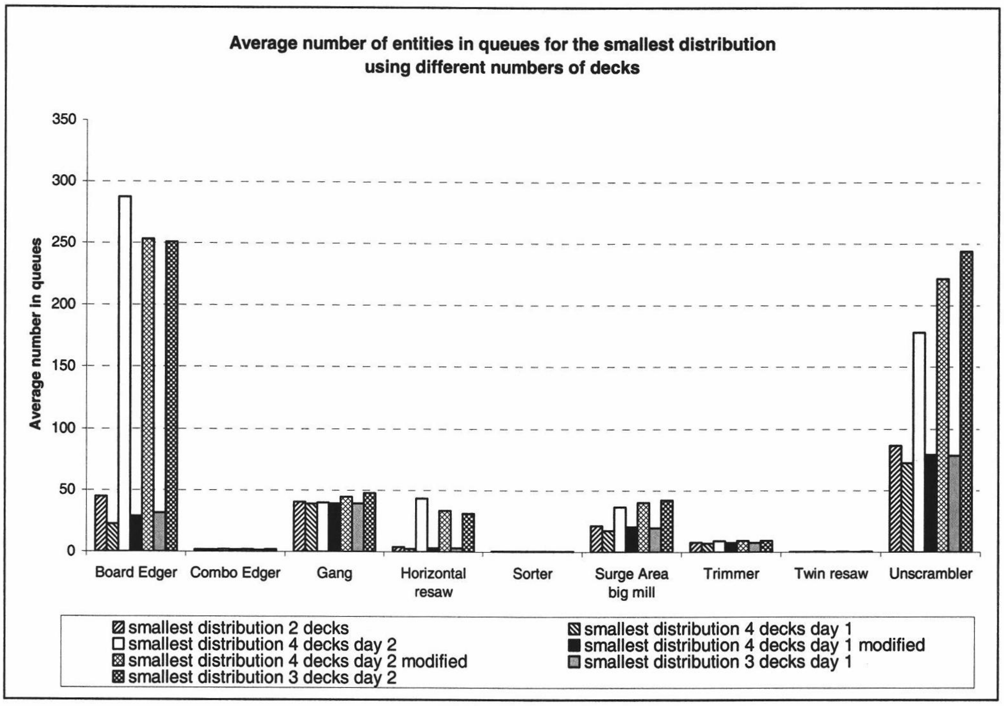


Figure 74. Average number of entities in queues for the smallest distribution using different numbers of decks.

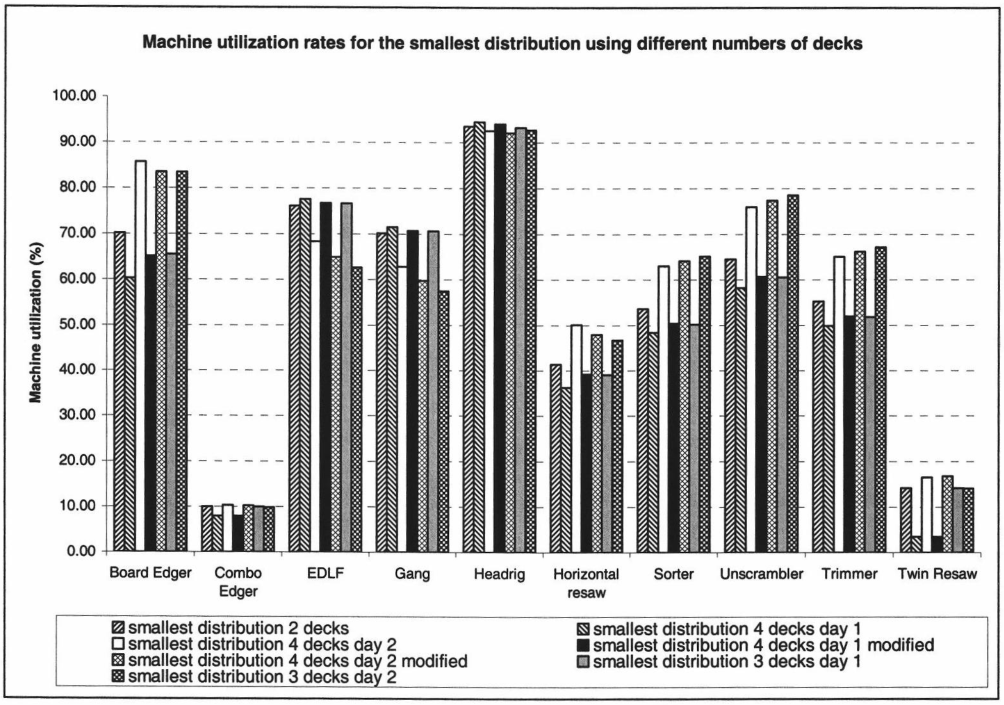


Figure 75. Machine utilization rates for the smallest distribution using different numbers of decks.

From the results displayed in Table 24 and Figures 76 and 77, it can be seen that processing small-diameter logs, when using the current 2 deck sort, results in a significant drop in production (13.1%) (Tables C- 54 and C- 56). However, the results summarized in Table 24 also show that just a minimal change in the sorting results in a decrease in production of only 6.4% when using a 3 deck sort strategy and a decrease of 7.0% and 9.6% when using the 4 deck sort and the 4 deck sort modified, respectively. Thus, the 3 deck sort is better. This is true in terms of production but also in terms of implementation. As a matter of fact, the 3 deck sort is easier to realize as the three different decks match more or less the distribution of logs that can be found in a truck load. The main advantage of this sorting solution, besides the fact that it minimizes the drop in production, is that it can be executed without having to scale all the incoming logs.

Table 24. Production comparison for different sorting strategies using the smallest distribution.

With unscrambler capacity = 320 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from current production (=18868 boards)
2 decks	16397	16397	-13.1%
3 decks day 1	15365	17661.5	**-6.4%**
3 decks day 2	19958		
4 decks day 1	14797	17051	-9.6%
4 decks day 2	19305		
4 decks mod day 1	15431	17543.5	-7.0%
4 decks mod day 2	19656		

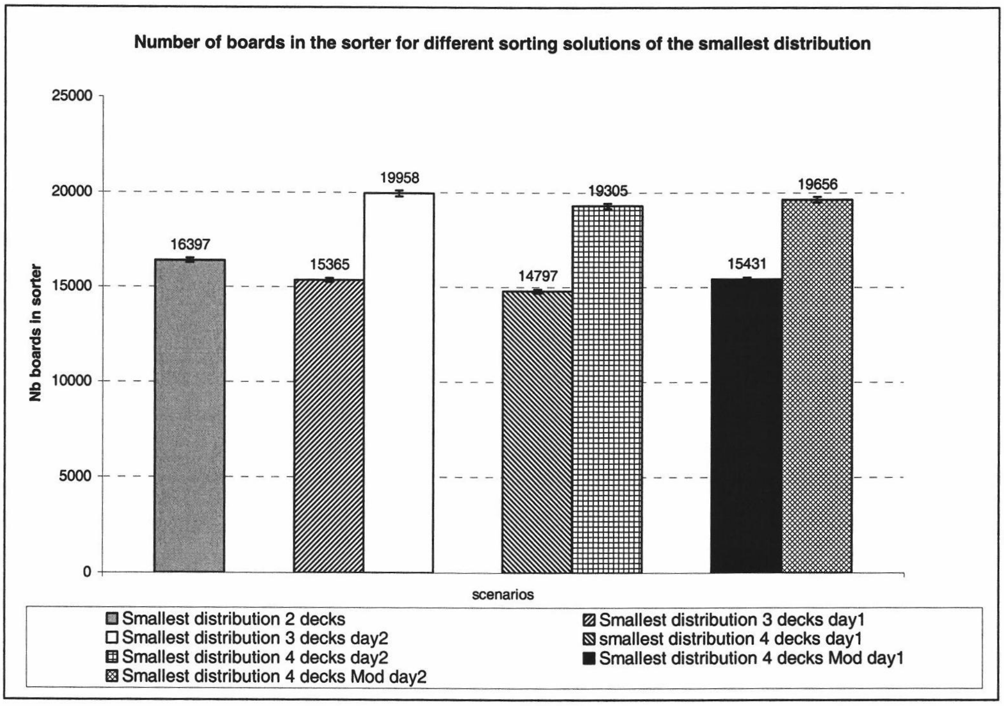


Figure 76. Number of boards in the sorter per day for different sorting solutions of the smallest distribution.

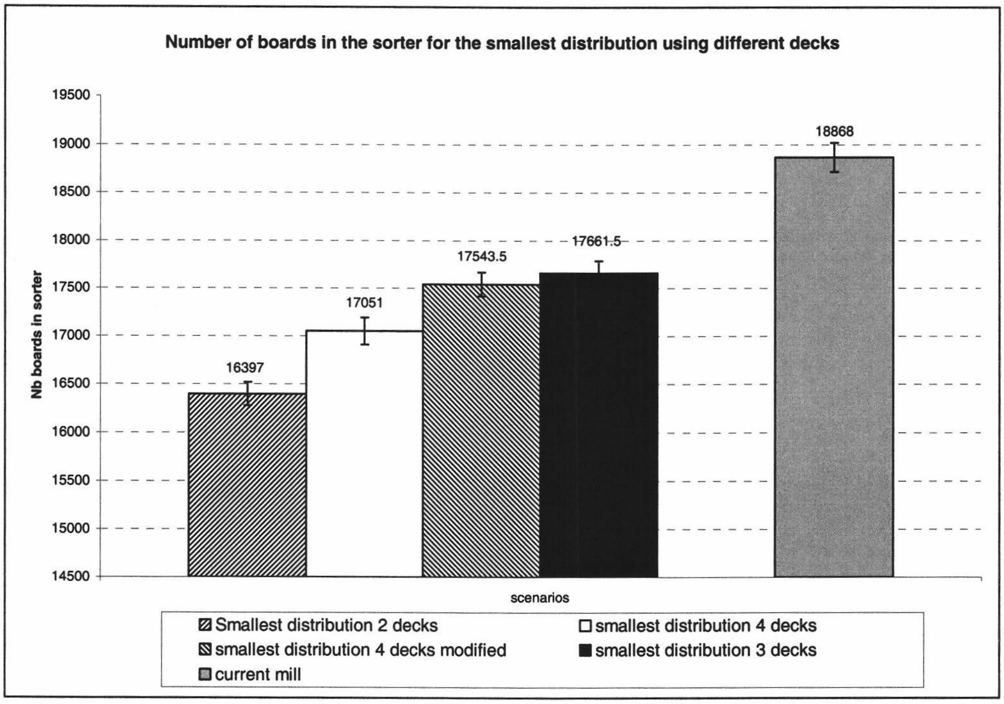


Figure 77. Number of boards in the sorter per day for different sorting solutions of the smallest distribution (production over 2 days has been averaged).

Table 25 summarizes the number of logs needed per day to implement the sorting solutions tested in the model. As previously explained, it is very important that the mill personnel closely monitor the diameter of the logs that are in the yard. In this case, it is even more critical as they need to make sure they have enough big diameter logs to feed the big log side when processing small-diameter logs at the EDLF.

Table 25. Number of logs necessary per day for each sorting solution of the smallest distribution.

Number of logs necessary per day for each sorting strategy of the smallest distribution

diameter	2 decks	3 decks		4 decks		4 decks modified	
	Day 1	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
5	139	163	0	198	0	163	0
6	481	565	0	685	0	564	0
7	175	206	0	250	0	206	0
8	127	149	0	0	389	149	0
9	44	52	0	0	136	52	0
10	42	0	246	0	130	0	307
11	25	0	148	0	78	0	185
12	18	0	107	0	56	0	133
13	17	0	96	0	50	0	120
14	15	0	90	0	47	0	112
15	15	0	87	0	46	0	109
16	13	0	77	0	41	0	23
17	13	0	77	0	41	0	23
18	55	55	54	0	67	0	50
19	60	60	59	0	73	0	55
20	23	23	23	0	28	0	21
21	18	18	18	100	0	100	0
22	9	9	9	49	0	49	0

5.2.2.1 Influence of increasing the unscrambler conveyor capacity

The same sorting strategies were implemented in the model with the unscrambler capacity set to 1200. Results displayed in Table 26 and Figure 78 show that increasing the unscrambler capacity allows the production, when using small-diameter logs, to be almost equal to the production when using the current log distribution (-3.1% difference).

Table 26. Production comparison for different sorting strategies using the smallest distribution and the unscrambler capacity set to 1200.

With unscrambler capacity = 1200 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from current production (=18868 boards)
2 decks	17143	17143	-9.1%
3 decks day 1	16071	18286.5	**-3.1%**
3 decks day 2	20502		
4 decks day 1	15452	17613.5	-6.6%
4 decks day 2	19775		
4 decks mod day 1	16127	18142	-3.8%
4 decks mod day 2	20157		

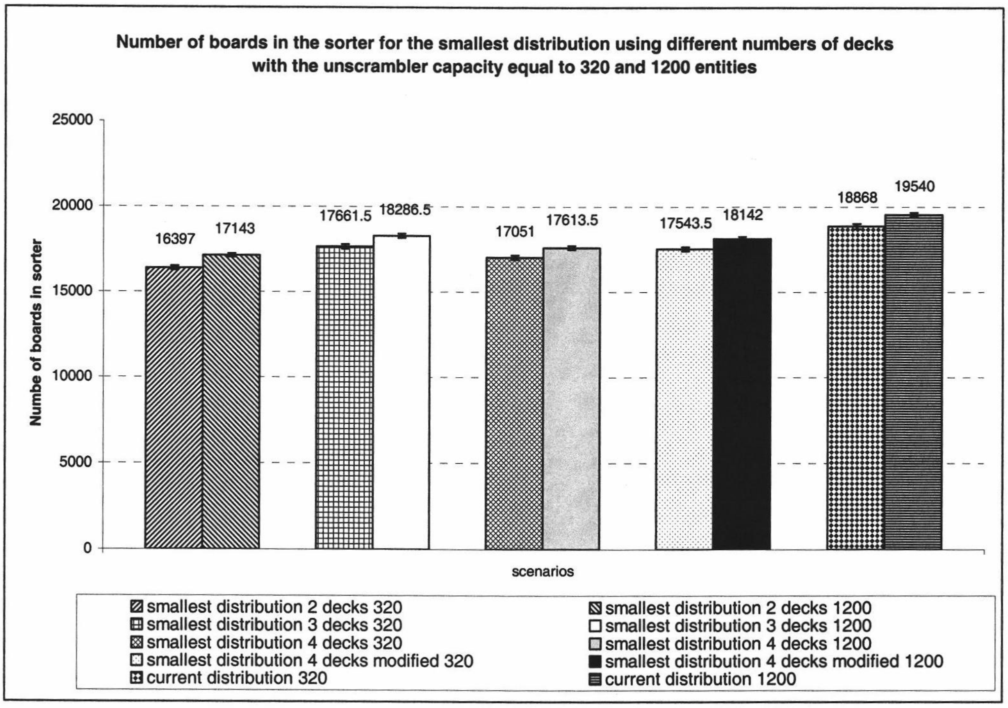


Figure 78. Number of boards in the sorter per day when using different numbers of decks for the smallest distribution with the unscrambler capacity equal to 320 and 1200 entities.

5.2.3 Intermediate distribution

The different sorting strategies were also implemented using the intermediate log distribution. The same remarks concerning the queues at the board edger and the unscrambler as well as the machine utilization rates can be made when using the intermediate distribution as when using the smallest one.

From the results displayed in Table 27 and Figures 79 and 80, it can be seen that processing small-diameter logs, when using the current 2 deck sort, results in a significant drop in production (10.1%) (Tables C- 54 and C- 59). However, the results summarized in Table 27 also show that just a minimal change in sorting results in a decrease in production of only 4.7% when using a 3 deck sort strategy. Thus, sorting the log yard into 3 or 4 decks is beneficial in terms of production when processing small-diameter logs. Using a 3 deck sort with the intermediate distribution produces about the same results as when using a 3 deck sort with the smallest distribution (317 boards difference).

Table 27. Production comparison for different sorting strategies using the intermediate distribution.

With unscrambler capacity = 320 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from current production (=18868 boards)
2 decks	16971	16971	-10.1%
3 decks day 1	15388	17978.5	**-4.7%**
3 decks day 2	19354		
4 decks day 1	16100	17371	-7.9%
4 decks day 2	19674		
4 decks mod day 1	16033	17887	-5.2%
4 decks mod day 2	19924		

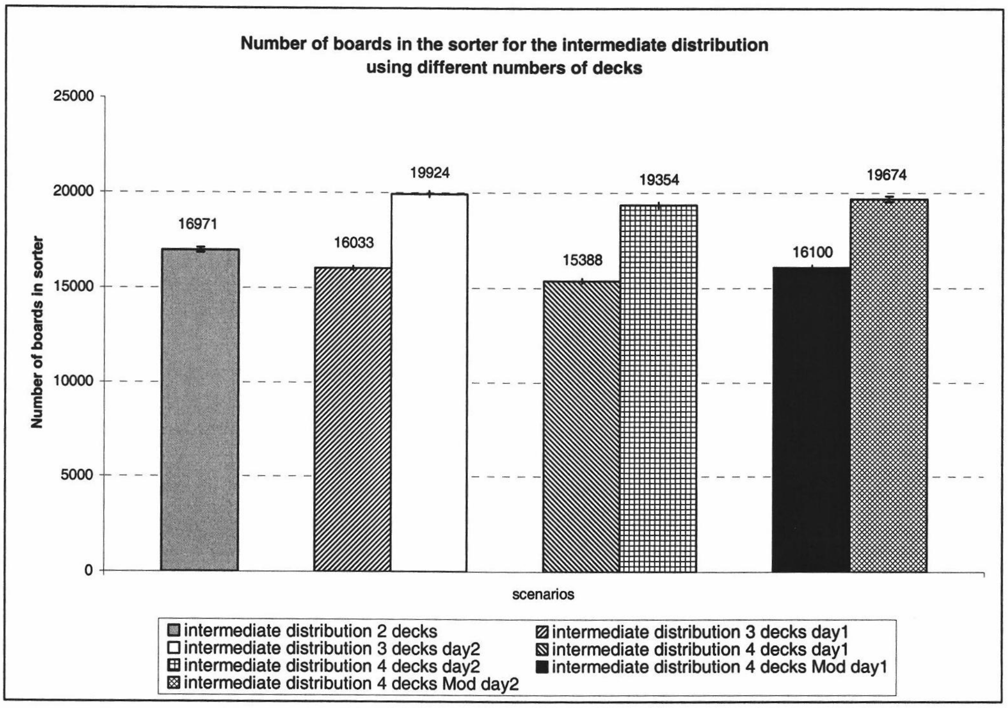


Figure 79. Number of boards in the sorter per day for different sorting solutions of the intermediate distribution.

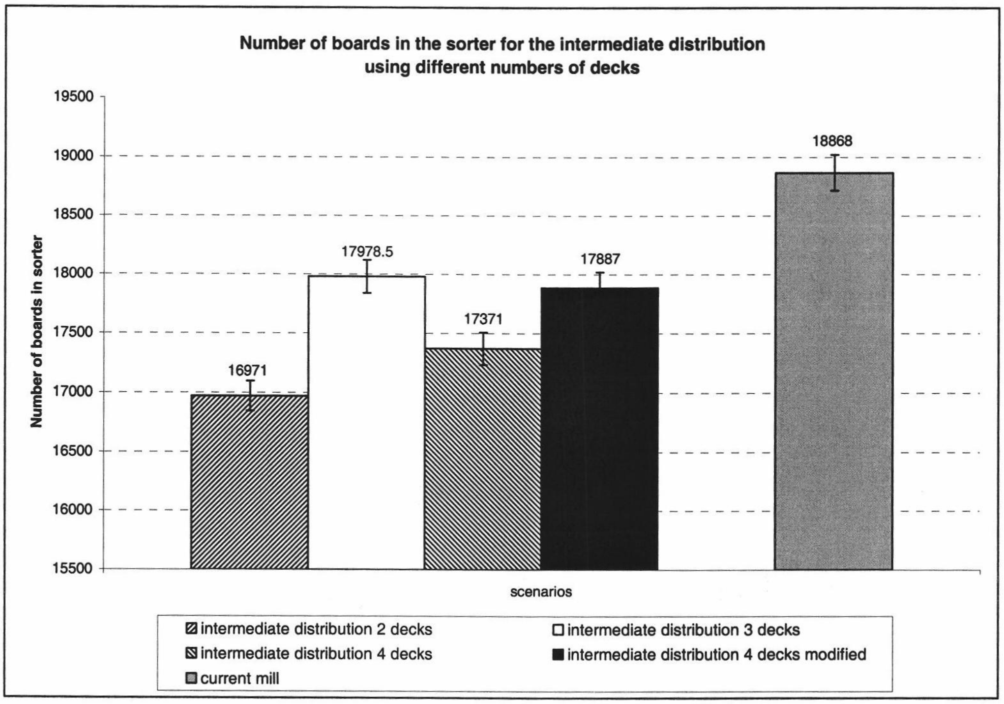


Figure 80. Number of boards in the sorter per day for different sorting solutions of the intermediate distribution (production over 2 days has been averaged).

Table 28 summarizes the number of logs necessary per day in order to implement in the real log yard the sorting solutions tested in the model. For the same reason given with the smallest distribution, it is essential that the personnel in charge of the log yard make sure they have enough big diameter logs that are processed at the headrig when feeding the EDLF with the small-diameter material.

Table 28. Number of logs necessary per day for each sorting solution of the intermediate distribution.

Number of logs necessary per day for each sorting strategy of the intermediate distribution							
diameter	2 decks	3 decks		4 decks		4 decks modified	
	Day 1	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
5	139	163	0	198	0	163	0
6	481	565	0	685	0	564	0
7	175	206	0	250	0	206	0
8	127	149	0	0	389	149	0
9	44	52	0	0	136	52	0
10	42	0	246	0	130	0	307
11	25	0	148	0	78	0	185
12	18	0	107	0	56	0	133
13	17	0	96	0	50	0	120
14	15	0	90	0	47	0	112
15	15	0	87	0	46	0	109
16	13	0	77	0	41	0	23
17	13	0	77	0	41	0	23
18	55	55	54	0	67	0	50
19	60	60	59	0	73	0	55
20	23	23	23	0	28	0	21
21	18	18	18	100	0	100	0
22	9	9	9	49	0	49	0

5.2.3.1 Influence of increasing the unscrambler conveyor capacity

The same sorting strategies were implemented in the model with the unscrambler capacity set to 1200. Results displayed in Table 29 and Figure 81 show that increasing the unscrambler capacity allows the production, when using small-diameter logs, to be almost equal to the production when using the current log distribution (1.4% difference).

Table 29. Production comparison for different sorting strategies using the intermediate distribution and the unscrambler capacity set to 1200.

With unscrambler capacity = 1200 entities			
Decks	Number of boards in sorter	Average number of boards in sorter per day	Change from current production (=18868 boards)
2 decks	17731	17731	-6.0%
3 decks day 1	16720	18600	**-1.4%**
3 decks day 2	20480		
4 decks day 1	16041	17880	-5.2%
4 decks day 2	19719		
4 decks mod day 1	16859	18504	-1.9%
4 decks mod day 2	20149		

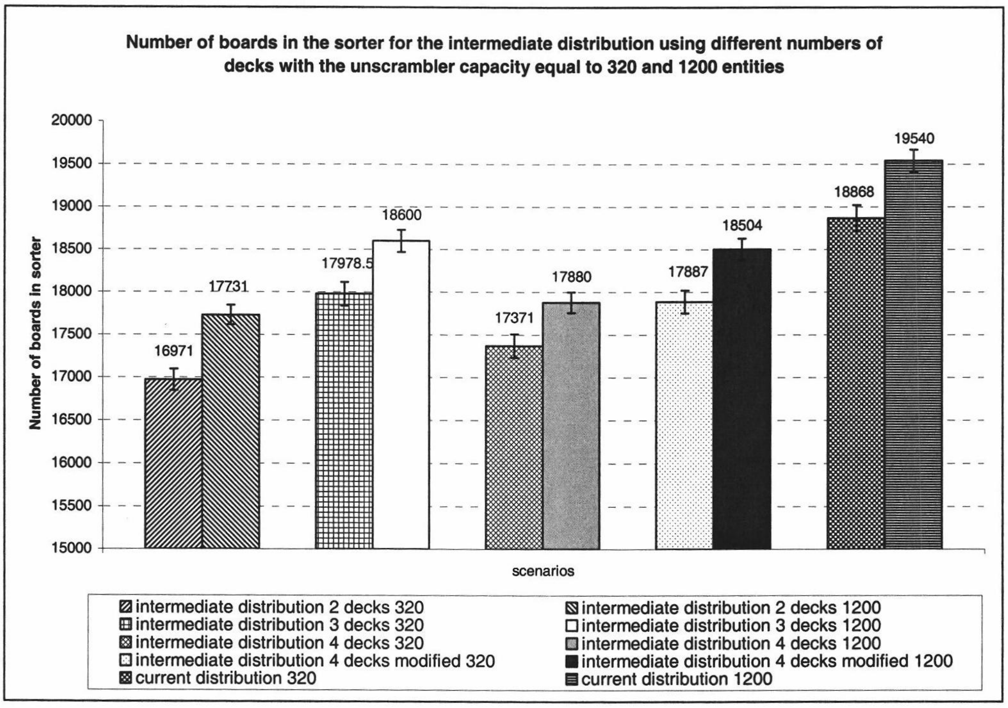


Figure 81. Number of boards in the sorter per day when using different numbers of decks for the intermediate distribution with the unscrambler capacity equal to 320 and 1200 entities.

Many conclusions can be drawn about implementing the sorting strategies for the three different log input distributions. First, introducing higher percentages of small-diameter logs in the input mix will result in a significant decrease in production if the current 2 deck sort is retained. Thus, switching from the current log distribution to the intermediate or smallest log distribution has a large impact on the mill's production. However, it has been shown that just a minimal change in the sorting, such as using a 3 deck sort, will be highly beneficial and will limit the decrease in production encountered by the use of small-diameter logs. The 3 deck sort is probably the easiest one to implement as the distribution of the logs for each of the decks correspond more or less to the distribution of material that can be found in the truck loads. Thus, using a 3 deck sort can be realized without necessarily having to scale all the incoming logs. Also, there is not much difference in production between using the smallest distribution or the intermediate one, even if there was a way to get rid of the 5 inch logs. Finally, implementing log yard sorting requires closely monitoring what is in the yard and making sure that the different decks are appropriately supplied in order to realize the desired sort. The personnel in charge of the log yard will have to pay greater attention to the type of material they are purchasing when processing small-diameter timber so there are enough big diameter logs to compensate for the small ones.

6. CONCLUSIONS AND FUTURE RESEARCH RECOMMENDATIONS

Discrete-event simulation was used to determine methods to increase the efficient utilization of small-diameter timber at the Warm Springs Forest Products Industries sawmill, focusing on the log yard. Before the computer model developed for this research could be used to address the small-diameter timber issue, it had to be first used to investigate and optimize the overall current sawmill process. Different scenarios were run in order to identify potential bottlenecks and to examine ways of removing them. It was shown that the headrig is the limiting factor on the big log side and that its utilization rate doesn't go beyond 93%. On the small log side, the unscrambler was identified as the bottleneck, and the consequences resulting from overflowing the unscrambler conveyor were illustrated. Having the unscrambler conveyor reach its maximum capacity caused the utilization rate of machines upstream to drop because those machines had to stop until the number of boards waiting at the unscrambler decreased. It is possible to improve both the flow and production by increasing the unscrambler conveyor capacity. Allowing a larger number of boards on the unscrambler conveyor resulted in a better gang edger utilization rate because it didn't have to stop as often. As the gang edger worked better, the EDLF was able to process more segments, which had an immediate consequence of increasing the mill's production. Increasing the unscrambler conveyor capacity up to 800 boards resulted in an increase in production ranging from 2.6 to 5.3%. The model was also used to experiment with operating strategies such as having a second operator helping in directing the flow before boards reach the horizontal resaw. It was shown that as long as the percentage of boards sent directly to the horizontal resaw remained below 80%, there wasn't any significant difference in terms of production.

The second part of the research focused on the introduction of small-diameter timber into the log mix. From a production standpoint, it is known that processing smaller diameter logs results in a decrease in production as fewer boards can be recovered out of small logs. However, past studies have shown that log sorting is an essential condition to achieving higher production in the sawmill. Therefore, the model was first used to quantify the production drop that would result from processing smaller diameter logs. It was then modified to test different log sorting solutions on three different log distributions. The three log distributions tested were the current log distribution and two distributions including greater amounts of small-diameter timber (5 to 7 inches). When using different sorting solutions on the current log distribution, no significant change in the number of boards produced could be seen. Processing logs from the smaller and the smallest diameter distributions resulted in significant decreases in production (from 10.1 to 13.1%) when using the current two deck sort. However, it was shown that implementing a three or four deck sort on any of the small log distributions considerably minimized the drop in production observed when using the two decks sort. Implementing a three deck sort seems to be the easiest way to sort the yard as the distribution of the logs in each of the decks should match the log distribution of a truck load, limiting the need for scaling the incoming logs. However, in order of being able to create those three decks, the mill will have to pay greater attention to the diameter of the logs they purchase and closely monitor the diameter that are in the yard as they need to make sure that they have enough big diameter logs to feed in the big log side to compensate for the small-diameter ones being processed on the small log side.

This research showed a number of advantages of using simulation when studying an existing sawmill. People in the mill can physically see things happen. However, they may not be aware of the ramifications and the cascading effects on the machines upstream. For instance, as they are able to clear the unscrambler conveyor, they may not see how the queue at the unscrambler affects the overall flow. Simulation has demonstrated the importance of showing how machines in the mill are related to one another and how a problem occurring at one location can affect the entire mill flow and production. Thus, the computer model developed for this research has been shown to be a very valuable tool the sawmill can use to investigate production and log supply issues.

Finally, a few improvements could be made to the model for conducting further studies. Due to the loss of the trimmer data during the test run, no information can be provided about board footage. Thus, all the results and statistics in this research were based on piece count only. However, future work could be done with log breakdown models like BOF or SAW3D. Those sawing simulation programs would provide the final width, thickness and length of the boards in order to determine board footage. Another test run could also be run to compare the board footage production of the mill with the board footage estimation provided by those breakdown models. In addition, more data, especially for the downtimes, could be collected in order to increase the degree of accuracy of the model. Adding more scanners in the mill and being able to retrieve information from them would greatly increase the level of accuracy in the data collected and would thus provide a more reliable and precise computer model. Scanning and tracking all the incoming logs could also improve the accuracy of the information on the log sizes available in the log yard. The model could also be used to study other scenarios of interest such as the influence of the trimmer's downtimes on the unscrambler queue and other machine utilization rates. Future work could also focus on testing mathematical algorithms that will search for other optimized sorting and feeding strategies.

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APPENDICES

Appendix A. Breakdown Figures and Summary Tables of Collected Data

Table A- 1. Percentage of diameters in the log yard from 12/31/03 to 6/30/04.

Diameter (inches)	5	6	7	8	9	10	11	12
Percentage (%)	0.02	29.40	10.19	9.03	8.11	7.74	7.73	5.50
Diameter (inches)	13	14	15	16	17	18	19	20
Percentage (%)	4.92	4.03	3.44	2.60	2.24	2.29	1.50	0.58
Diameter (inches)	21	22	23	24	25	26	27	28
Percentage (%)	0.45	0.08	0.02	0.03	0.04	0.01	0.01	0.01
Diameter (inches)	29	30	31					
Percentage (%)	0.01	0.01	0.01					

Table A- 2. Average length for each log diameter.

Diameter (inches)	5	6	7	8	9	10	11	12
Average length (feet)	21	26	32	34	34	32	32	32
Diameter (inches)	13	14	15	16	17	18	19	20
Average length (feet)	32	32	31	31	31	30	30	21
Diameter (inches)	21	22	23	24	25	26	27	28
Average length (feet)	22	32	28	32	29	31	34	31
Diameter (inches)	29	30	31					
Average length (feet)	34	30	34					

Table A- 3. Bucking solutions.

Log (feet)	Segment 1 (feet)	Segment 2 (feet)
20	20	0
21	10	10
22	10	12
23	10	12
24	10	14
25	10	14
26	10	16
27	10	16
28	12	16
29	12	16
30	14	16
31	14	16
32	16	16
33	16	16
34	16	16
35	16	18
36	20	16
37	16	20
38	20	18
39	20	18
40	20	20
41	20	20
42	20	20
43	20	20
44	20	20
45	20	20
46	20	20

Table A- 4. Bucking solutions applied to the model.

Log		1st segment		2nd segment	
Diameter (inches)	**average length (feet)**	**Diameter (inches)**	**Length (feet)**	**Diameter (inches)**	**Length (feet)**
5	21	5	10	6	10
6	26	6	10	7	16
7	32	7	16	9	16
8	34	8	16	10	16
9	34	9	16	11	16
10	32	10	16	12	16
11	32	11	16	13	16
12	32	12	16	14	16
13	32	13	16	15	16
14	32	14	16	16	16
15	31	15	14	16	16
16	31	16	14	17	16
17	31	17	14	18	16
18	30	18	14	19	16
19	30	19	14	20	16
20	21	20	10	21	10
21	22	21	10	22	12
22	32	22	16	24	16
23	28	23	12	24	16
24	32	24	16	26	16
25	29	25	12	26	16
26	31	26	14	27	16
27	34	27	16	29	16
28	31	28	14	28	16
29	34	29	16	31	16
30	30	30	14	31	16
31	34	31	14	32	16
32	32	32	16	34	16

Diameter (inch)	Nb sideboards	Cant size (inch)	Nb cant boards
5	0	4	1
6	1	4	3
7	2	4	3
8	2	6	3
9	2	6	4
10	2	6	5
11	2	8	5
12	2	8	5
13	2	10	6
14	2	10	6
15	2	10	6
16	2	12	7
17	2	12	8
18	4	12	8
19	4	12	9
20	4	12	10

Figure A- 1. Breakdown at the small mill.

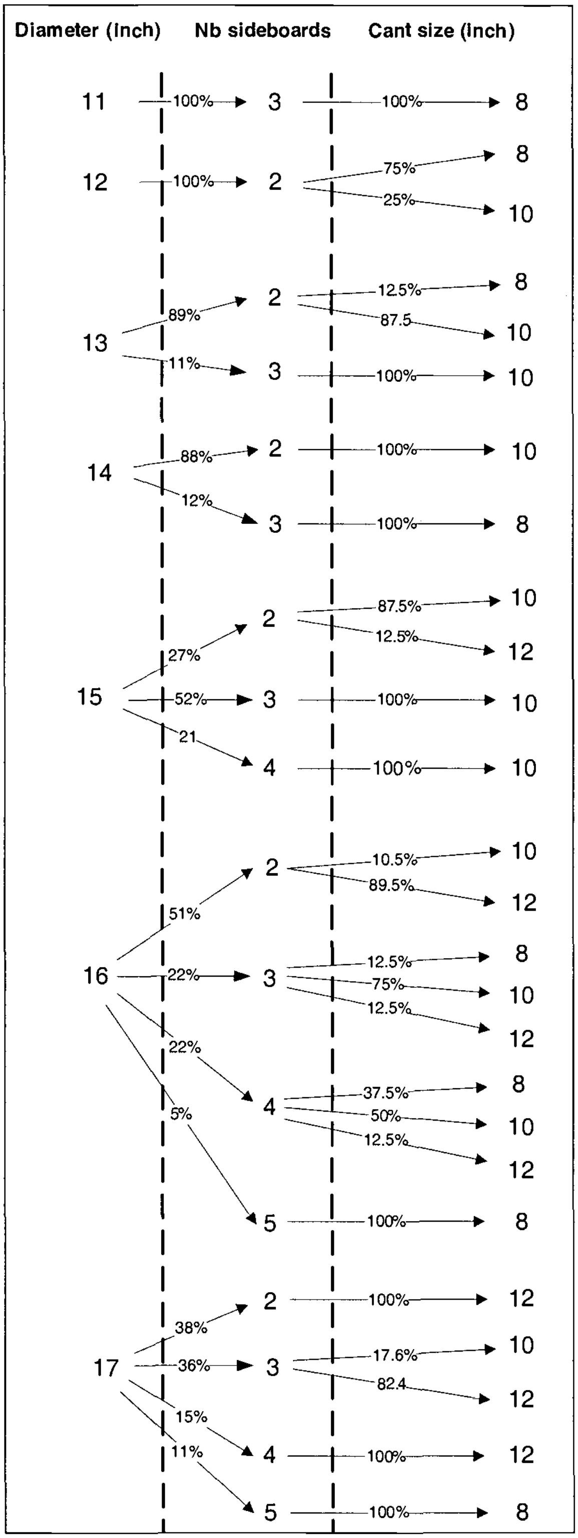

Figure A- 2. Breakdwon at the big mill.

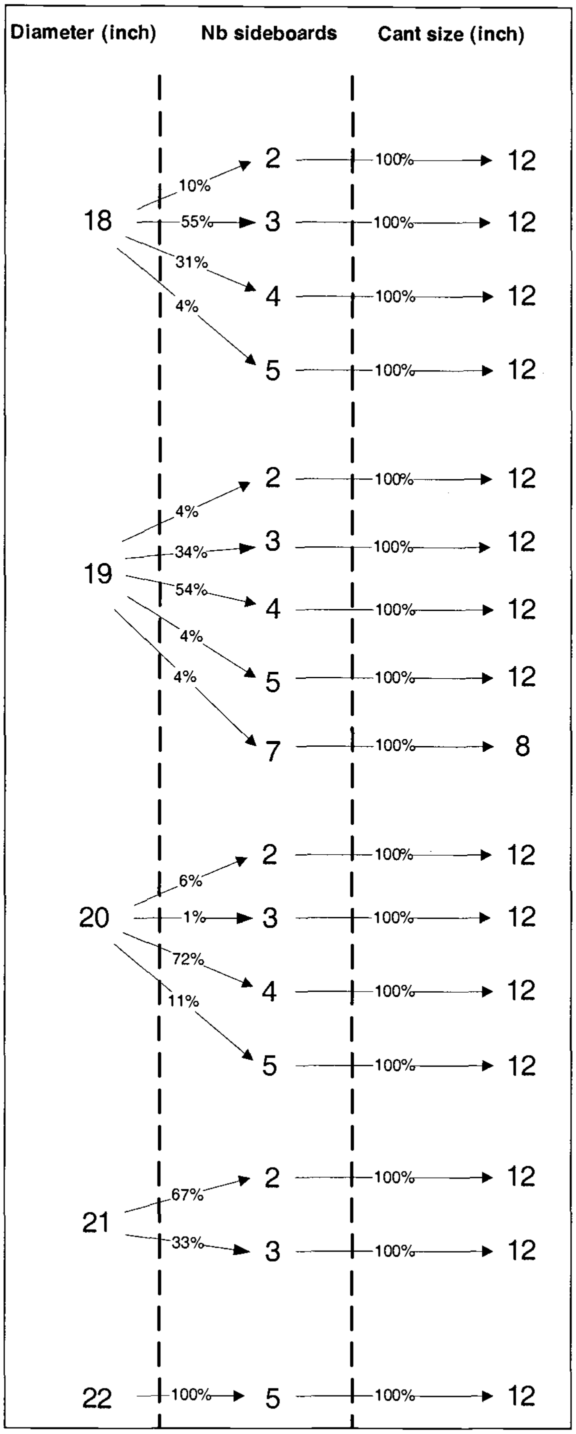

Figure A- 3. Breakdown at the big mill (continued).

Table A- 5. Uptimes and downtimes distributions.

Reason	Distribution
Uptimes	
EDLF	-0.001+480*BETA (0.461,0.175)
EDLF slabs	68+412*BETA(0.351,0.046)
Out of logs	15+480*BETA(0.946,0.29)
Logs crossed	4+476*BETA(0.192,0.0596)
EDLF saw change	TRIA(3,440,480)
Resaw	-0.001+510*BETA(0.705,0.197)
Board edger	57+453*BETA(0.543,0.184)
Gang	-0.001+GAMM(269,0.68)
Gang saw change	73+437*BETA(0.304,0.0477)
Trimmer	3+GAMM(231,0.834)
Sorter	TRIA(3,500,510)
Small chipper	6+504*BETA(0.285,0.0712)
Headrig	15+495*BETA(0.336,0.335)
Combo edger	-0.001+510*BETA(0.326,0.158)
Twin resaw	100+410*BETA(0.702,0.197)
Downtimes	
Reason	
EDLF	0.5+LOGN(9.19,24.1)
EDLF slabs	3.5+LOGN(5.69,7.01)
Out of logs	0.5+WEIB(14.7,0.97)
Logs crossed	1.5+WEIB(3.32,1.45)
EDLF saw change	NORM(10.1,1.27)
Resaw	5.5+10*BETA(0.766,0.683)
Board edger	7.5+28*BETA(0.372,0.259)
Gang	0.999+WEIB(8.81,0.827)
Gang saw change	POIS(10.7)
Trimmer	1.5+LOGN(12.1,13)
Sorter	4.5+EXPO(17.9)
Small chipper	1.5+26*BETA(0.643,0.53)
Headrig	4.5+EXPO(9.3)
Combo edger	4.5+33*BETA(0.383,1.25)
Twin resaw	5.5+10*BETA(0.766,0.683)

Table A- 6. Processing times at the EDLF.

	EDLF Band mill – 6FT – Mc Donough			
Arbor RPM	535			
Rim speed	10,084.536 SFPM			
	Speed 1	**Speed 2**	**Speed 3**	**Speed 4**
Speed	200 FPM	250 FPM	300 FPM	400 FPM
Depth of cut	16'' and over	10'' to 16''	6'' to 10''	6''
Tooth bite	0.040	0.050	0.60	Chip only
Tooth pitch	2.0426	2.0426	2.0426	solution
Gullet Feed Index	0.6437	0.6455	0.4828	No saws

Table A- 7. Processing times at the horizontal resaw.

	Horizontal resaw Band mill – 6FT – Mc Donough			
Rim speed	10,046.836 SFPM			
Saw length	40' x 11'' wide			
	Speed 1	**Speed 2**	**Speed 3**	**Speed 4**
Speed	200 FPM	250 FPM	325 FPM	500 FPM
Depth of cut	16'' and over	10'' to 16''	6'' to 10''	
Tooth bite	0.04479	0.05598	0.0727	No saw in cut
Tooth pitch	2.250	2.250	2.250	
Gullet Feed Index	0.5573	0.5660	0.4528	

Table A- 8. Processing times at the gang.

12” Schurman Gang Edger			
Horse power Top Arbor	400		
Horse power Bottom Arbor	700 (two 350s)		
Top Arbor RPM	2153		
Bottom Arbor RPM	2156		
Saw diameter	20 1/8”		
Number of teeth	34		
Gullet Area	0.5825892		
Hook	30°		
	Speed 1	**Speed 2**	**Speed 3**
Top Arbor Feed Speed	125 FPM	175 FPM	
Depth of cut	6”	2”	
Tooth bite	0.0204912	0.0286877	
Tooth pitch	2.250	2.250	
Required Gullet Area	0.3037368	0.1434385	
Bottom Arbor Feed Speed	125 FPM	175 FPM	220 FPM
Depth of cut	6”	6”	6”
Tooth bite	0.0204627	0.0286478	0.0360144
Required Gullet Area	0.3069405	0.429717	0.540216

So for cants that are 4 to 6 inches wide, the speed is 220 FPM, for cants that are 6 to 8 inches wide, the speed is 175 FPM and finally for cants that are 10 to 12 inches wide

Table A- 9. Processing times at the board edger.

USNR Board Edger	
Arbor RPM	2800 RPM
Horse power	150
Saw diameter	12”
Plate	0.120
Kerf	0 .170
Teeth	56
Feed speed	750 FPM
Tooth bite	0.0573

Table A- 10. Processing times at the twin resaw.

	Big Mill Twin Resaw Band mill 6FT Kockums Air Strain	
RPM	472	
Rim Speed	8,897 SFPM	
	Speed 1	**Speed 2**
Speed	190 FPM	210 FPM
Tooth pitch	2.1116 average 5 tooth Variable pitch variable depth	2.1116
Depth of cut	14” maximum	4” to 10”
Tooth bite	0.0450	0.0498
Gullet Feed Index	0.5979	0.4720

Table A- 11. Processing times at the combination edger.

	Mc Gehee Combination Edger Big Mill	
Arbor Speed	2099 RPM	
Rim Speed	8,897 SFPM	
	Gang side	**Board Side**
speed	144 FPM	436.5 FPM
saws	23 1/8 x 32 teeth x 0.100 plate	23 1/8 x 56 teeth x 0.100 plate
Gullet depth	5/8”	3/8”
Depth of cut	Maximum 8”	2”
Tooth bite	0.0251	0.0353

Table A- 12. Processing times (in seconds) at the headrig.

Diameter (inch)	**Processing time (seconds)**
11	38 (based on one observation
12	26.5 + 34 * BETA(0.0508, 0.0606)
13	POIS(49.8)
14	POIS(46.2)
15	POIS(58.8)
16	36.5 + GAMM(8.37, 2.35)
17	NORM(61.3, 14.5)
18	39.5 + 41 * BETA(1.47, 1.64)
19	NORM(68.9, 14.3)
20	POIS(70.4)
21	POIS(78.5)
22	72.5 + 19 * BETA(0.464, 0.371)

Appendix B. Input and Results Tables of the Model Running with Downtimes

Table B- 1. Percentages of log diameters going through the EDLF in the model.

Percentages of log diameters going through the EDLF (model)	
Diameter (inches)	**Percentage (%)**
5	0.02
6	30.97
7	10.73
8	9.51
9	8.54
10	8.15
11	8.14
12	5.8
13	5.19
14	4.24
15	3.62
16	2.74
17	2.37
average diameter	**9.20**

Table B- 2. Percentages of segment diameters going through the EDLF in the model.

Percentages of segment diameters going through the EDLF (model)	
Diameter (inches)	**Percentage (%)**
5	0.01
6	15.47
7	20.82
8	4.76
9	9.63
10	8.83
11	8.35
12	6.96
13	6.70
14	5.01
15	4.42
16	5.31
17	2.55
18	1.18
average diameter	**10.00**

Table B- 3. Percentages of log diameters going through the headrig in the model.

Percentages of log diameters going through the Headrig (model)	
Diameter (inches)	**Percentage (%)**
13	0.78
14	2.33
15	10.85
16	14.73
17	13.18
18	11.63
19	14.73
20	19.38
21	7.75
22	4.65
average diameter	**18.07**

Table B- 4. Percentages of segments diameters going through the headrig in the model.

Percentages of segment diameters going through the Headrig (model)	
Diameter (inches)	**Percentage (%)**
13	0.41
14	1.20
15	5.97
16	8.64
17	12.24
18	13.22
19	14.18
20	14.11
21	11.51
22	12.18
23	4.01
24	2.33
average diameter	**19.05**

Table B- 5. Minimun and maximum across replications, 95% confidence interval low and high bound and 95% confidence interval for the machines' queues for 500 replications.

Machines	Min across replications	Max across replications	95% CI low bound	95% CI high bound	95% CI Half-width
board-edger	0	843	205.4	224.1	9.37
combination edger	0	44	1.684	1.938	0.127
gang	0	80	40.41	42.44	1.015
HR	0	230	19.35	23.85	2.252
sorter	0	13	0.4697	0.5535	0.0419
surge area	0	596	29.53	34.53	2.498
trimmer	0	122	8.586	9.43	0.4217
Twin resaw	0	28	0.4458	0.5087	0.03148
unscrambler	0	920	128.6	138.1	4.751

Table B- 6. Minimun and maximum across replications, 95% confidence interval low and high bound and 95% confidence interval for the machines' utilizations for 500 replications.

Machines	Min across replications	Max across replications	95% CI low bound	95% CI high bound	95% CI Half-width
board-edger	0	100	82.01	83.54	0.76
combination edger	0	100	9.32	9.42	0.05
gang	0	100	71.48	72.99	0.76
HR	0	100	65.82	67.24	0.71
sorter	0	100	91.78	92.62	0.42
trimmer	0	100	60.45	61.39	0.47
Twin resaw	0	100	72.85	73.98	0.57
unscrambler	0	100	13.33	13.50	0.08

Table B- 7. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 200 boards with capacities of 400, 600, 800, 1000 and 1200.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
400 entities	-172	2160	190	13800	24100	500
200 entities				13300	24100	500
		Means are equal at 0.05 level				
600 entities	-318	2190	192	13800	24100	500
200 entities				10800	23900	500
		Means are not equal at 0.05 level				
800 entities	-570	2040	179	13800	24100	500
200 entities				14500	24500	500
		Means are not equal at 0.05 level				
1000 entities	-644	2100	184	13800	24100	500
200 entities				13300	24100	500
		Means are not equal at 0.05 level				
1200 entities	-727	2110	185	13800	24100	500
200 entities				14700	24400	500
		Means are not equal at 0.05 level				

Table B- 8. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 400 boards with capacities of 200, 600, 800, 1000 and 1200.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
200 entities	172	2160	190	13300	24100	500
400 entities				13800	24100	500
			Means are equal at 0.05 level			
600 entities	-146	2080	183	13300	24100	500
400 entities				10800	23900	500
			Means are equal at 0.05 level			
800 entities	-398	2020	177	13300	24100	500
400 entities				14500	24500	500
			Means are not equal at 0.05 level			
1000 entities	-472	2040	179	13300	24100	500
400 entities				13300	24100	500
			Means are not equal at 0.05 level			
1200 entities	-555	2140	188	13300	24100	500
400 entities				14700	24400	500
			Means are not equal at 0.05 level			

Table B- 9. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 600 boards with capacities of 200, 400, 800, 1000 and 1200.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
200 entities	318	2190	192	10800	23900	500
600 entities				13800	24100	500
		Means are not equal at 0.05 level				
400 entities	146	2080	183	10800	23900	500
600 entities				13300	24100	500
		Means are equal at 0.05 level				
800 entities	-252	2000	175	10800	23900	500
600 entities				14500	24500	500
		Means are not equal at 0.05 level				
1000 entities	-326	2100	185	10800	23900	500
600 entities				13300	24100	500
		Means are not equal at 0.05 level				
1200 entities	-409	2060	181	10800	23900	500
600 entities				14700	24400	500
		Means are not equal at 0.05 level				

Table B- 10. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 800 boards with capacities of 200, 400, 600, 1000 and 1200.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
200 entities	570	2040	179	14500	24500	500
800 entities				13800	24100	500
Means are not equal at 0.05 level						
400 entities	398	2020	177	14500	24500	500
800 entities				13300	24100	500
Means are not equal at 0.05 level						
600 entities	252	2000	175	14500	24500	500
800 entities				10800	23900	500
Means are not equal at 0.05 level						
1000 entities	-73.3	1900	167	14500	24500	500
800 entities				13300	24100	500
Means are equal at 0.05 level						
1200 entities	-156	1880	165	14500	24500	500
800 entities				14700	24400	500
Means are equal at 0.05 level						

Table B- 11. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 1000 boards with capacities of 200, 400, 600, 8000 and 1200.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
200 entities	644	2100	184	13300	24100	500
1000 entities				13800	24100	500
Means are not equal at 0.05 level						
400 entities	472	2040	179	13300	24100	500
1000 entities				13300	24100	500
Means are not equal at 0.05 level						
600 entities	326	2100	185	13300	24100	500
1000 entities				10800	23900	500
Means are not equal at 0.05 level						
800 entities	73.3	1900	167	13300	24100	500
1000 entities				14500	24500	500
Means are equal at 0.05 level						
1200 entities	-83.1	1910	168	13300	24100	500
1000 entities				14700	24400	500
Means are equal at 0.05 level						

Table B- 12. Paired-T-test means comparison: Comparison of the number of boards in the sorter for an unscrambler maximum capacity of 1200 boards with capacities of 200, 400, 600, 8000 and 1000.

Identifier	Est. mean difference	Standard deviation	95% Confidence Interval half-width	Minimum value	Maximum value	Number of observations
200 entities	727	2110	185	14700	24400	500
1200 entities				13800	24100	500
		Means are not equal at 0.05 level				
400 entities	555	2140	188	14700	24400	500
1200 entities				13300	24100	500
		Means are not equal at 0.05 level				
600 entities	409	2060	181	14700	24400	500
1200 entities				10800	23900	500
		Means are not equal at 0.05 level				
800 entities	156	1880	165	14700	24400	500
1200 entities				14500	24500	500
		Means are equal at 0.05 level				
1000 entities	83.1	1910	168	14700	24400	500
1200 entities				13300	24100	500
		Means are equal at 0.05 level				

Appendix C. Log Yard Distributions and Decks Tables

Table C- 1. Log yard current distribution.

Current distribution						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on pieces)**
5	1	20.67	20	18.32	**0.002**	**0.017**
6	1339	25.84	30	40172.77	**4.345**	**24.579**
7	464	31.76	60	27855.21	**3.013**	**8.521**
8	411	33.60	70	28785.22	**3.113**	**7.548**
9	369	33.50	100	36905.13	**3.992**	**6.774**
10	353	32.22	120	42309.14	**4.576**	**6.471**
11	352	32.26	140	49305.35	**5.333**	**6.464**
12	254	31.79	160	40581.52	**4.389**	**4.655**
13	228	31.65	190	43367.92	**4.691**	**4.190**
14	214	32.49	230	49190.93	**5.321**	**3.926**
15	207	31.46	280	57979.92	**6.271**	**3.801**
16	183	31.07	310	56648.12	**6.127**	**3.354**
17	183	30.59	360	65894.84	**7.127**	**3.360**
18	404	30.06	400	161408.00	**17.458**	**7.407**
19	265	29.81	450	119154.50	**12.888**	**4.860**
20	103	21.28	370	38048.88	**4.115**	**1.888**
21	80	22.45	420	33437.90	**3.617**	**1.461**
22	14	31.93	670	9128.37	**0.987**	**0.250**
23	4	27.56	660	2580.35	**0.279**	**0.072**
24	6	31.73	810	4510.28	**0.488**	**0.102**
25	7	29.47	830	5801.64	**0.628**	**0.128**
26	1	30.50	970	1379.03	**0.149**	**0.026**
27	2	33.50	1160	2198.86	**0.238**	**0.035**
28	1	31.00	1130	1338.75	**0.145**	**0.022**
29	1	34.00	1290	961.10	**0.104**	**0.014**
30	2	30.00	1230	2914.44	**0.315**	**0.043**
31	1	34.00	1510	1788.95	**0.193**	**0.022**
32	1	32.00	1470	870.78	**0.094**	**0.011**
Total	5448			924536.20	**100.00**	**100.00**

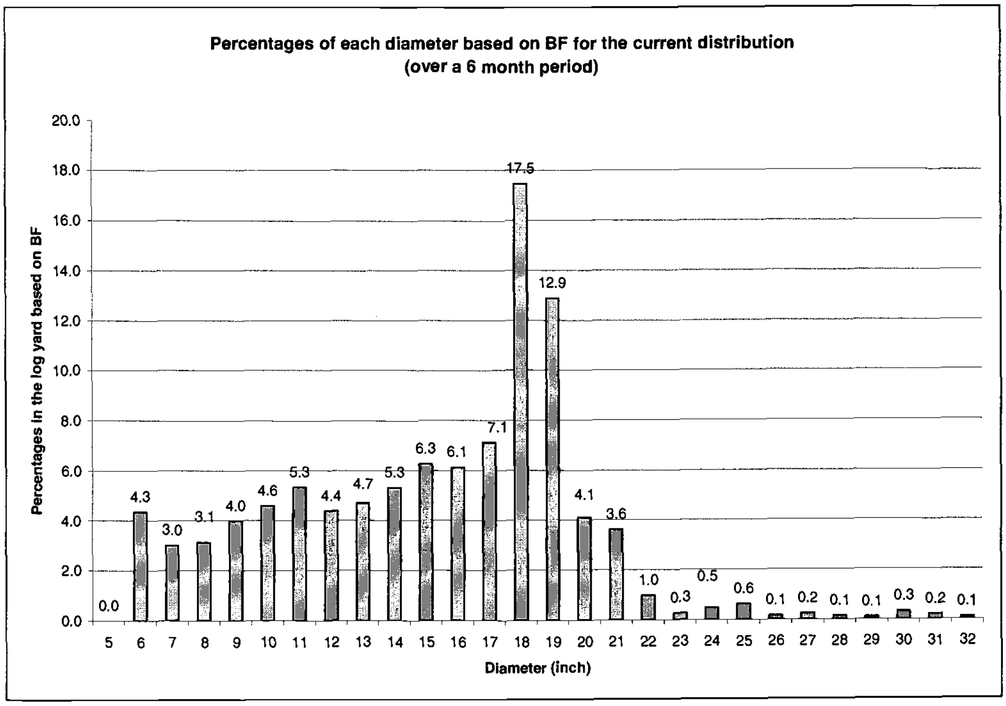

Figure C- 1. Percentages of each diameter based on BF for the current distribution over a 6 month period.

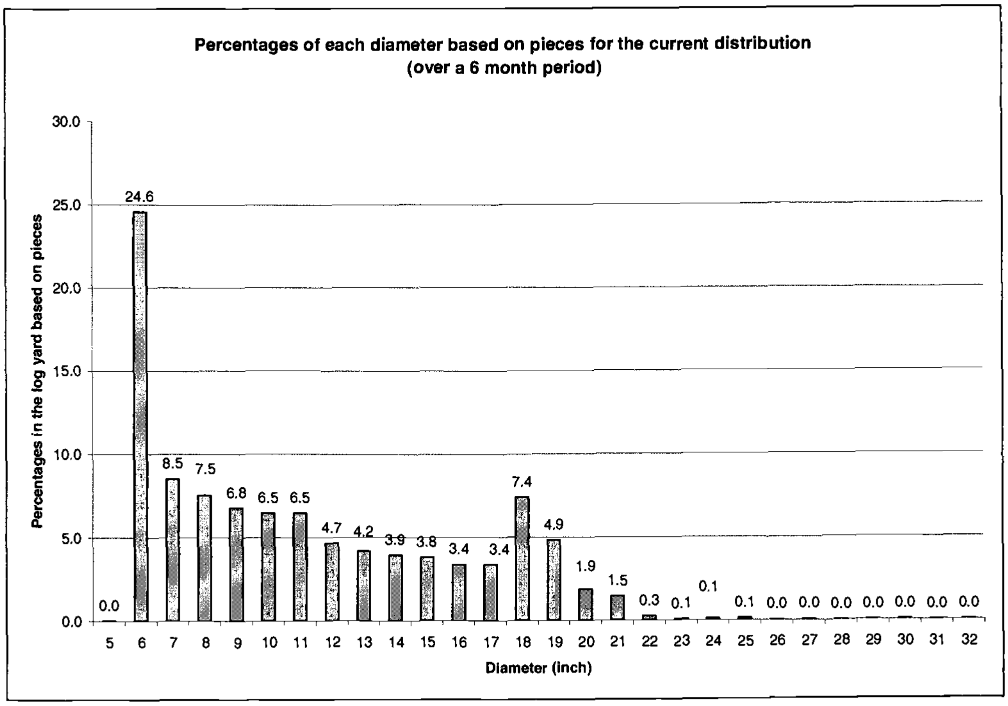

Figure C- 2. Percentages of each diameter based on pieces for the current distribution over a 6 month period.

Table C- 2. Intermediate distribution.

After introduction of small diameter logs (intermediate distribution)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on pieces)**
5	1158	20.67	20	23168.85	**2.506**	**11.453**
6	4010	25.84	30	120300.66	**13.012**	**39.645**
7	1461	31.76	60	87664.53	**9.482**	**14.445**
8	1057	33.60	70	73962.90	**8.000**	**10.446**
9	369	33.50	100	36905.13	**3.992**	**3.649**
10	353	32.22	120	42309.14	**4.576**	**3.486**
11	212	32.26	140	29722.95	**3.215**	**2.099**
12	153	31.79	160	24463.93	**2.646**	**1.512**
13	138	31.65	190	26143.67	**2.828**	**1.360**
14	129	32.49	230	29653.97	**3.207**	**1.275**
15	125	31.46	280	34952.28	**3.781**	**1.234**
16	110	31.07	310	34149.42	**3.694**	**1.089**
17	110	30.59	360	39723.66	**4.297**	**1.091**
18	243	30.06	400	97302.26	**10.524**	**2.405**
19	265	29.81	450	119154.50	**12.888**	**2.618**
20	103	21.28	370	38048.88	**4.115**	**1.017**
21	80	22.45	420	33437.90	**3.617**	**0.787**
22	14	31.93	670	9128.37	**0.987**	**0.135**
23	4	27.56	660	2580.35	**0.279**	**0.039**
24	6	31.73	810	4510.28	**0.488**	**0.055**
25	7	29.47	830	5801.64	**0.628**	**0.069**
26	1	30.50	970	1379.03	**0.149**	**0.014**
27	2	33.50	1160	2198.86	**0.238**	**0.019**
28	1	31.00	1130	1338.75	**0.145**	**0.012**
29	1	34.00	1290	961.10	**0.104**	**0.007**
30	2	30.00	1230	2914.44	**0.315**	**0.023**
31	1	34.00	1510	1788.95	**0.193**	**0.012**
32	1	32.00	1470	870.78	**0.094**	**0.006**
Total	10115			924537.18	**100.000**	**100.000**

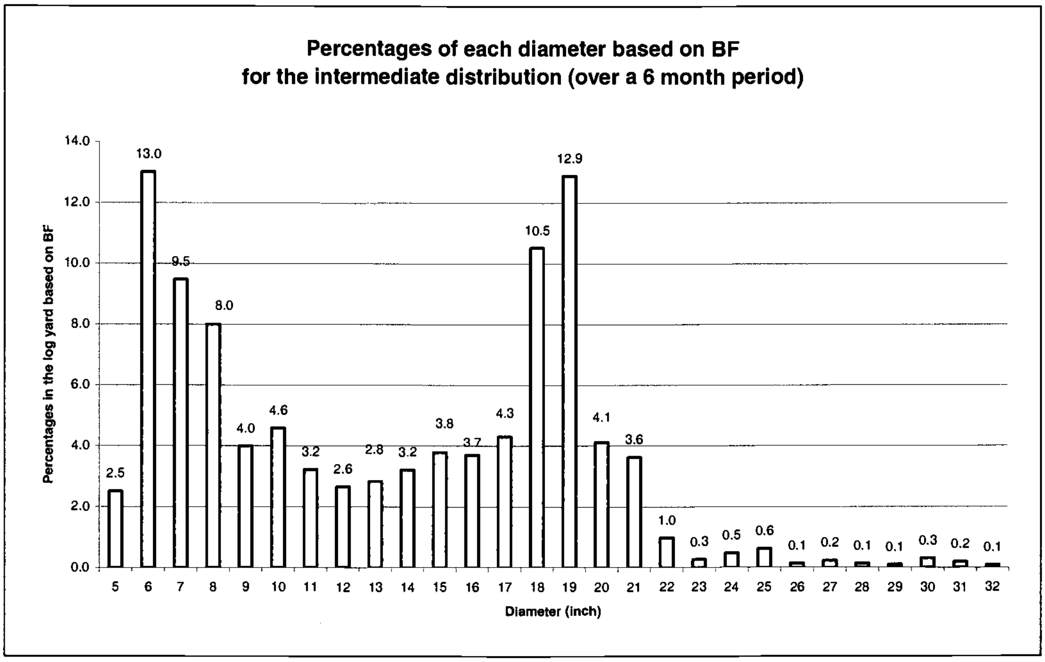

Figure C- 3. Percentages of each diameter based on BF for the intermediate distribution over a 6 month period.

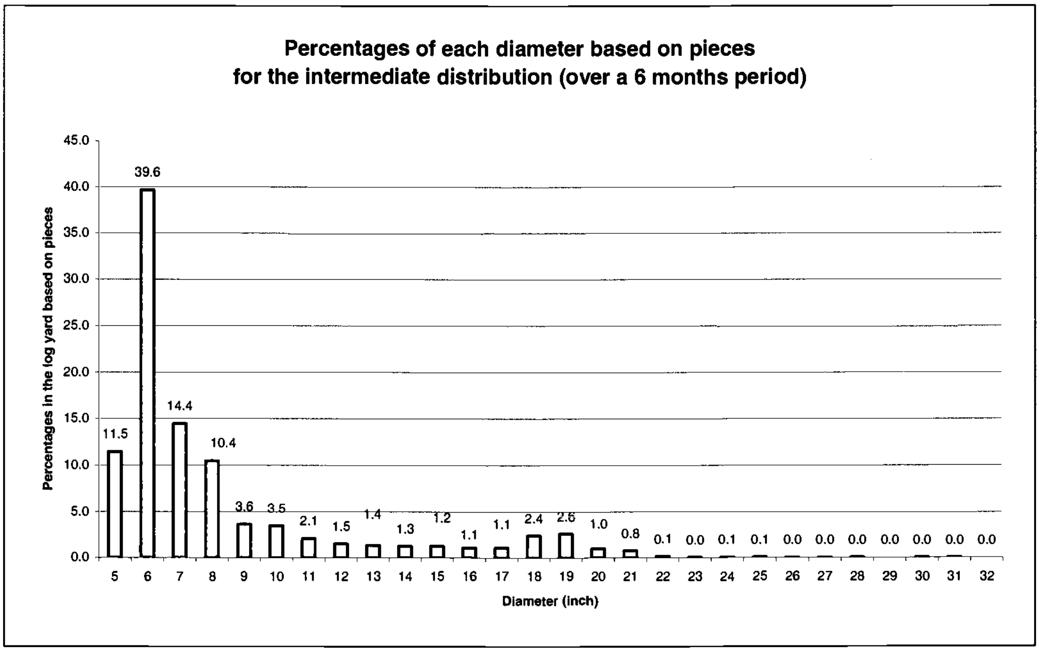

Figure C- 4. Percentages of each diameter based on pieces for the intermediate distribution over a 6 month period.

Table C- 3. Smallest distribution.

After introduction of small diameter logs (smallest distribution)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on pieces)**
5	2314	20.67	20	46282.28	**5.006**	**21.642**
6	3625	25.84	30	108743.95	**11.762**	**33.900**
7	1268	31.76	60	76107.82	**8.232**	**11.863**
8	1057	33.60	70	73962.90	**8.000**	**9.882**
9	369	33.50	100	36905.13	**3.992**	**3.451**
10	353	32.22	120	42309.14	**4.576**	**3.297**
11	212	32.26	140	29722.95	**3.215**	**1.986**
12	153	31.79	160	24463.93	**2.646**	**1.430**
13	138	31.65	190	26143.67	**2.828**	**1.287**
14	129	32.49	230	29653.97	**3.207**	**1.206**
15	125	31.46	280	34952.28	**3.781**	**1.167**
16	110	31.07	310	34149.42	**3.694**	**1.030**
17	110	30.59	360	39723.66	**4.297**	**1.032**
18	243	30.06	400	97302.26	**10.524**	**2.275**
19	265	29.81	450	119154.50	**12.888**	**2.476**
20	103	21.28	370	38048.88	**4.115**	**0.962**
21	80	22.45	420	33437.90	**3.617**	**0.745**
22	14	31.93	670	9128.37	**0.987**	**0.127**
23	4	27.56	660	2580.35	**0.279**	**0.037**
24	6	31.73	810	4510.28	**0.488**	**0.052**
25	7	29.47	830	5801.64	**0.628**	**0.065**
26	1	30.50	970	1379.03	**0.149**	**0.013**
27	2	33.50	1160	2198.86	**0.238**	**0.018**
28	1	31.00	1130	1338.75	**0.145**	**0.011**
29	1	34.00	1290	961.10	**0.104**	**0.007**
30	2	30.00	1230	2914.44	**0.315**	**0.022**
31	1	34.00	1510	1788.95	**0.193**	**0.011**
32	1	32.00	1470	870.78	**0.094**	**0.006**
Total	10693			924537.18	**100.000**	**100.000**

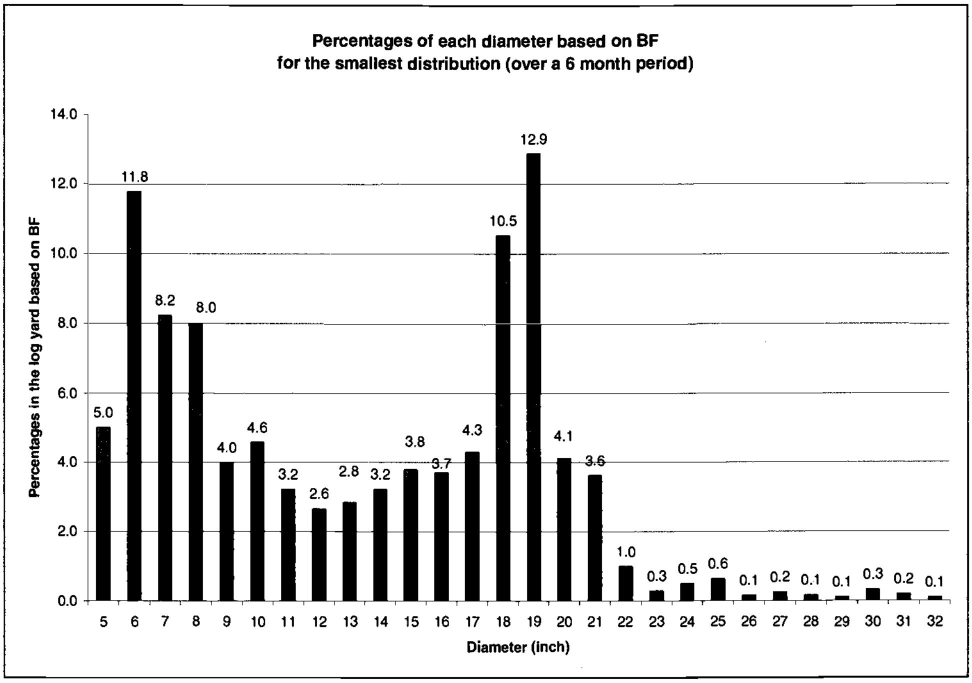

Figure C- 5. Percentages of each diameter based on BF for the smallest distribution over a 6 month period.

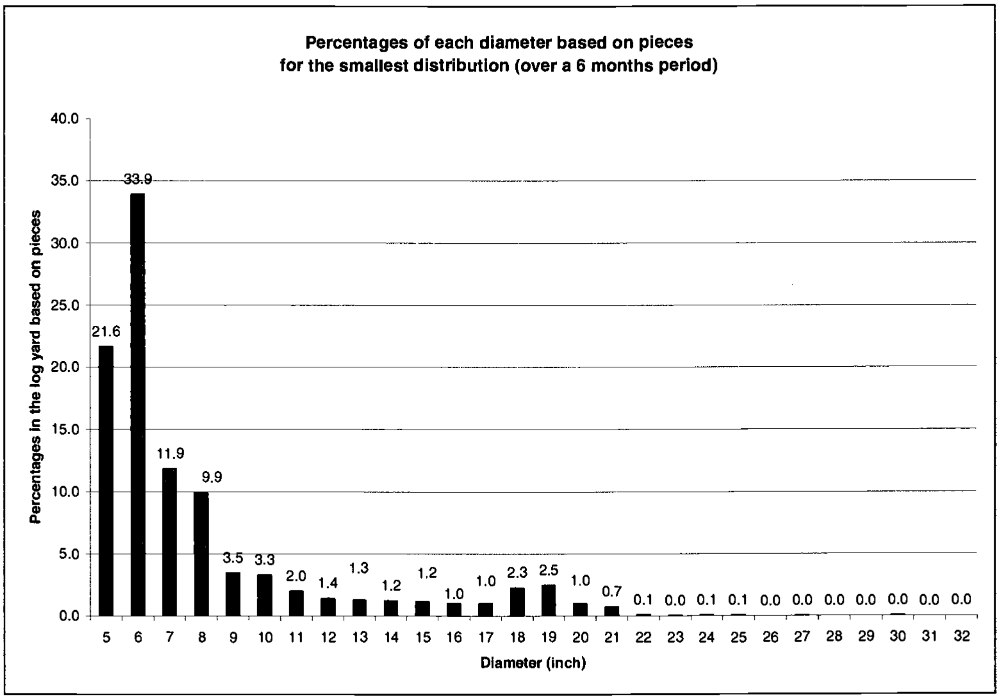

Figure C- 6. Percentages of each diameter based on pieces for the smallest distribution over a 6 month period.

Table C- 4. Deck 1 - current distribution with 2 decks.

Deck 5-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1	20.67	20.00	18.32	0.00	0.02
6	1339	25.84	30.00	40172.77	7.45	29.38
7	464	31.76	60.00	27855.21	5.17	10.19
8	411	33.60	70.00	28785.22	5.34	9.02
9	369	33.50	100.00	36905.13	6.85	8.10
10	353	32.22	120.00	42309.14	7.85	7.74
11	352	32.26	140.00	49305.35	9.15	7.73
12	254	31.79	160.00	40581.52	7.53	5.56
13	228	31.65	190.00	43367.92	8.05	5.01
14	214	32.49	230.00	49190.93	9.13	4.69
15	207	31.46	280.00	57979.92	10.76	4.54
16	183	31.07	310.00	56648.12	10.51	4.01
17	183	30.59	360.00	65894.84	12.23	4.02
total	4558			539014.38	100.00	100.00

Table C- 5. Deck 2 - current distribution with 2 decks.

Deck 18 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	14	31.93	670.00	9128.37	2.37	1.53
23	4	27.56	660.00	2580.35	0.67	0.42
24	6	31.73	810.00	4510.28	1.17	0.63
25	7	29.47	830.00	5801.64	1.50	0.78
26	1	30.50	970.00	1379.03	0.36	0.16
27	2	33.50	1160.00	2198.86	0.57	0.21
28	1	31.00	1130.00	1338.75	0.35	0.13
29	1	34.00	1290.00	961.10	0.25	0.08
30	2	30.00	1230.00	2914.44	0.76	0.27
31	1	34.00	1510.00	1788.95	0.46	0.13
32	1	32.00	1470.00	870.78	0.23	0.07
total	890			385521.82	100.00	100.00

Table C- 6. Deck 2 - current distribution with 2 decks (as used in the model).

Deck 18 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	39	31.93	670.00	33472.54	8.68	4.41
total	890			385521.82	100.00	100.00

Table C- 7. Deck 1 - current distribution with 3 decks.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1	20.67	20.00	18.32	0.01	0.04
6	1339	25.84	30.00	40172.77	30.04	51.81
7	464	31.76	60.00	27855.21	20.83	17.96
8	411	33.60	70.00	28785.22	21.52	15.91
9	369	33.50	100.00	36905.13	27.60	14.28
total	2585			133736.64	100.00	100.00

Table C- 8. Deck 2 - current distribution with 3 decks.

			Deck 10-17			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	10.44	17.86
11	352	32.26	140.00	49305.35	12.17	17.85
12	254	31.79	160.00	40581.52	10.01	12.86
13	228	31.65	190.00	43367.92	10.70	11.57
14	214	32.49	230.00	49190.93	12.14	10.84
15	207	31.46	280.00	57979.92	14.31	10.50
16	183	31.07	310.00	56648.12	13.98	9.26
17	183	30.59	360.00	65894.84	16.26	9.27
total	1973			405277.74	100.00	100.00

Table C- 9. Deck 3 - current distribution with 3 decks.

Deck 18 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	14	31.93	670.00	9128.37	2.37	1.53
23	4	27.56	660.00	2580.35	0.67	0.42
24	6	31.73	810.00	4510.28	1.17	0.63
25	7	29.47	830.00	5801.64	1.50	0.78
26	1	30.50	970.00	1379.03	0.36	0.16
27	2	33.50	1160.00	2198.86	0.57	0.21
28	1	31.00	1130.00	1338.75	0.35	0.13
29	1	34.00	1290.00	961.10	0.25	0.08
30	2	30.00	1230.00	2914.44	0.76	0.27
31	1	34.00	1510.00	1788.95	0.46	0.13
32	1	32.00	1470.00	870.78	0.23	0.07
total	890			385521.82	100.00	100.00

Table C- 10. Deck 3 - current distribution with 3 decks (as used in the model).

Deck 18 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	39	31.93	670.00	33472.54	8.68	4.41
total	890			385521.82	100.00	100.00

Table C- 11. Deck 1 - current distribution with 3 decks - modified.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1	20.67	20.00	18.32	0.01	0.02
6	1339	25.84	30.00	40172.77	17.83	40.71
7	464	31.76	60.00	27855.21	12.36	14.12
8	411	33.60	70.00	28785.22	12.77	12.50
9	369	33.50	100.00	36905.13	16.38	11.22
10	353	32.22	120.00	42309.14	18.77	10.72
11	352	32.26	140.00	49305.35	21.88	10.71
total	3289			225351.13	100.00	100.00

Table C- 12. Deck 2 - current distribution with 3 decks – modified.

Deck 12-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
12	254	31.79	160.00	40581.52	12.94	19.99
13	228	31.65	190.00	43367.92	13.83	17.99
14	214	32.49	230.00	49190.93	15.68	16.85
15	207	31.46	280.00	57979.92	18.48	16.34
16	183	31.07	310.00	56648.12	18.06	14.40
17	183	30.59	360.00	65894.84	21.01	14.43
total	1269			313663.25	100.00	100.00

Table C- 13. Deck 3 - current distribution with 3 decks - modified.

Deck 18 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	14	31.93	670.00	9128.37	2.37	1.53
23	4	27.56	660.00	2580.35	0.67	0.42
24	6	31.73	810.00	4510.28	1.17	0.63
25	7	29.47	830.00	5801.64	1.50	0.78
26	1	30.50	970.00	1379.03	0.36	0.16
27	2	33.50	1160.00	2198.86	0.57	0.21
28	1	31.00	1130.00	1338.75	0.35	0.13
29	1	34.00	1290.00	961.10	0.25	0.08
30	2	30.00	1230.00	2914.44	0.76	0.27
31	1	34.00	1510.00	1788.95	0.46	0.13
32	1	32.00	1470.00	870.78	0.23	0.07
total	890			385521.82	100.00	100.03

Table C- 14. Deck 1 - current distribution with 3 decks - modified (as used in the model).

Deck 18 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	404	30.06	400.00	161408.00	41.87	45.34
19	265	29.81	450.00	119154.50	30.91	29.75
20	103	21.28	370.00	38048.88	9.87	11.55
21	80	22.45	420.00	33437.90	8.67	8.95
22	39	31.93	670.00	33472.54	8.68	4.41
total	890			385521.82	100.00	100.00

Table C- 15. Deck 1 - current distribution with 4 decks.

			Deck 5-9			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1	20.67	20.00	18.32	0.01	0.04
6	1339	25.84	30.00	40172.77	30.04	51.81
7	464	31.76	60.00	27855.21	20.83	17.96
8	411	33.60	70.00	28785.22	21.52	15.91
9	369	33.50	100.00	36905.13	27.60	14.28
total	2585			133736.64	100.00	100.00

Table C- 16. Deck 2 - current distribution with 4 decks.

Deck 10-15						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	14.96	21.94
11	352	32.26	140.00	49305.35	17.44	21.91
12	254	31.79	160.00	40581.52	14.35	15.78
13	228	31.65	190.00	43367.92	15.34	14.19
14	214	32.49	230.00	49190.93	17.40	13.30
15	207	31.46	280.00	57979.92	20.51	12.88
total	1608			282734.78	100.00	100.00

Table C- 17. Deck 3 - current distribution with 4 decks.

Deck 16-20						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
16	183	31.07	310.00	56648.12	12.84	16.07
17	183	30.59	360.00	65894.84	14.94	16.11
18	404	30.06	400.00	161408.00	36.59	35.49
19	265	29.81	450.00	119154.50	27.01	23.29
20	103	21.28	370.00	38048.88	8.62	9.04
total	1137			441154.35	100.00	100.00

Table C- 18. Deck 4 - current distribution with 4 decks.

			Deck 21 and above			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	14	31.93	670.00	9128.37	13.64	11.45
23	4	27.56	660.00	2580.35	3.86	3.27
24	6	31.73	810.00	4510.28	6.74	4.68
25	7	29.47	830.00	5801.64	8.67	5.87
26	1	30.50	970.00	1379.03	2.06	1.18
27	2	33.50	1160.00	2198.86	3.29	1.56
28	1	31.00	1130.00	1338.75	2.00	1.00
29	1	34.00	1290.00	961.10	1.44	0.62
30	2	30.00	1230.00	2914.44	4.36	1.97
31	1	34.00	1510.00	1788.95	2.67	1.00
32	1	32.00	1470.00	870.78	1.30	0.50
total	119			66910.44	100.00	100.00

Table C- 19. Deck 4 - current distribution with 4 decks (as used in the model).

Deck 21 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	39	31.93	670.00	33472.54	50.03	33.10
total	119			66910.44	100.00	100.00

Table C- 20. Deck 1 - intermediate distribution with 2 decks.

Deck 5-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1158	20.67	20.00	23168.85	3.84	12.34
6	4010	25.84	30.00	120300.66	19.95	42.73
7	1461	31.76	60.00	87664.53	14.54	15.57
8	1057	33.60	70.00	73962.90	12.26	11.26
9	369	33.50	100.00	36905.13	6.12	3.93
10	353	32.22	120.00	42309.14	7.02	3.76
11	212	32.26	140.00	29722.95	4.93	2.26
12	153	31.79	160.00	24463.93	4.06	1.63
13	138	31.65	190.00	26143.67	4.33	1.47
14	129	32.49	230.00	29653.97	4.92	1.37
15	125	31.46	280.00	34952.28	5.80	1.33
16	110	31.07	310.00	34149.42	5.66	1.17
17	110	30.59	360.00	39723.66	6.59	1.18
total	9385			603121.10	100.00	100.00

Table C- 21. Deck 2 - intermediate distribution with 2 decks.

Deck 18 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	14	31.93	670.00	9128.37	2.84	1.87
23	4	27.56	660.00	2580.35	0.80	0.54
24	6	31.73	810.00	4510.28	1.40	0.76
25	7	29.47	830.00	5801.64	1.81	0.96
26	1	30.50	970.00	1379.03	0.43	0.19
27	2	33.50	1160.00	2198.86	0.68	0.26
28	1	31.00	1130.00	1338.75	0.42	0.16
29	1	34.00	1290.00	961.10	0.30	0.10
30	2	30.00	1230.00	2914.44	0.91	0.32
31	1	34.00	1510.00	1788.95	0.56	0.16
32	1	32.00	1470.00	870.78	0.27	0.08
total	730			321416.08	100.00	100.00

Table C- 22. Deck 2 - intermediate distribution with 2 decks (as used in the model).

Deck 18 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	39	31.93	670	33472.54	10.41	5.41
total	730			321416.08	100.00	100.00

Table C- 23. Deck 1 - intermediate distribution with 3 decks.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1158	20.67	20.00	23168.85	6.77	14.38
6	4010	25.84	30.00	120300.66	35.18	49.78
7	1461	31.76	60.00	87664.53	25.63	18.14
8	1057	33.60	70.00	73962.90	21.63	13.12
9	369	33.50	100.00	36905.13	10.79	4.58
total	8055			342002.08	100.00	100.00

Table C- 24. Deck 2 - intermediate distribution with 3 decks.

			Deck 10-17			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	16.20	26.51
11	212	32.26	140.00	29722.95	11.38	15.96
12	153	31.79	160.00	24463.93	9.37	11.50
13	138	31.65	190.00	26143.67	10.01	10.35
14	129	32.49	230.00	29653.97	11.36	9.68
15	125	31.46	280.00	34952.28	13.39	9.38
16	110	31.07	310.00	34149.42	13.08	8.27
17	110	30.59	360.00	39723.66	15.21	8.30
total	1330			261119.02	100.00	100.00

Table C- 25. Deck 3 - intermediate distribution with 3 decks.

			Deck 18 and above			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	14	31.93	670.00	9128.37	2.84	1.87
23	4	27.56	660.00	2580.35	0.80	0.54
24	6	31.73	810.00	4510.28	1.40	0.76
25	7	29.47	830.00	5801.64	1.81	0.96
26	1	30.50	970.00	1379.03	0.43	0.19
27	2	33.50	1160.00	2198.86	0.68	0.26
28	1	31.00	1130.00	1338.75	0.42	0.16
29	1	34.00	1290.00	961.10	0.30	0.10
30	2	30.00	1230.00	2914.44	0.91	0.32
31	1	34.00	1510.00	1788.95	0.56	0.16
32	1	32.00	1470.00	870.78	0.27	0.08
total	730			321416.08	100.00	100.00

Table C- 26. Deck 3 - intermediate distribution with 3 decks (as used in the model).

			Deck 18 and above MODEL			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	39	31.93	670	33472.54	10.41	5.41
total	730			321416.08	100.00	100.00

Table C- 27. Deck 1 - intermediate distribution with 4 decks.

Deck 5-7						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1158	20.67	20.00	23168.85	10.02	17.47
6	4010	25.84	30.00	120300.66	52.05	60.49
7	1461	31.76	60.00	87664.53	37.93	22.04
total	6630			231134.05	100.00	100.00

Table C- 28. Deck 2 - intermediate distribution with 4 decks.

Deck 8-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
8	1057	33.60	70.00	73962.90	19.88	38.35
9	369	33.50	100.00	36905.13	9.92	13.40
10	353	32.22	120.00	42309.14	11.37	12.80
11	212	32.26	140.00	29722.95	7.99	7.71
12	153	31.79	160.00	24463.93	6.58	5.55
13	138	31.65	190.00	26143.67	7.03	4.98
14	129	32.49	230.00	29653.97	7.97	4.68
15	125	31.46	280.00	34952.28	9.40	4.53
16	110	31.07	310.00	34149.42	9.18	4.00
17	110	30.59	360.00	39723.66	10.68	4.01
total	2755			371987.05	100.00	100.00

Table C- 29. Deck 3 - intermediate distribution with 4 decks.

Deck 18-20						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	38.23	39.82
19	265	29.81	450.00	119154.50	46.82	43.34
20	103	21.28	370.00	38048.88	14.95	16.84
total	611			254505.64	100.00	100.00

Table C- 30. Deck 4 - intermediate distribution with 4 decks.

Deck 21 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	14	31.93	670.00	9128.37	13.64	11.45
23	4	27.56	660.00	2580.35	3.86	3.27
24	6	31.73	810.00	4510.28	6.74	4.66
25	7	29.47	830.00	5801.64	8.67	5.87
26	1	30.50	970.00	1379.03	2.06	1.17
27	2	33.50	1160.00	2198.86	3.29	1.57
28	1	31.00	1130.00	1338.75	2.00	1.00
29	1	34.00	1290.00	961.10	1.44	0.63
30	2	30.00	1230.00	2914.44	4.36	1.99
31	1	34.00	1510.00	1788.95	2.67	1.00
32	1	32.00	1470.00	870.78	1.30	0.50
total	119			66910.44	100.00	100.00

Table C- 31. Deck 4 - intermediate distribution with 4 decks (as used in the model).

Deck 21 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	39	31.93	670.00	33472.54	50.03	33.10
total	119			66910.44	100.00	100.08

Table C- 32. Deck 1 - intermediate distribution with 4 decks - modified.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1158	20.67	20.00	23168.85	6.77	14.38
6	4010	25.84	30.00	120300.66	35.18	49.78
7	1461	31.76	60.00	87664.53	25.63	18.14
8	1057	33.60	70.00	73962.90	21.63	13.12
9	369	33.50	100.00	36905.13	10.79	4.58
total	8055			342002.08	100.00	100.00

Table C- 33. Deck 2 - intermediate distribution with 4 decks - modified.

Deck 10-15						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	22.60	31.79
11	212	32.26	140.00	29722.95	15.87	19.14
12	153	31.79	160.00	24463.93	13.07	13.78
13	138	31.65	190.00	26143.67	13.96	12.41
14	129	32.49	230.00	29653.97	15.84	11.63
15	125	31.46	280.00	34952.28	18.67	11.26
total	1109			187245.94	100.00	100.00

Table C- 34. Deck 3 - intermediate distribution with 4 decks - modified.

Deck 16-20						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
16	110	31.07	310.00	34149.42	10.40	13.26
17	110	30.59	360.00	39723.66	12.10	13.26
18	243	30.06	400.00	97302.26	29.63	29.25
19	265	29.81	450.00	119154.50	36.29	31.86
20	103	21.28	370.00	38048.88	11.59	12.37
total	831			328378.73	100.00	100.00

Table C- 35. Deck 4 - intermediate distribution with 4 decks - modified.

Deck 21 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	14	31.93	670.00	9128.37	13.64	11.45
23	4	27.56	660.00	2580.35	3.86	3.27
24	6	31.73	810.00	4510.28	6.74	4.66
25	7	29.47	830.00	5801.64	8.67	5.87
26	1	30.50	970.00	1379.03	2.06	1.17
27	2	33.50	1160.00	2198.86	3.29	1.57
28	1	31.00	1130.00	1338.75	2.00	1.00
29	1	34.00	1290.00	961.10	1.44	0.63
30	2	30.00	1230.00	2914.44	4.36	1.98
31	1	34.00	1510.00	1788.95	2.67	1.00
32	1	32.00	1470.00	870.78	1.30	0.50
total	119			66910.44	100.00	100.00

Table C- 36. Deck 4 - intermediate distribution with 4 decks - modified (as used in the model).

Deck 21 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	39	31.93	670.00	33472.54	50.03	33.10
total	119			66910.44	100.00	100.00

Table C- 37. Deck 1 - smallest distribution with 2 decks.

Deck 5-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
5	2314.11	20.67	20.00	46282.28	7.67	23.23
6	3624.80	25.84	30.00	108743.95	18.03	36.38
7	1268.46	31.76	60.00	76107.82	12.62	12.73
8	1056.61	33.60	70.00	73962.90	12.26	10.61
9	369.05	33.50	100.00	36905.13	6.12	3.70
10	352.58	32.22	120.00	42309.14	7.02	3.54
11	212.31	32.26	140.00	29722.95	4.93	2.13
12	152.90	31.79	160.00	24463.93	4.06	1.53
13	137.60	31.65	190.00	26143.67	4.33	1.38
14	128.93	32.49	230.00	29653.97	4.92	1.29
15	124.83	31.46	280.00	34952.28	5.80	1.25
16	110.16	31.07	310.00	34149.42	5.66	1.11
17	110.34	30.59	360.00	39723.66	6.59	1.11
total	9962.68			603121.10	100.00	100.00

Table C- 38. Deck 2 - smallest distribution with 2 decks.

Deck 18-22						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243.26	30.06	400.00	97302.26	30.27	33.32
19	264.79	29.81	450.00	119154.50	37.07	36.27
20	102.83	21.28	370.00	38048.88	11.84	14.09
21	79.61	22.45	420.00	33437.90	10.40	10.91
22	13.62	31.93	670.00	9128.37	2.84	1.87
23	3.91	27.56	660.00	2580.35	0.80	0.54
24	5.57	31.73	810.00	4510.28	1.40	0.76
25	6.99	29.47	830.00	5801.64	1.81	0.96
26	1.42	30.50	970.00	1379.03	0.43	0.19
27	1.90	33.50	1160.00	2198.86	0.68	0.26
28	1.18	31.00	1130.00	1338.75	0.42	0.16
29	0.75	34.00	1290.00	961.10	0.30	0.10
30	2.37	30.00	1230.00	2914.44	0.91	0.32
31	1.18	34.00	1510.00	1788.95	0.56	0.16
32	0.59	32.00	1470.00	870.78	0.27	0.08
total	729.98			321416.08	100.00	100.00

Table C- 39. Deck 2 - smallest distribution with 2 decks (as used in the model).

Deck 18-22 (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243.26	30.06	400.00	97302.26	30.273	33.324
19	264.79	29.81	450.00	119154.50	37.072	36.273
20	102.83	21.28	370.00	38048.88	11.838	14.087
21	79.61	22.45	420.00	33437.90	10.403	10.906
22	39.49	31.93		33472.54	10.414	5.409
total	729.98			321416.08	100.00	100.00

Table C- 40. Deck 1 - smallest distribution with 3 decks.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	2314	20.67	20.00	46282.28	13.53	26.81
6	3625	25.84	30.00	108743.95	31.80	41.99
7	1268	31.76	60.00	76107.82	22.25	14.69
8	1057	33.60	70.00	73962.90	21.63	12.24
9	369	33.50	100.00	36905.13	10.79	4.27
total	8633			342002.08	100.00	100.00

Table C- 41. Deck 2 - smallest distribution with 3 decks.

			Deck 10-17			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	16.20	26.53
11	212	32.26	140.00	29722.95	11.38	15.97
12	153	31.79	160.00	24463.93	9.37	11.50
13	138	31.65	190.00	26143.67	10.01	10.35
14	129	32.49	230.00	29653.97	11.36	9.69
15	125	31.46	280.00	34952.28	13.39	9.39
16	110	31.07	310.00	34149.42	13.08	8.28
17	110	30.59	360.00	39723.66	15.21	8.30
total	1330			261119.02	100.00	100.00

Table C- 42. Deck 3 - smallest distribution with 3 decks.

Deck 18 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	14	31.93	670.00	9128.37	2.84	1.87
23	4	27.56	660.00	2580.35	0.80	0.54
24	6	31.73	810.00	4510.28	1.40	0.76
25	7	29.47	830.00	5801.64	1.81	0.96
26	1	30.50	970.00	1379.03	0.43	0.19
27	2	33.50	1160.00	2198.86	0.68	0.26
28	1	31.00	1130.00	1338.75	0.42	0.16
29	1	34.00	1290.00	961.10	0.30	0.10
30	2	30.00	1230.00	2914.44	0.91	0.32
31	1	34.00	1510.00	1788.95	0.56	0.16
32	1	32.00	1470.00	870.78	0.27	0.08
total	730			321416.08	100.00	100.00

Table C- 43. Deck 3 - smallest distribution with 3 decks (as used in the model).

Deck 18 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400.00	97302.26	30.27	33.32
19	265	29.81	450.00	119154.50	37.07	36.27
20	103	21.28	370.00	38048.88	11.84	14.09
21	80	22.45	420.00	33437.90	10.40	10.91
22	39	31.93	670.00	33472.54	10.41	5.41
total	730			321416.08	100.00	100.00

Table C- 44. Deck 1 - smallest distribution with 4 decks.

			Deck 5-7			
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	2314	20.67	20	46282.28	20.02	32.11
6	3625	25.84	30	108743.95	47.05	50.29
7	1268	31.76	60	76107.82	32.93	17.60
total	7207			231134.05	100.00	100.00

Table C- 45. Deck 2 - smallest distribution with 4 decks.

Deck 8-17						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
8	1057	33.60	70	73962.90	19.88	38.35
9	369	33.50	100	36905.13	9.92	13.39
10	353	32.22	120	42309.14	11.37	12.80
11	212	32.26	140	29722.95	7.99	7.71
12	153	31.79	160	24463.93	6.58	5.55
13	138	31.65	190	26143.67	7.03	4.99
14	129	32.49	230	29653.97	7.97	4.68
15	125	31.46	280	34952.28	9.40	4.53
16	110	31.07	310	34149.42	9.18	4.00
17	110	30.59	360	39723.66	10.68	4.00
total	2755			371987.05	100.00	100.00

Table C- 46. Deck 3 - smallest distribution with 4 decks.

Deck 18-20						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
18	243	30.06	400	97302.26	38.23	39.82
19	265	29.81	450	119154.50	46.82	43.35
20	103	21.28	370	38048.88	14.95	16.83
total	611			254505.64	100.00	100.00

Table C- 47. Deck 4 - smallest distribution with 4 decks.

Deck 21 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420	33437.90	49.97	66.85
22	14	31.93	670	9128.37	13.64	11.44
23	4	27.56	660	2580.35	3.86	3.28
24	6	31.73	810	4510.28	6.74	4.68
25	7	29.47	830	5801.64	8.67	5.87
26	1	30.50	970	1379.03	2.06	1.19
27	2	33.50	1160	2198.86	3.29	1.59
28	1	31.00	1130	1338.75	2.00	0.99
29	1	34.00	1290	961.10	1.44	0.63
30	2	30.00	1230	2914.44	4.36	1.99
31	1	34.00	1510	1788.95	2.67	0.99
32	1	32.00	1470	870.78	1.30	0.50
total	119			66910.44	100.00	100.00

Table C- 48. Deck 4 - smallest distribution with 4 decks (as used in the model).

Deck 21 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420	33437.90	49.97	66.85
22	39	31.93	670	33472.54	50.03	33.15
total	119			66910.44	100.00	100.00

Table C- 49. Deck 1 - smallest distribution with 4 decks - modified.

Deck 5-9						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**Total BF**	**% (based on BF)**	**% (based on piece count)**
5	1158	20.67	20.00	23168.85	6.77	14.38
6	4010	25.84	30.00	120300.66	35.18	49.78
7	1461	31.76	60.00	87664.53	25.63	18.14
8	1057	33.60	70.00	73962.90	21.63	13.12
9	369	33.50	100.00	36905.13	10.79	4.58
total	8055			342002.08	100.00	100.00

Table C- 50. Deck 2 - smallest distribution with 4 decks - modified.

Deck 10-15						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
10	353	32.22	120.00	42309.14	22.60	31.79
11	212	32.26	140.00	29722.95	15.87	19.14
12	153	31.79	160.00	24463.93	13.07	13.78
13	138	31.65	190.00	26143.67	13.96	12.41
14	129	32.49	230.00	29653.97	15.84	11.63
15	125	31.46	280.00	34952.28	18.67	11.26
total	1109			187245.94	100.00	100.00

Table C- 51. Deck 3 - smallest distribution with 4 decks - modified.

Deck 16-20						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
16	110	31.07	310.00	34149.42	10.40	13.26
17	110	30.59	360.00	39723.66	12.10	13.26
18	243	30.06	400.00	97302.26	29.63	29.25
19	265	29.81	450.00	119154.50	36.29	31.86
20	103	21.28	370.00	38048.88	11.59	12.37
total	831			328378.73	100.00	100.00

Table C- 52. Deck 4 - smallest distribution with 4 decks - modified.

Deck 21 and above						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	14	31.93	670.00	9128.37	13.64	11.45
23	4	27.56	660.00	2580.35	3.86	3.27
24	6	31.73	810.00	4510.28	6.74	4.66
25	7	29.47	830.00	5801.64	8.67	5.87
26	1	30.50	970.00	1379.03	2.06	1.17
27	2	33.50	1160.00	2198.86	3.29	1.57
28	1	31.00	1130.00	1338.75	2.00	1.00
29	1	34.00	1290.00	961.10	1.44	0.63
30	2	30.00	1230.00	2914.44	4.36	1.98
31	1	34.00	1510.00	1788.95	2.67	1.00
32	1	32.00	1470.00	870.78	1.30	0.50
total	119			66910.44	100.00	100.00

Table C- 53. Deck 4 - smallest distribution with 4 decks - modified (as used in the model).

Deck 21 and above (MODEL)						
Diameter	**Average number of logs over 6 months**	**Average length**	**BF/log**	**total BF**	**% (based on BF)**	**% (based on piece count)**
21	80	22.45	420.00	33437.90	49.97	66.90
22	39	31.93	670.00	33472.54	50.03	33.10
total	119			66910.44	100.00	100.00

Table C- 54. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the current distribution with different decks sorts.

Boards in the sorter per day with the current distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	11490	22300	18720 - 19020	151.3
3 decks day 1	9465	20360	16810 - 17080	133.1
3 decks day 2	9485	23550	19930 - 20240	151.6
3 decks modified day 1	11960	20740	17530 - 17800	136.1
3 decks modified day 2	12960	23700	20000 - 20330	165.4
4 decks day 1	9553	20110	16890 - 17150	126.6
4 decks day 2	11840	23200	19540 - 19850	156.2

Table C- 55. Minimun and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the current distribution with different decks sorts and the unscrambler capacity set to 1200.

Boards in the sorter per day with the current distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	13620	22210	19410 - 19670	131.5
3 decks day 1	11500	20490	17520 - 17770	124.6
3 decks day 2	8355	24080	20360 - 20670	153.3
3 decks modified day 1	11560	21610	18270 - 18520	126.1
3 decks modified day 2	9166	24240	20590 - 20920	164.80
4 decks day 1	9459	20450	17700 - 17930	117.1
4 decks day 2	14080	23320	20190 - 20460	134.2

Table C- 56. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the smallest distribution with different decks sorts.

Boards in the sorter per day with the smallest distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	9321	19820	16280 – 16520	119.1
3 decks day 1	10000	17980	15250 – 15480	116
3 decks day 2	11030	23410	19800 – 20120	162
4 decks day 1	9776	17440	14690 – 14900	106.5
4 decks day 2	10260	22300	19160 – 19450	144.6
4 decks modified day 1	11280	18060	15320 – 15540	107.9
4 decks modified day 2	12180	23550	19500 – 19810	150.9

Table C- 57. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the smallest distribution with different decks sorts and the unscrambler capacity set to 1200.

Boards in the sorter per day with the smallest distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	12110	20060	17030 – 17250	111.7
3 decks day 1	9723	18420	15970 – 16180	104
3 decks day 2	11580	23710	20350 – 20650	149.2
4 decks day 1	10460	17750	15360 – 15540	90.95
4 decks day 2	13450	22430	19640 – 19910	131.5
4 decks modified day 1	11900	18510	16030 – 16220	96.27
4 decks modified day 2	11710	23390	20010 – 20310	148.4

Table C- 58. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the intermediate distribution with different decks sorts.

Boards in the sorter per day with the intermediate distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	12050	19940	16850 – 17100	124.3
3 decks day 1	8270	19020	15920 – 16150	117.8
3 decks day 2	11030	23410	19760 – 20090	161.6
4 decks day 1	7218	17920	15260 – 15520	127.6
4 decks day 2	10260	22410	19210 – 19500	143.7
4 decks modified day 1	11520	19090	15980 – 16220	115.7
4 decks modified day 2	12180	23550	19520 - 19830	151.2

Table C- 59. Minimum and maximum across replications, 95% confidence interval and 95% confidence interval half-width for the number of boards in the sorter per day using the intermediate distribution with different decks sorts and the unscrambler capacity set to 1200.

Boards in the sorter per day with the intermediate distribution and different decks sorts				
decks	min across replications	max across replications	95% Conf. Int.	95% CI Half-width
2 decks	12430	20480	17620 – 17840	113.5
3 decks day 1	10300	19320	16610 – 16830	106.9
3 decks day 2	11580	23710	20330 – 20630	150.3
4 decks day 1	7446	18340	15930 – 16150	111
4 decks day 2	13450	22430	19590 – 19850	131.4
4 decks modified day 1	12390	19220	16760 – 16960	102.5
4 decks modified day 2	11710	23390	20000 - 20300	146.7

Appendix D. Distributions Used to Compare the Influence of the Regular Day Mix and the Optquest Mix on the Overall Process

Table D- 1. Percentages of log diameters going through the EDLF for the regular day mix (model).

Percentages of log diameters going through the EDLF (model)	
Diameter (inches)	**Percentage (%)**
5	0.02
6	30.97
7	10.73
8	9.51
9	8.54
10	8.15
11	8.14
12	5.8
13	5.19
14	4.24
15	3.62
16	2.74
17	2.37
average diameter	**9.20**

Table D- 2. Percentages of log diameters going through the headrig for the regular day mix (model).

Percentages of log diameters going through the headrig (model)	
Diameter (inches)	**Percentage (%)**
13	0.78
14	2.33
15	10.85
16	14.73
17	13.18
18	11.63
19	14.73
20	19.38
21	7.75
22	4.65
average diameter	**18.07**

Table D- 3. Percentages of log diameters going through the EDLF for the Optquest mix (model).

Percentages of log diameters going through the EDLF (model)	
Diameter (inches)	**Percentage (%)**
5	0.92
6	2.36
7	1.82
8	1.44
9	2.75
10	2.93
11	0.00
12	0.16
13	7.79
14	25.67
15	18.16
16	16.32
17	19.68
average diameter	**14.28**

Table D- 4. Percentages of log diameters going through the headrig for the Optquest mix (model).

Percentages of log diameters going through the headrig (model)	
Diameter (inches)	**Percentage (%)**
11	0.00
12	0.00
13	0.00
14	0.00
15	0.00
16	0.00
17	0.00
18	3.92
19	21.04
20	20.01
21	26.13
22	28.90
average diameter	**20.55**