Activity-based product costing in a hardwood sawmill through the use of discrete-event simulation

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(ABSTRACT)

The purpose of this research was to quantify the impact of the log variables: length, grade, and scaling diameter, on the cost of producing hardwood lumber, using the activity-based costing technique. The usual technique of calculating hardwood lumber product costs is based upon traditional cost accounting, where manufacturing costs are allocated to the products based upon the volume of each product that is produced. With the traditional cost accounting procedure, the variation in the resources used to process the logs is not taken into consideration. As a result, when the cost to manufacture the products is subtracted from the market value of the products, the resulting profit levels of the products may not be truly representative of the actual resources consumed in manufacturing the product.

Using discrete-event simulation, two hardwood sawmills were modeled and a series of experiments were conducted which would not have been feasible to conduct on the mill floors. Results from the simulation experiments illustrated that the activity-based and traditional cost accounting techniques allocated different amounts of manufacturing costs to the products. The largest difference between the two cost accounting techniques was found to be the amount of raw material costs allocated to the products. For one of the

sawmills modeled, log grade was identified as having the greatest influence on determining product costs and total manufacturing costs. Results from the model of the second sawmill however demonstrated that log diameter had a greater impact on determining product costs and total manufacturing costs. The commonality of the results from the two simulation models was that the differences in the volume of lumber produced, between the logs that were studied, was a critical component in determining which log parameter had the most effect on changing the dynamics of the sawmill system.

To enable hardwood managers a more precise method of allocating raw material costs to the lumber products, a methodology was developed that uses the principles of activity-based costing to allocate raw material costs. The proposed methodology, termed the lumber yield method, uses lumber yield values from logs with similar characteristics to allocate raw material costs to the lumber products. Analysis of the output from the simulation models illustrated that with the lumber yield method, the amount of raw material costs allocated to the products was not significantly different than the amount allocated by the activity-based costing method. The calculated raw material costs of the products were however, found to be significantly different between the lumber yield method and the traditional volume costing method.

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SECTION I. INTRODUCTION

1. Problem and its setting

1.1. Background

A characteristic of the hardwood sawmill industry is that the log to lumber conversion process will yield products that have different quality, volume, and market value. The log to lumber conversion process involves three primary operations: (1) primary log breakdown, (2) lumber edging, and (3) lumber trimming. A majority of sawmill firms use machine centers that have specific singular functions to perform these operations. However, because of the natural variability of logs, products that have the same quality, volume, and market value will not necessarily be manufactured in an identical manner. The pertinent differences or variables between logs that are measured by hardwood sawmill firms are species, diameter, grade, and length. These variables cause differences in the operation times of the machine centers and can also directly affect the number and types of machine centers that are used to process a log into lumber (Howard 1993). Also, given that the outer-diameter portion of a hardwood log will produce lumber of higher quality and value than the inner portion, significant variability within individual logs affects processing decisions, too (Malcolm 2000). Keeping track of how individual entities in a sawmill system are processed is not done in practice because it is a costly activity and there is a prevailing perception within the industry that volume is the driving factor of product costs. Knowledge is lacking as to: (1) How the cost of processing hardwood logs into standard grade lumber varies with log characteristics, and (2) How the cost to produce the same grade and volume of lumber varies with log characteristics.

Manufacturing costs in the sawmill traditionally have been calculated by dividing the fixed and variable operating costs incurred for the same period of time, by the volume of lumber produced in a given time period (White 1980). However, because different log characteristics directly affect the products manufactured and, that each log produces a different quantity and quality of products, it is wrong to assume that all of the lumber produced consume manufacturing costs only as a function of volume (Johansson and Rosling 2002).

A procedure for calculating the variable cost of processing individual logs was developed by Howard (1993). The procedure first involves measuring the processing function of each machine center as either a board feet per hour measurement variable or as processing time per board variable. The variable cost of each machine center per hour is then calculated by adding together hourly labor costs, hourly repair and maintenance costs, and hourly utility costs. The variable cost per log is then calculated based upon processing time and number of sawmill machine centers that were used to process a log. Application of the procedure was applied to a case study in a softwood sawmill where the procedure was used to identify trends in processing costs as a function of scaling diameter (Howard 1993). The relationship between processing cost and other log variables such as grade, species, and length was not reported. Howard did not examine how different log characteristics can affect the cost of the products produced. Further research is warranted to develop a cost model that can be used to examine differences in product costs as a function of log variables.

Overall, there is an opportunity to further the understanding of the costs associated with manufacturing hardwood lumber. A greater understanding of these costs would allow hardwood lumber manufacturers to more accurately estimate their margin of profit when purchasing both standing timber and logs. The results of this project include new processing cost models and procedures for collecting information that are needed to accurately predict the cost of manufacturing hardwood lumber.

1.2. Problem statement

Even without consideration for the amount of assets spent on procuring logs, the cost of sawing logs into lumber makes up a large amount of a hardwood sawmill's operating budget. The production process of a hardwood sawmill yields multiple grades of lumber from logs that have a variety of different input characteristics. Because multiple products are simultaneously manufactured, it is difficult to assign a cost to the lumber produced that reflects how logs are processed differently due to log grade, scaling diameter, or log length.

1.3. The hypothesis

It is the hypothesis of this research that the log to lumber manufacturing costs and the cost of the products produced can be more accurately calculated by taking into account the effect that different log characteristics have on processing time and machine utilization. By ignoring or failing to appropriately analyze manufacturing costs, determinants of cost inefficiencies can remain unidentified. A 1999 survey of the hardwood sawmill industry in Virginia (Bowe et al. 1999) identified that managers would like to have a greater understanding of the components related to plant management and finance, and also product pricing.

1.4. The objectives

The purpose of this research was to quantify the impact of the log variables, length, grade, and scaling diameter, on hardwood lumber product costs using activity-based costing techniques. The objectives of this research included:

1. Compare the differences in product costs calculated from the traditional cost accounting technique and activity-based costing technique.

2. Demonstrate how the differences in the calculated product cost values, between the traditional and activity-based cost accounting techniques are related to the manner in which the costing techniques allocate manufacturing costs to the products.

3. Development and testing a new methodology for determining the cost of manufacturing hardwood lumber.

1.5. Approach

To meet the objectives of this research project, the discrete-event simulation technique was used to perform an activity-based cost analysis. Two discrete-event simulation models were developed based upon manufacturing information collected from two hardwood sawmills. The ARENA simulation software package from Rockwell Software Inc. was used to build the models. The reasons for using discrete-event simulation included:

1. It would have been disruptive to change the operating procedure of a hardwood sawmill to meet the experimental designs of this research project.

2. Measuring and collecting the experimental results in an actual sawmill system would have involved the tracking of each individual board that is sawn from every log during a production run, which is impractical in an actual production system.

1.6. Significance of the study

Hardwood logs of different species, grade, diameter, and length are not processed identically. The cost of the lumber produced in a sawmill varies directly with the labor and machine resources utilized during the production process. It has not been studied how the cost to produce the same grade and volume of lumber varies with log characteristics, by using a methodology that accounts the interactions between the different sawmill machine centers.

2. Literature review

2.1. The sawn lumber industry

The sawn lumber industry can be divided into firms that primarily produce softwood lumber and firms that primarily produce hardwood lumber. The majority of the softwood lumber that is sawn in the United States is used as building construction material while hardwood lumber is primarily used for flooring, case goods, and furniture (Haygreen and Bowyer 1989). The biological difference between softwood and hardwood species is that hardwoods produce seeds within ovaries and softwoods produce seeds that lack a covering layer (Hoadley 1992). The end-use of both hardwood and softwood species is largely based on the specific gravity (density) of the species.

Specific gravity is the ratio of the density of a material to the density of water and is useful when comparing the softness or hardness of different wood species. Softwood species in general have a low specific gravity, which facilitates ease of use as a structural construction material. Hardwood species, on average, have a high specific gravity, which increases the strength properties of the wood, making them more suitable for applications such as baseball bats, furniture, and flooring.

In 2002, there was an estimated 47.3 billion board feet of lumber produced in the United States. Of this amount, hardwood lumber production accounted for 11.0 billion board feet and the production of softwood lumber was 36.3 billion board feet (U.S. Census Bureau 2003). The majority of the hardwood lumber was produced in the eastern United States and the production of softwood lumber was divided almost evenly between the eastern (including southern states) and western United States (U.S. Census Bureau 2003). Statistics from 1997 show that at the time there were 1,063 hardwood lumber sawmills and 735 softwood lumber sawmills operating in the United States (U.S. Census Bureau 1997). Sawmills, which employed less than one hundred people at the time of the census, were not included in this count.

In general, the softwood sawmill industry produces greater volumes of lumber and utilizes more advanced processing technology than the hardwood lumber industry (Bowe et al. 2001, Bowe et al. 2002). There is a lack of knowledge pertaining to plant management financing and product pricing by managers of hardwood sawmills as illustrated by Bowe et al. (1999). This may be a contributing factor to the hesitancy of hardwood sawmill firms to invest capital in new processing technology.

2.2. Overview of the hardwood lumber manufacturing process

Hardwood lumber is manufactured by a collection of machine centers that have specific functions and must work in conjunction with one another to produce lumber. Collectively, these machines make up a manufacturing system known as a sawmill. As with all manufacturing systems, a hardwood sawmill has material input, flow of material through the system, and material output. Hardwoods logs are the primary input for hardwood sawmills. Flow of material within a hardwood sawmill most often involves a system of conveyers to transport materials from one machine to another. The three main processes that are involved in the manufacture of hardwood lumber are primary breakdown, edging, and trimming (Figure I-1). Primary log breakdown is done at the "headrig", edging is done at the "edger", and trimming is done at the "trimmer".

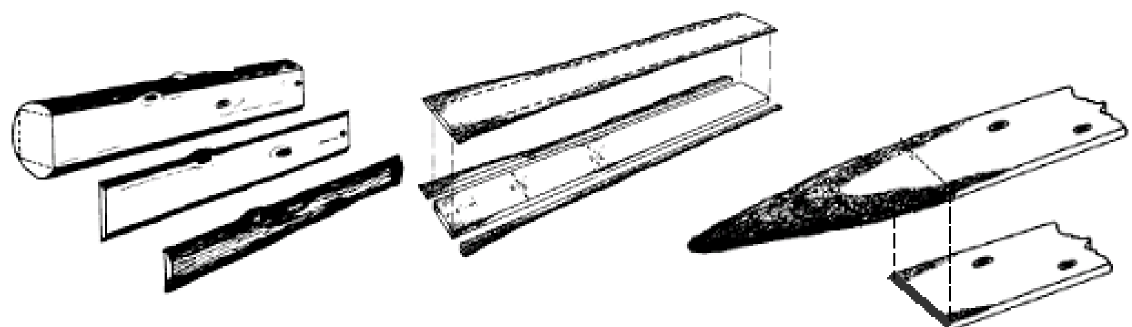

Figure I-1. The three basic processes involved in the manufacture of hardwood lumber. Adapted from Malcolm (2000).

The number of machine centers used in a sawmill and the production rates of the machine centers are dependant on variables such as region, mill layout, and level of technology (Bowe et al. 2001). Usually the material that exits a hardwood sawmill is random width unsurfaced lumber that is then sorted by species, grade, and length. In the United States, lumber volume is measured in board feet, where one board foot is dimensionally equivalent to a one-inch thick by one-foot long by one-foot wide object. In terms of volume, one board foot is equal to 144 cubic inches.

Lumber grade is a descriptive variable that measures the quality of the lumber. In most cases hardwood lumber is "*graded on the basis of the size and number of* *cuttings (pieces) which can be obtained from a board when it is cut up and used in the manufacture of a hardwood product such as furniture, flooring, or interior house trim*" (NHLA 1971). Figure I-2 illustrates how the minimum percentage of clear area and required number of cuttings varies between four lumber grades.

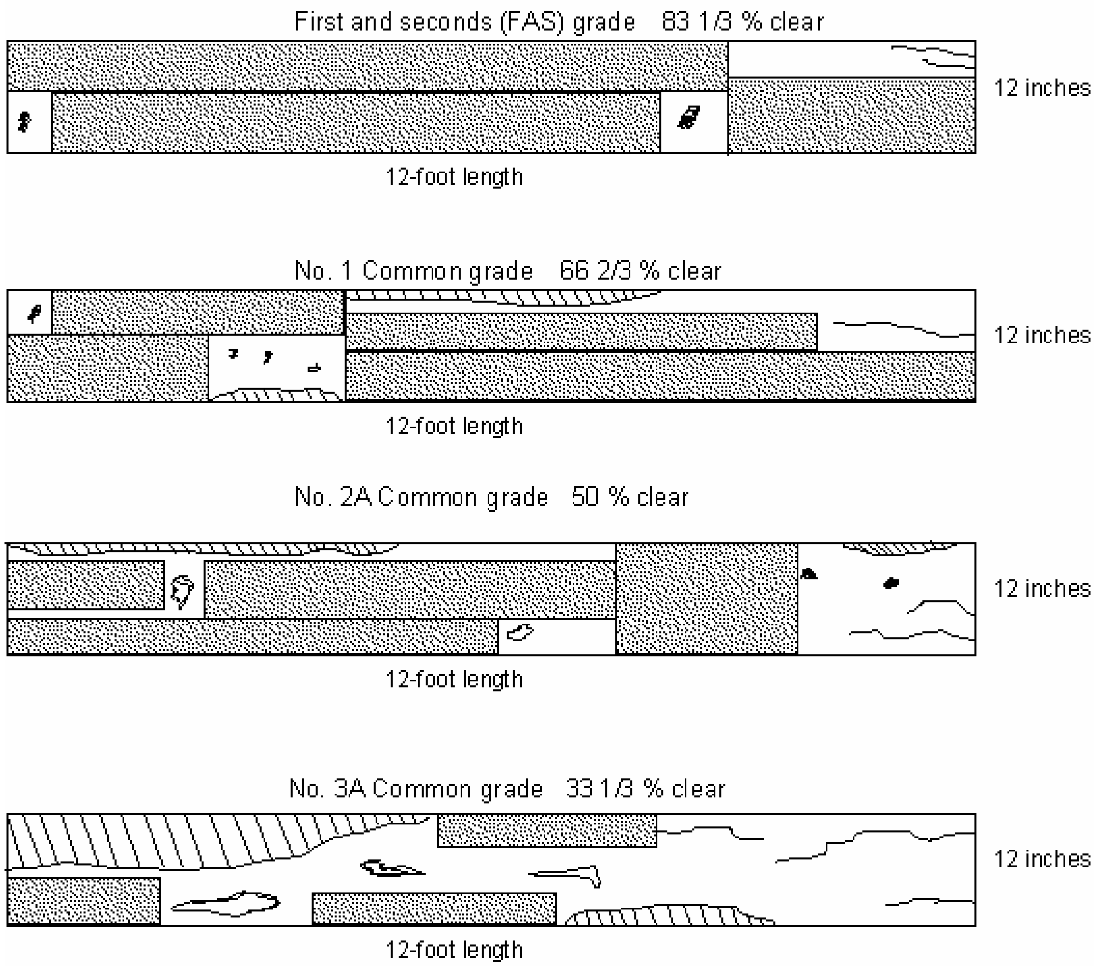

Figure I-2. Illustration of four lumber grades. Areas shaded gray represent clear areas. Adapted from Smith (1967).

2.2.1. Characteristics of the input material

For a hardwood sawmill, the input material that is used in the manufacturing process is a hardwood log. Because of natural variability the size, shape, and quality of logs found at a hardwood sawmill will differ greatly. Because of this, the majority of hardwood sawmills classify logs based upon species, grade, and volume.

Log length and diameter strongly influence the potential volume (board feet) of lumber that can be obtained from a log. Volume is calculated as a function of scaling diameter (small end diameter inside of bark), the length of a log, soundness, and straightness. The most commonly used formulas utilized within the U.S. forest products industry to calculate volume is the International ¼ - inch kerf log rule, the Scribner Decimal C log rule, and the Doyle log rule (Bond 2000). To simplify the process of calculating log volume, tables for each log rule were created which present log volume as a function of scaling diameter and log length (Table I-1). It is known within the hardwood industry that the International ¼ - inch kerf, Scribner Decimal C, and Doyle log rules will sometimes report different volumes, for logs of identical diameters and lengths as illustrated in Table I-1 (Freese 1973, Bond 2000).

Table I-1. Excerpts from the Doyle, Scribner Decimal C, and International ¼- inch kerf log volume tables

Doyle log rule			
Scaling diameter (inches)	**Volume (bd.ft.) Log length (ft) 8**	**10**	**12**
9	12	16	19
10	18	22	27
11	24	31	37
12	32	40	48
13	40	51	61
33	420	526	631
34	450	562	675
35	480	601	721

Scribner log rule			
Scaling diameter (inches)	**Volume (bd.ft.) Log length (ft) 8**	**10**	**12**
9	20	25	30
10	25	32	40
11	32	40	50
12	39	49	59
13	48	61	73
33	392	490	588
34	400	500	600
35	438	547	657

International ¼" log rule			
Scaling diameter (inches)	**Volume (bd.ft.) Log length (ft) 8**	**10**	**12**
9	20	30	35
10	30	35	45
11	35	45	55
12	45	55	70
13	55	70	85
33	400	500	605
34	425	535	645
35	450	565	686

Studies, which compared the actual volume of lumber sawn from a log to the estimated volume, have shown that the Doyle log rule and the Scribner Decimal C log rule both underestimate the volume of small diameter logs (Freese 1973, Martin and

Savage 1996). It has also been shown that in comparison to the other log rules, the International ¼ - inch kerf log rule most accurately estimates the volume of lumber that can be sawn from a log. The Doyle log rule is the most commonly used method of scaling hardwood logs in the eastern portion of the United States (Freese 1973, Martin and Savage 1996, Bond 2000). Besides the three log rules discussed there are fifty-two other documented log rules (Freese 1973). Many of these log rules were established to represent the percentage of lumber that is recovered from logs that originate from a specific region of the United States.

Log grade is a classification value that relates the potential quality and volume of the lumber that can be sawn from a log. High grade logs have few or no knots, are straight in form, relatively free of rot or decay, are large in diameter, and do not have any visual characteristics that would cause an undesirable discoloration of the lumber (i.e., mineral spots, gum pockets) (Vaughan et al. 1966). Table I-2 was created by the U.S.D.A. Forest Service as a guideline for the classification and specifications of log grades. Typically, individual sawmills will develop their own specifications for log grades. It has been shown in research studies, that high-grade logs yield more valuable lumber than low-grade logs (Vaughan et al. 1966, Hanks et al. 1980, White 1980). The fact that a log will produce low value lumber and high value lumber along with other low value waste products (e.g. sawdust, bard mulch) has been termed the "sawmill paradox" (Grönlund 1992).

According to a nationwide survey conducted in 2003, it is the perception of hardwood lumber manufacturers that little or no profit is realized from the low-grade lumber that is sawn from a log (Cumbo et al. 2003). This perception is subject to change depending on the price of low-grade lumber and the method used to calculate the cost of manufacturing low-grade lumber.

Table I-2. U.S.D.A Forest Service specifications for log grades. Adapted from Vaughan et al. (1966).

<table>
<tr><td colspan="2" rowspan="2">Grading factors</td><td colspan="8">Log grades</td></tr>
<tr><td colspan="3">F1</td><td colspan="4">F2</td><td>F3</td></tr>
<tr><td colspan="2">Position in tree</td><td>Butts only</td><td colspan="2">Butts and uppers</td><td colspan="4">Butts and uppers</td><td>Butts and uppers</td></tr>
<tr><td colspan="2">Scaling diameter(in.)</td><td>13-15</td><td>16-19</td><td>20+</td><td colspan="2">11</td><td colspan="2">12+</td><td></td></tr>
<tr><td colspan="2">Length without trim(ft)</td><td colspan="3">10+</td><td>10+</td><td>8-9</td><td>10-11</td><td>12+</td><td>8+</td></tr>
<tr><td rowspan="3">Clear cuttings on each 3 best faces</td><td>Minimum length(ft)</td><td>7</td><td>5</td><td>3</td><td>3</td><td>3</td><td>3</td><td>3</td><td>2</td></tr>
<tr><td>Maximum number</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>2</td><td>3</td><td>No limit</td></tr>
<tr><td>Fraction of log length required in clear cutting</td><td>5/6</td><td>5/6</td><td>5/6</td><td>2/3</td><td>3/4</td><td>2/3</td><td>2/3</td><td>1/2</td></tr>
<tr><td rowspan="2">Sweep and crook allowance</td><td>For logs with less than ¼ of end in sound defects</td><td colspan="3">15%</td><td colspan="4">30%</td><td>50%</td></tr>
<tr><td>For logs with more than ¼ of end in sound defects</td><td colspan="3">10%</td><td colspan="4">20%</td><td>35%</td></tr>
<tr><td colspan="2">Total scaling deduction including sweep and crook</td><td colspan="3">30%</td><td colspan="4">50%</td><td>50%</td></tr>
</table>

For a more detailed table refer to: Vaughan, C.L., A.C. Wollin, K.A. McDonald, E.H. Bulgrin. 1966. Hardwood log grades for standard lumber. Research Paper FPL – 63. U.S.D.A. Forest Service. 54p.

Another important variable of the input material is the species. Different species of hardwood logs have different market values, which is a function of the supply of logs available to the market, the demand for a particular species of lumber, and the types of markets from which the demand is emanating. A log species such as red oak (*Quercus rubra*) will produce lumber that has different mechanical, physical, and perceived aesthetic properties than a log species such as basswood (*Tilia americana*). With hardwood logs, the perceived aesthetic value of the lumber is a much more important determinant of value than the physical or mechanical properties (Haygreen and Bowyer 1989). In contrast, the value of softwood log species is more a function of the mechanical and physical properties of the lumber than the aesthetic properties.

The market price for logs is not static and will fluctuate over time. The fluctuation is often dependent on the available supply of logs. The availability can be directly affected by weather that inhibits the removal of logs from the forest. An increase in the market price for logs will follow an increase in the demand for logs. The market value of logs will also fluctuate from year to year as the consumer's preference for a particular lumber species changes. Table I-3 is a comparison of the prices between species and log grades that a sawmill in West Virginia was willing to pay for logs (effective October 2002).

Table I-3. A comparison of the prices paid for logs between species and log grades (Effective October 2002)

	Price of logs per 1,000 board feet (MBF) for two log species	
Log grade*	**Basswood**	**Red oak**
Prime	$225	$650
Clear	200	550
Select	150	400
Mill	150	200

*Log grades are mill specific and may not reflect the log grade specifications of other sawmills

The value of a wood species is driven by market demand and is not a function of a sawmill's processing procedure or efficiency. However, more time and energy may be spent in processing high value species than low value species because of the difference in value of the lumber produced. Often differences in processing times, between species are a function of the physical properties of the species. Basswood has a lower specific gravity than red oak and thus can be fed through cutting machines at a greater speed while maintaining sufficient dimensional uniformity.

This difference becomes clearly apparent when observing differences in headrig feed rates between species of wood with a high specific gravity to a species with a low specific gravity (Table I-4). However, it is apparent in Table I-4 that the higher value wood species also have greater specific gravity values compared to the lower value wood species. Based upon this, there may be an interaction between the specific gravity of a wood species, the market value of the wood, and the effect on processing time. Limited research exists that has examined differences in the cost to produce lumber between species.

Table I-4. Recommended feed rates as a function of specific gravity for bandsaw and circular saw headrigs. Adapted from Lunstrum (1985)

Specific gravity	Species	Relative market value	Range of recommended feed rates (feet per minute) Bandsaw	Circle saw
< 0.46	Basswood Aspen	Low	8,500 –10,000	9,500 – 12,000
> 0.46	Red oak Hard maple Cherry	High	7,500 – 8,500	7,500 – 9,500

Another input characteristic is log length. Hardwood sawmills typically purchase logs cut to even two-foot lengths. On average, the lengths of hardwood logs are between eight and sixteen feet. Usually the logs include an extra 6 inches of material to compensate for any checking and cracking that occurs on the ends of the logs during storage. This material is later trimmed off the individual pieces of lumber. Longer length logs will produce more volume of lumber that shorter length logs. In addition, log length can be a determinant of log grade. In terms of processing, there is a linear relationship between log length and the feed rates of some machine centers. As illustrated in Table I-5, log length does have an effect on processing time at the headrig.

Table I-5. Carriage speed values derived from log length and time. Adapted from Lunstrum (1993).

Time required for the log to pass through the saw	**Log length (ft)**				
	8	**10**	**12**	**14**	**16**
Seconds	- - - - - Feet per minute - - - - -				
2	240	300	360	420	480
3	160	200	2406	280	320
4	120	150	180	210	240
5	96	120	144	168	192
6	80	100	120	140	160

2.2.2. Description of the machine centers in a hardwood sawmill

The machine center involved in the primary breakdown of a log is the headsaw. Collectively the headsaw along with a log carriage and a log turner make up what is known as a headrig. Headrig types include circular saws and bandsaws. The main difference between these two types of headrigs is that a circular saw has a larger kerf than a bandsaw. A thinner kerf saw results in a greater yield of lumber from a log because the cutting area of the blade is smaller in dimension. The headrig machine center is generally considered the limiting constraint in sawmill production rates (White 1980).

Some hardwood sawmills will also incorporate a line-bar resaw into the primary breakdown of a log. A line-bar resaw is similar to a bandsaw found in a woodworking shop. A line-bar resaw can only process a log that has at least two flat surfaces, which are created at the headrig. The benefits of a line-bar resaw include less deviation in lumber thickness and it helps the headrig to become less of a limiting constraint. At both the headrig and line-bar resaw machine centers the operator has the opportunity to rotate or turn the log, which is done to maximize the volume of high-grade lumber produced from a log.

Another machine center, which can be used in addition to a headrig for primary breakdown, is a gangsaw. The gangsaw machine center can only process a log that has a minimum of two flat surfaces. Logs are processed at the gangsaw by passing through a bank of saws, which are in a fixed position on a rotating arbor. The spacing of the saws controls the thickness of the lumber produced.

The edging process is done at the edger machine station. At the edger machine station, lumber that does not have square and parallel edges along the length of the board is passed through two saws on a rotating arbor. At least one of the saws on the arbor is a floating saw, which is capable of moving perpendicular to the arbor. Depending on the type of edger, placement of the floating saw is controlled either by an operator or by a computer. Lumber exiting the edger will be smaller in width than when entering the edger and will have two square edges in the lengthwise direction. If a board already has two square edges in the lengthwise direction, it will be routed around the edger machine station.

The trimming process in done at the trimmer machine station. The function of a trimmer station is to make the ends of a piece of lumber square. This process can be done by a bank of independent drop saws or it can be done with a chain saw or circular handsaw. Depending on the type of trimmer, a human operator or a computer can control the placement of the cut. While not every piece of lumber may need to be trimmed most sawmills are arranged so that all material goes through the trimmer before exiting the sawmill.

2.2.3. Material flow through the system

Figure I-3 is a diagram of the material flow through a hypothetical sawmill system. The three machine centers in Figure I-3 are the headrig, edger, and trimmer. These three machine centers are the core machine centers of a hardwood sawmill. Depending on the technology level of the sawmill there may also be intermediate machine centers. The arrows in Figure I-3 represent the flow of materials through the system. If boards sawn at the headrig do not need to be edged, they will be routed directly to the trimmer. The trimmer station is the final machine center in the system and typically, material cannot be routed around it due to the arrangement of the machine centers and material handling procedures. Material is moved between the machine centers by conveyors.

Missing from Figure I-3 is the debarker machine center located before the headrig station. The function of the debarker machine center is to remove the bark from a log. Removing the bark from logs helps to prevent stones and other abrasives, lodged in the bark, from dulling the saws of the machine centers downstream from the debarker. Debarking is also done to ensure that the lumber produced is free of bark for phyto sanitary reasons and that the by-products (i.e. wood chips) are free of impurities (Denig 1993). While removing the bark from logs does reduce maintenance costs and can increase yield, it is not necessary to produce lumber.

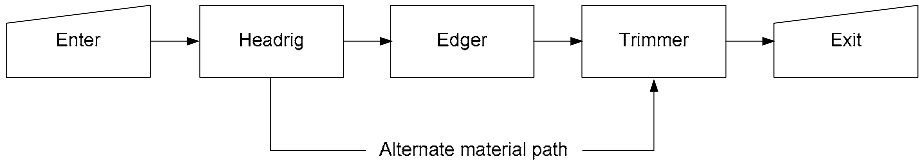

Figure I-3. The basic material flow pattern in a hypothetical sawmill.

What is unique about the flow of materials in a hardwood sawmill that is different from other manufacturing environments is that the rate and amount of material that is sent to the machine centers is not constant. Starting at the headrig the amount and rate of material sent to the edger is a function of both the diameter of the log and the operator of the headrig. Based upon geometry it can be shown that as the diameter of a log increases the number of boards sent to the edger from the headrig increases (Meimban 1991).

Up to this point lumber is the only material that has been identified as the product produced in the log to lumber conversion process. While lumber is the primary product produced, large amounts of by-products are also produced in the sawing process. The Virginia Department of Forestry estimated that in 1996, hardwood sawmills in Virginia produced 1.0 million tons of chips, 667,600 tons of sawdust, and 506,700 tons of bark (Alderman 1998). Markets do exist for these by-products, but the value is significantly less than the market value of lumber. The processing and handling of the waste material, which includes sawdust, chips, bark, and the outside slabs of a log, does involve the procurement, maintenance, and operation of equipment, which has no direct function in the processing of lumber. Nor does the equipment add value to the lumber produced. The costs associated with the operation of this type of equipment are typically allocated to fixed overhead costs.

2.2.4. Material output

With the exception of by-products, the output of material from a hardwood sawmill is lumber, railroad ties and pallet cants. Hardwood lumber is random in width and trimmed to two-foot intervals. Pallet cants are typically 3.5 x 6 inches in dimension and are trimmed to two-foot intervals. Railroad ties are 6 x 8 inches or 7 x 9 inches in dimension and are also trimmed to two-foot intervals. After exiting the sawmill system through the trimmer machine center, the above mentioned sawmill products are routed to a sorting area by means of a conveyor. At the sorting area, the lumber is inspected by a human who assigns a grade to each individual piece of lumber. The volume of each piece of lumber may also be recorded. This is the first point in the manufacturing process where products are evaluated for quality and market value can be assigned. The railroad ties and pallet cants are typically not graded at the sawmill. Table I-6 presents an abbreviated list of the standards used for hardwood lumber grading. Table I-7 presents the most commonly used designations of lumber grades, along with respective market values and percentage of usable material that defines the grade.

Table I-6. Abbreviated standards for hardwood lumber grading. Adapted from Smith (1967)

<table>
<tr><th rowspan="2">Basic requirements</th><th colspan="7">Hardwood lumber grades</th></tr>
<tr><th>FAS</th><th>F1F</th><th>Select</th><th>#1 Com</th><th>#2A & 2B</th><th>#3A Com</th><th>#3B Com</th></tr>
<tr><td>Minimum size board</td><td>6” x 8’</td><td>6” x 8’</td><td>4” x 6’</td><td>3” x 4’</td><td>3” x 4’</td><td>3” x 4’</td><td>3” x 4’</td></tr>
<tr><td>Minimum size cutting</td><td>4” x 5’
3” x 7’</td><td colspan="2" rowspan="2">Better face to grade FAS
Poor face to grade #1 Com</td><td>4” x 2’
3” x 3’</td><td>3” x 2’</td><td>3” x 2’</td><td>Not less than 1 ½” wide containing 36 sq. inches</td></tr>
<tr><td>Minimum yield of clear material</td><td>83-$^{1}/_{3}$%</td><td>66-$^{2}/_{3}$%</td><td>50%</td><td>33-$^{1}/_{3}$%</td><td>25%</td></tr>
</table>

For a more detailed list of standards refer to: NHLA. 2003. Rules for the Measurement and Inspection of Hardwood and Cypress. Memphis, TN. 129 pgs.

Table I-7. The most commonly used designations of lumber grades and relative market value

Lumber grade	**Relative market value**	**Minimum percentage of clear defect-free material**
FAS	Highest	83-1/3%
F1F		83-1/3%
SELECT		83-1/3%
#1 COM		66-2/3%
#2A & 2B		50%
#3A COM		33-1/3%
#3B COM	Lowest	25%

As stated before the paradox of producing hardwood lumber is that a log will produce low value or low-grade lumber along with high value lumber in addition to waste products. For hardwood logs, it is generally recognized that the outer portion of a log due to the absence of defects will produce higher-grade lumber than the inner portion of a log (Malcolm 2000). Defects are defined as knots, frost cracks, and other physical features that can limit the amount of clear lumber that can be produced. The material found in the inner portion of a hardwood log will, in most instances, have a greater percentage of defects compared to the outer portions (Malcolm 2000). Figure I-4 illustrates a typical sawing pattern used to process hardwood logs and the boards that conventional knowledge states will be high grade and low grade (Malcolm 2000).

Lumber is typically sorted by length and grade while railroad ties and pallet cants are separated only by length. The process of sorting and stacking each individual piece of lumber is done manually or through an automated lumber handling system. The manual process of stacking lumber is typically done more often than the automated process (Denig 1993).

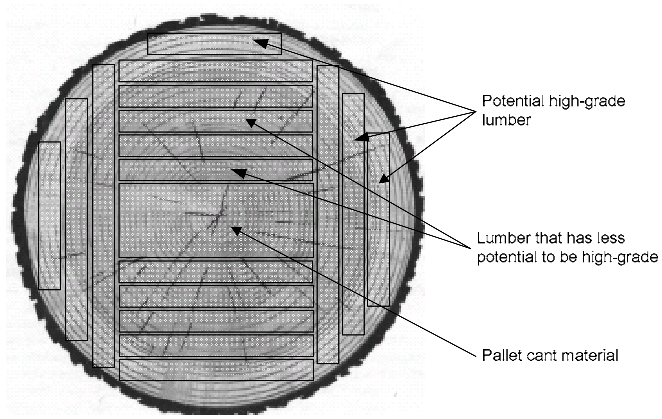

Figure I-4. A cross section of a hardwood log illustrating a typical sawing pattern and the boards that conventional knowledge states will be high grade and low grade (Malcolm 2000). Log diagram borrowed from Freese (1973).

3. Methods of measuring and evaluating sawmill performance

3.1. Lumber production

Sawmill performance can be expressed in a variety of ways. The simplest of these forms is to simply report on annual lumber production. By using annual production values, changes made in sawmill operations (i.e., new machine purchases, different operating procedures, etc.) can be evaluated in terms of either increased or decreased annual production values. However when using annual production as the only measurement criteria, it is difficult to identify specific areas within the sawmill system, which function as limiting constraints on the entire system.

3.2. Yield studies

Yield studies have been used within both softwood and hardwood sawmill industries to evaluate the amount of lumber that is obtained from logs. While yield studies done in softwood sawmills mostly focus on the volume of lumber produced, yield studies in the hardwood industry focus on the quality of lumber that is produced (White 1980). Yield studies can be conducted on individual logs or groups of logs with similar characteristics. Typically, within the sawmill industry, yield is measured for a group of logs by comparing the volume of logs going in the sawmill to the volume of lumber exiting the sawmill. From a yield study, percent overrun and the lumber recovery factor (LRF) can be determined which are defined in Equation I-1, and Equation I-2, respectively.

$$\textit{Overrun/underrun (\%)} = \frac{\textit{total lumber yield (bd.ft.)}}{\textit{gross log scale (bd.ft.)}} \qquad \textbf{Equation I-1}$$

$$\textit{Lumber recovery factor (LRF)} = \frac{\textit{total lumber yield (bd.ft.)}}{\textit{total log volume } (ft^3)} \qquad \textbf{Equation I-2}$$

The limiting factor of the overrun formula, is that the calculation of log volume will inherently be either underestimated or overestimated depending if the Doyle log rule, Scribner Decimal C rule or International ¼ - inch log rule is used. Because the LRF formula uses cubic feet as the log volume variable, the irregularities in estimating the volume of small and large diameter logs with the standard log rules is not a factor.

Volume yield studies have been used to find correlations between the kerf of saw blades and the amount of lumber produced. Wade et al. (1992) found that greater lumber recovery was measured when using bandsaw headrigs compared to circular headrigs. The differences in the volume of lumber recovered were attributed to the bandsaws having a smaller kerf, or cutting area than the circular saws.

A grade yield study in a hardwood sawmill will produce information that relates log grade to the grade of lumber produced. Similar to a volume yield study this method can be used on a single log or a group of logs of the same grade. It has been reported that typically a high-grade log will on average produce a greater amount of high-grade lumber compared to a low-grade log (Vaughan et al. 1966, Hanks et al. 1980, White 1980). Grade and yield studies provide information, which compares the price paid for a log to the value of the products derived from the log. While this is useful in determining recovery efficiency, it does not accurately identify the true cost of processing the log into lumber or the cost of producing lumber.

3.3. Time and motion studies

Time and motion studies are useful for analyzing the amount of time during a workday that is allocated to a specific activity. The one area of a sawmill system that is typically the focus of a time and motion study, is the headrig. Some of the operations that occur at the headrig include loading a log onto the carriage, log turning, and carriage return. These activities constitute some of the most time consuming activities that occur within a sawmill system (White 1980). Because the headrig is at the beginning of the sawmill system, it is often considered an area that constrains the other machine centers. Through time and motion studies, a specific activity such as log turning or log loading can be identified as an operating constraint during the log breakdown process. Improvements such as electronic setworks in the sawyers cab and faster log turners can then be justified if the overall production rate of the sawmill is estimated to increase. Time and motion studies can also be used to determine the effects that log length, diameter, and grade have on production rates.

3.4. Benchmarking

Benchmarking can be grouped into performance benchmarking, process benchmarking or strategic benchmarking (Andersen and Pettersen 1996). Performance benchmarking compares performance measures (either financial or operational) of one operation to another for comparison purposes. Within the hardwood sawmill industry, annual production, sales revenue, and number of employees are often benchmarks used to differentiate between large and small sawmill firms. Annual production that was reported from the top 50 lumber producing U.S. hardwood sawmills ranged from 12.5 million board feet to 94 million board feet (Anonymous 2001). A small hardwood firm will, in general, produce between two and 10 million board feet annually, have 19 or fewer employees, and have annual sales revenues of $1.6 million. A large hardwood sawmill firm, on average, will produce in excess of 11 million board feet annually; employ 20 or more people, and generate annual sales of $8.6 million (Bowe et al. 2001).

Process benchmarking is a comparison of the methods or processes between operations. This is done to learn how to improve operating procedures or methods based upon the success of another operation. The production rates and yields between sawmills operating bandsaw headrigs, and sawmills operating circular headrigs can be compared to demonstrate which headrig type is more efficient.

Strategic benchmarking is a comparison of the strategies (i.e., marketing, sawmill layout, equipment utilized) between operations. This is a more difficult type of benchmarking to perform because it involves collecting tightly guarded marketing strategies and business practices. However because lumber is a commodity item the marketing strategies of a hardwood sawmill are often limited, which is why so much effort is put into cost reduction and production efficiency improvements.

Maness and Wong (2002) developed a method for performance benchmarking the optimizing chop saw systems used in rough mills. The benchmarking procedure used grading accuracy, mark placement accuracy, scanning accuracy, chopping accuracy, and optimization accuracy as criteria for evaluating automatic chop saw systems. For the hardwood sawmill industry there is a lack of published performance benchmark information regarding the cost of producing lumber. One of the initial steps to creating such benchmark information would be to examine how different log characteristics affect the cost of producing lumber.

3.5. Cost-volume-profit analysis

Having the knowledge of what it costs to operate a sawmill is the first step in determining if a business is profitable, and can keep operating. A cost-volume-profit analysis will link changes in operating costs, revenues, and profits to changes in the volumes of products sold. This type of analysis is useful for estimating the number of products that must be sold at a given price to produce revenue that will either equal or exceed purchasing, manufacturing, and distribution costs. The cost-volume-profit analysis technique is useful to make predictions regarding profit, but the method does not consider every factor connected with the cost (Ainsworth and Deines 2003).

Assumptions of a cost-volume-profit analysis are that selling price, variable costs, and fixed costs remain constant regardless of the volume produced or sold. It also assumes that the volume produced will equal the volume that is sold within the same time period. The previous assumption also holds true if multiple products are produced, i.e., pallet cants, railroad ties, grade lumber (Ainsworth and Deines 2003). The results of a cost-volume-profit analysis are sufficient for general estimation purposes but are limited in identifying the cost of goods manufactured.

4. Components and methods of measuring the operating costs associated with the manufacture of hardwood lumber

4.1. The components

The four primary classifications of costs related to operating costs are (1) direct materials costs, (2) selling and administrative costs, (3) direct labor costs, and (4) manufacturing overhead costs (Ainsworth and Deines 2003). The direct materials cost is the amount of assets that are used to purchase logs. Direct labor cost is the wages of the personnel who are directly involved with the conversion process. Manufacturing overhead costs include all of the fixed costs that are necessary to operate the sawmill. Selling and administrative costs pertain to the wages and salaries of personnel who are not directly involved with the conversion process, but are necessary to operate the business.

4.2. The methods

Calculation of a sawmill's annual operating costs is done by adding up all the direct materials costs, direct labor costs, manufacturing overhead costs, sales, and administrative costs that have been incurred. Operating costs communicate the amount of assets that were used to operate for a given period of time. Operating costs do not communicate the amount of material that was produced or the cost of goods manufactured.

5. Components and methods of measuring the cost of lumber produced

5.1. The components

The cost of goods manufactured includes the cost of direct materials, direct labor, and manufacturing overhead (Ainsworth and Deines 2003). Note that unlike operating costs, selling and administrative costs are not included in the cost of goods manufactured. Direct materials can be physically traced to the final product and consume enough assets to be considered significant. When manufacturing hardwood lumber, the most significant direct material cost is the amount of assets used to purchase logs.

Direct labor costs are only allocated to employees who are directly involved in the manufacturing process (Ainsworth and Deines 2003). Examples of costs assigned to direct labor in a hardwood sawmill includes the wages for machine operators and material handlers. Maintenance personnel and supervisors who work directly in the sawmill and provide support for the manufacturing process are considered indirect labor. The salary and wage costs of indirect labor are included in manufacturing overhead costs.

Manufacturing overhead are all the indirect manufacturing costs that are incurred. Examples of costs included in manufacturing overhead are items used to maintain production equipment, utility costs, insurance costs, and applicable property taxes (Ainsworth and Deines 2003). The cost of a saw, the cost of equipment to sharpen the saws, and the wage paid to the saw filer are all examples of costs that would be allocated to manufacturing overhead costs.

5.2. The methods

5.2.1. Traditional cost accounting

Developed before World War I, traditional cost accounting divides costs into variable and fixed categories (Lere 2000). Labor costs, utility costs, direct material costs, and maintenance costs are examples of variable costs. With the traditional cost accounting system variable costs vary in proportion to volume of products manufactured. Examples of fixed costs include insurance costs, depreciation, and property taxes. Fixed costs do not change and are still incurred whether or not items are manufactured. Traditional cost accounting assumes that if a cost does not change with volume then it is a fixed cost.

Consequently, under the traditional cost accounting system, cost of goods manufactured is first calculated by identifying the fixed costs and variable cost of the manufacturing process. A dollar per unit cost is assigned to the variable costs, and a dollar cost is assigned to the fixed costs. When the manufacturing process is done, the appropriate variable costs are multiplied by the number of units produced and added to the sum of the fixed costs.

White (1980) states that calculating the cost of lumber produced is typically done by dividing the operating expenses that were incurred in a given period by the amount of lumber produced during the same time period. This calculation is presented in Equation I-3.

$$\textit{Sawing cost/bd.ft.} = \frac{\textit{Operating expense– log inventory costs}}{\textit{Total bd.ft. of lumber produced}} \quad \textbf{Equation I-3}$$

With Equation I-3, the cost of the lumber produced is directly proportional to the amount of lumber produced. The main limitation of the traditional cost accounting system is that fixed costs have to remain fixed and cannot be allocated to activities other than changes in volume produced. White (1980) also describes a method to identify and calculate the cost of lumber produced from an individual log (Equation I-4). The main limitation of this equation is that the fixed annual operating expenses are not allocated to the individual activities that occur when processing a log.

$$\textit{Cost of sawing an individual log} = (\textit{operating cost/hr.})(\textit{time required to saw log}) \quad \textbf{Equation I-4}$$

where:

$$\textit{Operating cost/hr.} = \frac{\textit{total annual operating expenses – log cost}}{(\textit{operating hrs. per day})(\textit{number of operating days per year})}$$

and:

Time required to saw log = Total elapsed time from when the log is loaded onto the carriage to when the final piece of lumber sawn from the logs exits the sawmill

Another difficulty in estimating the cost of the products manufactured in a hardwood sawmill is the presence of joint costs. Also known as, common costs, joint costs are costs that cannot be allocated to a specific product when a manufacturing process yields a number of products with different quality. (Balachandran and Ramakrishnan 1981; Billera et al. 1981). Using a traditional costing approach the joint costs are allocated to products, based upon the volume of each product produced.

In the production of hardwood lumber, the grade of the lumber and the value of the lumber are not known until after the processing procedure. The inability to segregate lumber products during sawing process and the large volume of lumber produced in a sawmill causes joint costs to occur between the lumber grades. The raw material cost of an individual log cannot be allocated directly to an individual board or group of boards unless the boards are tracked through the production process.

5.2.2. Activity-based costing

When labor and material costs were the largest costs associated with manufacturing, traditional cost accounting was very effective in calculating product costs. However, as manufacturing became more industrialized fixed overhead costs surpassed labor and material costs as the largest component of a manufacturing budget (Ainsworth and Deines 2003).

Developed in the late 1980's, activity-based costing (ABC) is an accounting methodology, which "*derives product costs as the sum of the activities that occur to make the product*" (Deakin and Maher 1991). Unlike traditional costing, the principles and methodology of the ABC accounting system recognizes that there are other measures of activity besides volume, which can cause costs to change. By assuming that volume is not the only catalyst to change costs, ABC allows fixed costs to become variable costs. The same cost components used in traditional costing are divided into unit-level, batch-level, product-level, and facility-level costs (Lere 2000). This allows high fixed overhead costs to be allocated to specific activities that occur in the manufacturing process.

One of the limitations to implementing an ABC costing method into a business is the time and knowledge required. Changing from a traditional cost accounting system to an ABC system is a daunting task that requires changes in the record keeping procedures of each department within a business (Lere 2000). The ABC costing method also does not take into account capital cost, investment risk, and cash flow factors, which are of particular interest to shareholders of stock, but are of minimum importance to a plant floor manager who needs a tool to track costs (Roztocki and Needy 1998).

Since it was first introduced several studies have examined the effectiveness of using ABC as a product costing method in sawmill operations. A case study conducted by Wessels and Vermaas (1998) at a softwood sawmill analyzed the benefits of implementing activity-based costing into a sawmill manufacturing environment. The case study concluded that the planning, control, and decision-making abilities of the management would improve under the activity-based costing method in comparison to the traditional costing method, already is use. It was however noted by Wessels and Vermaas that fully implementing the activity-based costing technique across all facets of the sawmill business (log procurement, sawing, drying, and sales) would be expensive and time-consuming.

Howard (1993) developed Equation I-5 to determine the variable cost of processing individual logs into lumber. Howard’s formula required that a variable cost function for each machine center to be calculated based upon the labor costs, maintenance costs, and utility costs that are incurred at each machine center. The cost to process an individual log is then the sum of fixed overhead costs and the variable cost of each machine center that was used to process an individual log.

$$LVC_i = \sum_{j=1}^{m} PT_{ij} \times MC_j + \sum_{j=m+1}^{n} PT_{ij} \times MC_j \qquad \textbf{Equation I-5}$$

where:

LVC = total variable cost for log i

PT_{Ij} = processing time for log i at machine center j

MC_j = variable costs per scheduled hour for machine center j

m = number of machine centers with processing time function in Group 1, used to process all or part of log i

n = total number of machine centers used to process all or part of log i

n – m = number of machine centers with processing time functions in Group 2, used to process all or part of log i

The Group 1 machine centers, referred to in Equation I-5, are machines where the processing times of individual boards or logs can be measured. Examples of Group 1 machine centers are debarkers, headrigs, and edgers. Group 2 machine centers simultaneously handle volumes of logs and lumber and do not facilitate the measuring of processing times for individual objects. Examples include conveyers, and log yard equipment. The variable costs of the Group 1 machine centers are measured as a function of the individual pieces. The variable costs of the Group 2 machine centers are measured as a function of volume (Howard 1993). Howard's equation does acknowledge that not all machine centers are uniformly utilized when processing logs.

As mentioned before, ABC was developed to allocate overhead fixed costs more accurately to the products based upon the activities performed to make the products. Traditional cost accounting is assumed to be inaccurate when overhead costs exceed direct labor and material costs (Ainsworth and Deines 2003).

6. Modeling the manufacturing processes

6.1. Introduction

Objectives of the manufacturing process include production improvement, cost reduction, and consistent product quality (Spedding and Chan 2001). Creating a representation of the manufacturing process facilitates performing what-if analysis of a particular process or operating mechanism. A model, which uses mathematical functions to represent a manufacturing system, as opposed to the physical functions of the system, is termed a simulation model (Law and Kelton 1991). Simulation models are separated into static or dynamic, deterministic or stochastic, and discrete or continuous (Law and Kelton 1991, Banks et al. 2001).

Dynamic simulations, model a system over an extended period of time. In comparison, static simulations only model a system at one point in time. Deterministic simulation produces an output for a given set of fixed nonrandom inputs, which differs from stochastic simulation where the inputs are random and variable. In a discrete simulation model, the system only changes when a predetermined event occurs. The frequency at which the catalyst event occurs is either random or based upon a statistical distribution. The system represented by a continuous simulation model is constantly changing as a function of continuous input factors (Law and Kelton 1991, Banks et al. 2001). A specific type of discrete simulation, discrete-event, is differentiated from other simulation techniques because analysis is done by numerical methods as opposed to analytical methods (Law and Kelton 1991, Banks et al. 2001).

Whatever type of simulation is used, following a concise process when performing a study using simulation facilitates ease of model development and reduces the potential of errors in the model. A step-wise process of performing a simulation study as discussed by Law and Kelton (1991), and Banks et al. (2001), involves a specific definition of the problem, statement of how the problem will be solved, and a systematic procedure to validate the model at regular intervals during the model building process.

6.2. Steps in performing a simulation study

Wiedenbeck and Kline (1994) document the development a furniture rough mill simulation model using a general simulation study process developed by Nance and Balci (1986). Collectively, the Nance-Balci Model Development Life Cycle is divided into ten study phases.

The first three study phases involve communicating the importance of the problem that initiated the research endeavor, definition of the problem and statement of research objectives, and the proposition of a technique to find a solution to the problem. These three initial study phases are done before anything else, in order to clearly define what needs to be modeled, and what information should be collected. The actual study phases that are directly involved in the develop of model are defining the objectives of the system, development of a conceptual model, communication of the model, programming the model, experiment with the model to determine optimum experimental design, implementation of the model to produce results, and finally validation of the model.

6.3. Relevant simulation work

Past research work, involving the simulation of a hardwood sawmill system, has focused on evaluating material flow by either replacement or rearrangement of machine centers. Most of this work used discrete-event simulation as a modeling platform. Models have also been developed which simulate the primary and secondary breakdown of a log by sawmill equipment. These models were used to predict some descriptive characteristic of the lumber produced as a function of the fixed input variables such as log species, grade, diameter, or length,. What has not been done is to model how the cost to process a log into lumber changes and how the cost to produce the same grade and volume of lumber varies based upon the effect that specific log variables have on a sawmill system.

Martin (1971) created the earliest simulation model of a hardwood sawmill, and used it to model the movement of materials in a sawmill between machine centers. Random number generators governed the rate at which materials moved and the amount of materials that were moved. The work done by Martin was completed in the early days of personal computing. Because of the computer technology available in 1971, only limited amounts of data could be entered into the simulation model.

In 1984, Adams utilized the FORTRAN programming language to develop a model for the purpose of analyzing machine type and layout in hardwood sawmills (Adams 1984). The model, known as DESIM, was composed of a forms program, a design program, a simulation program, and supporting data files. Under the DESIM model, machine processing times were governed by average processing time values collected from the sawmill that was modeled. Machine center downtime, log processing procedures, and material routing decisions were based upon probabilities calculated from measurements taken at the study mill.

The exact procedures for collecting machine processing times and other pertinent data is outlined by Adams (1985). As with the model developed by Martin in 1971, the slow processor speeds and limited memory of most personal computers in 1984 restricted the feasibility of using the DESIM model. Problems identified with DESIM included difficulty in accurately simulating the volume and characteristics of the material that came from the headrig. DESIM was also limited in that it could only simulate the processing of one lumber thickness (Adams 1988).

Meimban (1991) addressed these issues with the development of a simulation model that was capable of predicting the volume and grade of lumber sawn from logs for an infinite amount of lumber thicknesses. Modeling of the volume component was accomplished by using geometry to calculate the largest square that can be produced from a circular log with a given diameter. The grade of lumber produced was predicted by creating statistical look-up tables based upon numerous lumber yield studies that had been done by the U.S.D.A. Forest Service. Along with this Meimban also modeled processing delays, and material flow using the SIMAN simulation language. The purpose of Meimban's work was to create and validate a simulation model of a hardwood sawmill.

Lin (1993) developed a simulation model for the purpose of evaluating the economic feasibility of converting low-grade hardwood logs directly into dimension parts. For this research, simulation was necessary because at the time the model was developed, there was no processing facility that converted logs directly into dimension parts. The SIMAN IV/CINEMA simulation language was used to develop possible plant designs based upon data from rough mill and hardwood sawmill systems. Plant design was evaluated by the volume of dimension parts yielded in a given time period and return on sales financial data from each simulated plant design.

McClain (1994) developed a simulation model using the ARENA simulation language to evaluate the effect of machine replacement on the total output of a hardwood sawmill system. The simulation model was used to identify bottleneck areas in a case study sawmill. Experiments were also conducted using the simulation model to determine the optimal rate at which lumber should be sent to the trimmer machine center in order to prevent the trimmer machine center from becoming a bottleneck area.

Using a similar modeling approach, Wicklund (1995) conducted a case study at a hardwood sawmill to identify which log grade was the most profitable to process. A valid conclusion could not be made from this case study because of problems encountered in data collection. Despite this Wicklund was able to determine, through simulation, the optimum amount of time that a forklift should be available to the lumber sorting in order to prevent the lumber sorting area from becoming a bottleneck area.

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SECTION II. DATA COLLECTION PROCEDURES

1. Introduction

To meet the objectives of this research project two discrete-event simulation models were developed based upon the manufacturing information collected at a sawmill that annually produces approximately 35 million board feet (MMBF) of hardwood lumber and from a sawmill producing 7 MMBF of hardwood lumber per year. To differentiate between the two sawmill systems, the sawmill producing 35 MMBF of lumber annually will be subsequently referred to as the large volume sawmill and the other sawmill will be identified as the medium volume sawmill.

The purpose of this section is to describe the processes used to collect the manufacturing information from the two sawmills. The procedures used to collect information from the two sawmills was developed based upon literature authored by Mayer and Wiedenbeck (2005), White (1980), and Steele et al. (1981). These three pieces of literature provided guidelines and concepts behind the data collection procedures.

2. Data collection

2.1. Log sampling

To model the grade and volume of lumber produced at different machine centers, 50 red oak logs were sampled at the large volume sawmill and 38 red oak logs were sampled from the medium volume sawmill. The breakdown of log grade, diameter, and length for each sawmill is presented in Table II-1.

Table II-1. Number of logs samples per classification by mill

Sample location	Log grade[A]	Scaling diameter (in.)	Log length (ft.)	No. of logs sampled
Large volume sawmill	Prime	12-15	8	2
	Prime	12-15	12	10
	Prime	18-20	12	7
	Select	12-15	8	9
	Select	18-20	8	3
	Select	12-15	12	11
	Select	18-20	12	8
			Total	50
Medium volume sawmill	Prime	13-15	8	5
	Prime	19-21	8	1
	Prime	13-15	12	11
	Prime	19-21	12	1
	Select	13-15	8	8
	Select	13-15	12	9
	Select	19-21	12	3
			Total	38

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces

In sampling the logs it was decided beforehand to sample logs from two different log grade classes (Prime and Select); two log length classes (8- foot and 12 –foot), and two scaling diameter classes (small and medium). The diameter classes ended up being slightly different for each sawmill due to differences in log grading specifications. At the large volume sawmill scaling diameters between 12-15 inches were considered to be small, and scaling diameters between 19-21 inches were grouped into the medium size log category. Because of the log grading specifications used at the medium volume sawmill, logs with a scaling diameter of 12 inches and less were not considered to be of the Prime log grade. As a result, the small diameter log category for the medium volume sawmill was between 13-15 inches and the medium size log category was between 19-21 inches.

At the large volume sawmill the log grade, scaling diameter, and log length was based upon values assigned by an employee of the sawmill. For the medium volume sawmill the log characteristics were directly measured. The number of logs sampled varied between both sawmills because of the inability to control log input into the mill and the availability of logs that fit into each classification category.

2.2. Lumber yield from the sawmill machine centers

The purpose of this procedure was to track individual pieces of lumber from the logs identified in Table II-1 through the individual sawmill machine centers. This was accomplished by first painting both ends of an individual log before it entered the sawmill (Figure II-1). Several different colored lumber crayons were then used to track what machine centers processed the log or individual pieces of the log. For the large volume sawmill, four different colors of lumber crayons were used. A different color was used to mark the boards sent to the edger from the headrig, the boards sent to the edger from the band resaw, the boards sent directly to the trimmer from the band resaw, and the boards sent to the trimmer from the gangsaw (Figure II-2 and Figure II-3). Because of the manner in which the large volume sawmill processed logs, all of the boards produced at the headrig were sent to the edger and all of the boards produced at the gangsaw were sent directly to the trimmer. Therefore, it was only necessary at the band resaw to segregate between the boards sent to the edger and the boards sent directly to the trimmer.

Figure II-1. Photograph of a sample log

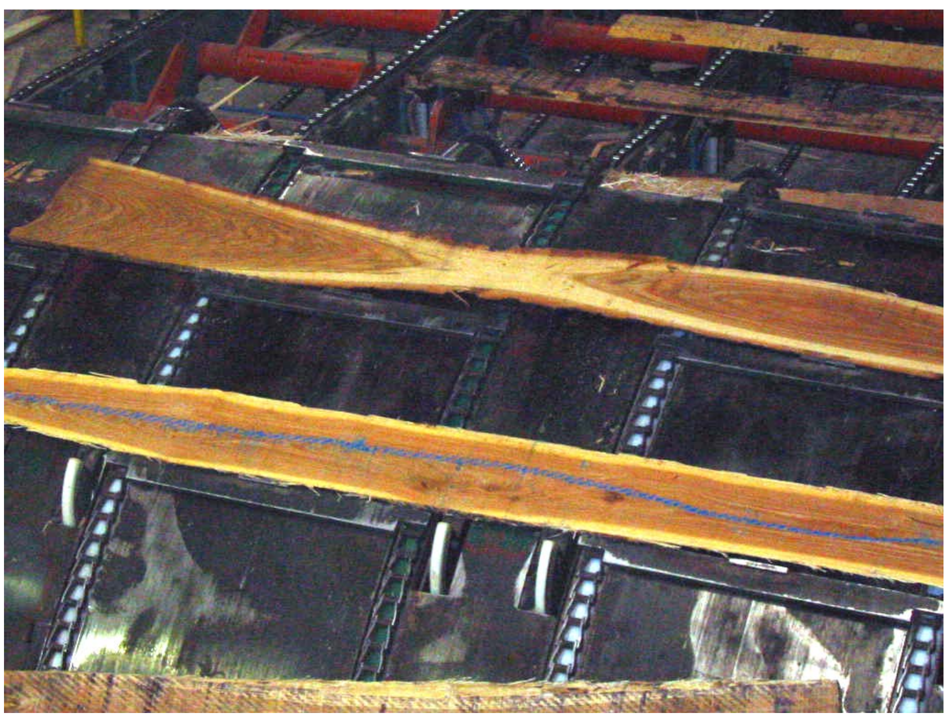


Figure II-2. Photograph of a marked board moving to the edger from the headrig

Figure II-3. Photograph of a marked board moving directly to the trimmer from the gangsaw

At the medium volume sawmill four different colors of lumber crayons were also used. However, because this sawmill does not operate a band resaw, it was necessary to segregate the lumber sent to the edger from the headrig and lumber sent directly to the trimmer. It was also necessary to segregate the lumber sent to the edger from the gangsaw and the lumber sent directly to the trimmer from the gangsaw.

For both sawmills, the grade and volume of lumber produced from the sampled logs were measured and recorded at the green chain, which is the output center for both sawmills. The task of recording the volume and grade was done by either the mill’s lumber inspector, or another person who volunteered to help in the study. At both sawmills, the lumber inspector employed by the sawmill, assigned the grade of each piece of lumber. However, the procedure for measuring the volume of each individual piece of lumber did differ between the two sawmills. The lumber inspector at the large volume sawmill directly calculated the surface measure of each board, but at the medium size sawmill, a person assisting in the project measured the nominal thickness, width, and length of the boards. The volume of each individual board was then calculated later by first using Equation II-1 and then multiplying the calculated surface measure by the nominal thickness of the board. Nominal thickness denotes the thickness of a board before it has been surfaced, and usually expressed in quarters of an inch.

$$Surface\ Measure = \frac{Width\ (in.) \times Length (ft.)}{12}$$ **Equation II-1**

where:

Width is measured to the precision of a quarter of an inch

Length is the nominal length of a board truncated to 8, 10, 12, 14, or 16-foot

As with any data collection procedure, there were errors in collecting the grade and volume of lumber information. The one error that was monitored and most significant to this project, was that information for some of the boards that had been marked at the machine centers was not collected. This error occurred because the person collecting the grade and volume information was not able to identify a board that had been marked. Possible explanations of why the marked boards could not be identified by the person collecting the information included: (1) the crayon mark on the board had been cut off and (2) the side of the board with the crayon mark was facing down when it came to the green chain and was not flipped over. To quantify the frequency with which this error occurred, the person marking the boards at the machine centers kept a running tally of boards marked, that was later compared to the number of boards the person on the green chain had recorded information from. Overall, the percent of boards where information was not recorded was six percent for the large volume sawmill and two percent for the medium volume sawmill. In comparison to the medium sawmill, the green chain at the large volume sawmill moves a larger volume of lumber, which may account for the greater percentage of missed boards. The data for an individual log was discarded if the information for more than one-quarter of the boards that had been marked was not recorded. Only one log sampled in the study had to discarded.

2.3. Machine center processing times

To effectively model the production rates at the sawmills, timing studies were conducted at each of the individual sawmill machine centers. The purpose of this section is to describe, in detail, how the processing times at each machine center were measured. Because two sawmills were studied, this section is divided into subsections, by sawmill and machine center. Additionally, the activities at each the machine centers that were considered to be unscheduled downtime are defined.

2.3.1. Large volume sawmill

The large volume sawmill studied for this project uses seven machine centers. The machine centers are described in great detail and unique features or functions of the machines important to the development of the simulation models are identified. Figure II-4 illustrates the location of the machine centers and conveyors in the large volume sawmill.

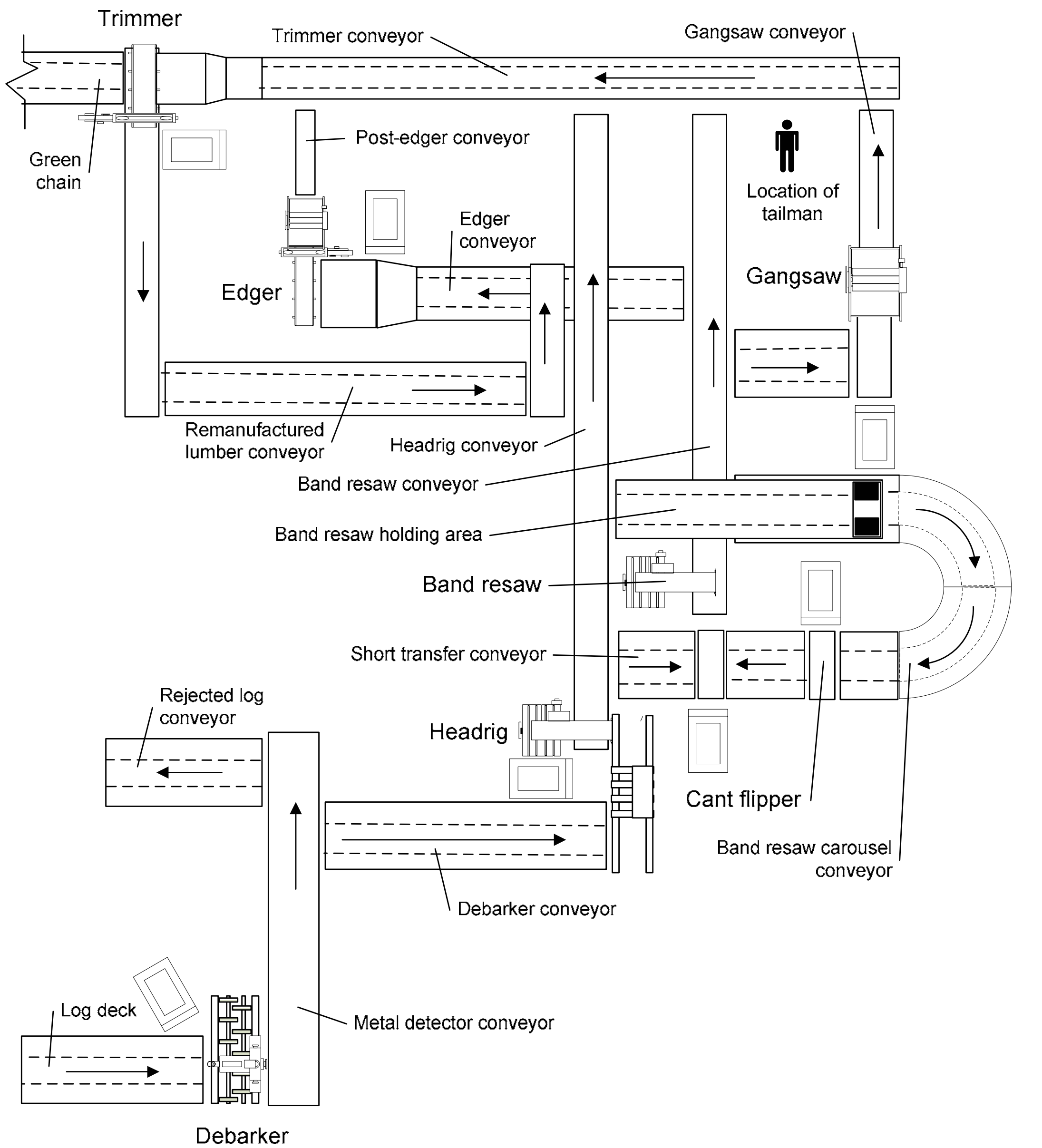


Figure II-4. Machine and conveyor layout at the large volume sawmill

2.3.1.1. Debarker machine center

The debarker at this sawmill was a rosser-head type debarker. Processing time was measured with a hand held stopwatch. Timing began when the rosser-head dropped down to begin debarking and ended when the rosser-head was tilted back up.

The timing of the debarking process was stopped and not recorded if: (1) delays during the debarking procedure where greater than one-minute in length, (2) delays occurred due to mechanical breakdown or, (3) delays were caused by blockage due to machine failure downstream from the debarker. Slight delays such as material handling problems were included in the overall processing time. It was observed at all of the sawmill machine centers that material handling was a consistent problem. At the debarker machine center, a common material handling problem was that the logs would become misaligned with the feed rollers used for turning the log. This would cause a slight delay, as the debarker operator repositioned the rosser-head on the log. These slight delays were included in the timing. The majority of unscheduled downtime, at this machine center, was due to the debarker operator having to leave his station and remove barcode tags from the ends of the logs.

A total of 62 timing observations were recorded at the debarker machine center, at different times during one work-shift. It should also be noted that the timing was done using yellow-poplar logs and not red oak logs. While there may be slight differences between the time it takes to debark a red oak and a yellow poplar log, this difference was considered inconsequential since the debarker machine center does not control other machine utilization rates as much as the headrig or band resaw machine centers do.

2.3.1.2. Headrig machine center

To facilitate understanding the terminology associated with the headrig machine center, Figure II-5 illustrates the main components of this machine center.

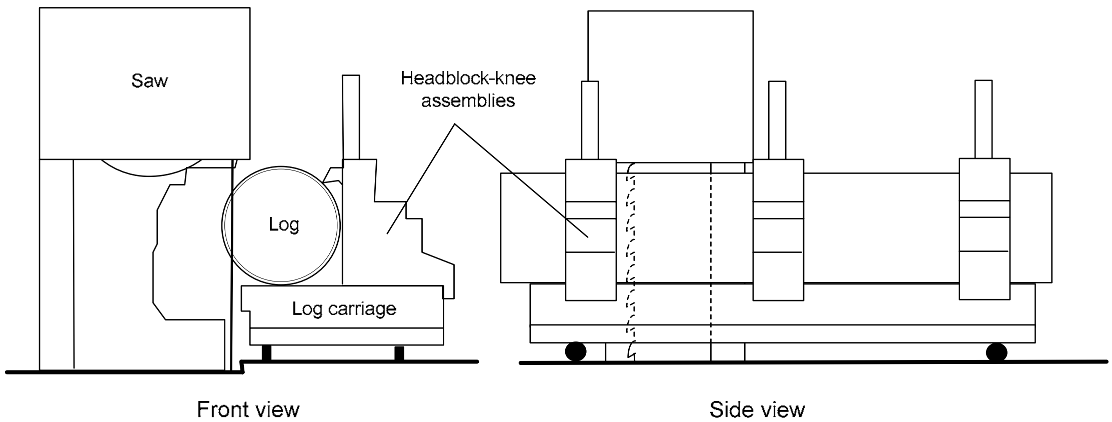


Figure II-5. Diagram of a hypothetical headrig machine center

The typical sawing procedure at the headrig for the large volume sawmill was to saw four faces on each log before sending the log to the band resaw, which is the next operation in log breakdown. Depending on the size of the log one or two boards may be produced during the four siding process. Because a number of different activities must occur to make one board, the activities had to be timed separately to accurately model this machine center. The main activities that occur at the headrig are:

1. Loading and positioning the log on the carriage
2. Move the carriage forward to the saw
3. The actual sawing process of the log passing through the saw
4. Returning the carriage to set up for a cut without rotating the log
5. Returning the carriage to the original log loading position
6. Rotating the log 90° or 180°
7. Unloading the log onto the headrig conveyor
8. Returning carriage to the original position after unloading the log onto the headrig conveyor

Each of these activities was timed individually on separate red oak logs varying in length between eight and sixteen feet. The number of timing measurements recorded for each activity at the headrig machine center is summarized in Table II-2. The number of timing measurements collected was dependant upon the perceived variability in total elapsed time of each activity and the time constraints of collecting the data.

Table II-2. Number of timing measurements collected for each activity of the headrig machine center at the large volume sawmill

Activity	**Number of timing measurements**
Loading and positioning the log on the carriage	145
Move the carriage forward to the saw	168
The actual sawing process of the log passing through the saw	26
Returning the carriage to set up for a cut without rotating the log	20
Returning the carriage to the original log loading position	20
Rotating the log 90° or 180°	124
Unloading the log onto the headrig conveyor	20
Returning the carriage to the original position after unloading the log on the headrig conveyor	65

The timing procedure for the *loading and positioning log activity*, referred to in Table II-2, began when a log was loaded onto the carriage, and ended when the carriage began to move forward. For the *move carriage forward toward saw activity*, timing began when the log was completely loaded onto the carriage and the carriage moved forward. This timing sequence ended when the log entered the saw. The *sawing activity* was timed from when the saw entered the log until the saw had exited the log. Times for the *sawing activity* included the elapsed time when sawing slabs and boards. Timings for the *returning the carriage to set up a cut without rotating log activity*, began when the saw had exited the log and ended when the carriage began moving towards the saw for the next cut. The timing for the *returning the carriage to the original log loading position activity* began when the log exited the saw. This timing sequence ended when the carriage came to a complete stop at the original log loading position. The timing of the *rotating the log 90° or 180° activity* began when the log turner was activated and ended when the carriage began moving towards the saw. At the end of the sawing process, the remaining portion of a log is unloaded unto the headrig conveyor. The *unloading the log onto the headrig conveyor activity* was timed from when the headblock-knee assemblies on the carriage began pushing the log off the carriage and ended when the log was on the headrig conveyor. Once the log is on the headrig conveyor and is in route to the band resaw, the carriage is returned to the original log loading position and the entire log sawing process at the headrig starts again. Timing for the *return carriage to original position after unloading the log on the headrig conveyor activity* began when the carriage started moving back to the original log loading position and ended when the carriage had returned to the original log loading position.

As with debarking process, material handling problems were evident at the headrig and were included in the processing times, if the delays were not greater than one minute or due to mechanical breakdowns. In addition to the timing measurements described above, an additional 70 timing measurements were collected at the headrig machine center. These additional 70 timings recorded the total cycle time of a log being processed at the headrig. The cycle times encompassed the total elapsed time from when a log was loaded onto the carriage to when it was unloaded onto the headrig conveyor. The headrig cycle times were collected from red oak logs varying in length between eight and sixteen feet with diameters ranging from twelve to twenty inches. This information was subsequently used to validate the model logic of the headrig machine center. A description of the logic used to model the headrig is presented in SECTION III.5 and a description of the model validation procedure is located in SECTION III.16.2.

2.3.1.3. Band resaw machine center

In comparison to the headrig, the band resaw machine center is a much simpler machine center in terms of the number of activities that occur. To accurately model this machine center, *log sawing time* was the only activity considered. The process of measuring the *log sawing time* at the band resaw began when the log entered the saw and ended when the log exited the saw. A total of 47 timing measurements were recorded using red oak logs between eight and sixteen feet in length.

The velocity and length of the conveyors that brought material to the band resaw and the cant positioner machine center, located before the band resaw were other factors that were observed to affect the production rate of the band resaw machine center. A detailed description of how the velocity and length of the conveyors were measured is discussed in SECTION II.2.5. Material handling was also observed to be a problem at the band resaw machine center, but the delays due to material handling errors were not included in the timing measurements of the sawing process. Instead, the delays caused by material handling errors at the band resaw machine center were classified as unscheduled downtime. The classification of material handling delays at the band resaw machine center, as unscheduled downtime was done because when material handling delays occurred they drastically slowed down the band resaw operation.

2.3.1.4. Cant positioner machine center

The purpose of the cant positioner machine center is to rotate the logs 180° or 90° on the band resaw carousel conveyor so that the side (face) of the log with the largest amount of clear material is facing the band resaw. The band resaw carousel conveyor is a large circular conveyor made up of four smaller conveyors that continuously transports logs to the band resaw station. The activity that the cant positioner machine center performs aids in maximizing the efficiency of the band resaw operation. By not having to rotate the logs, the operator of the band resaw has one less activity to perform which can help to decrease the cycle time of logs at the band resaw.

A total of 105 timing measurements were collected at the cant positioner machine center. The timing measurements encompassed the total elapsed time required to rotate an individual log either 90° or 180°. In addition, unscheduled downtime at the cant positioner machine center was recorded, which was for the most part caused by the conveyor chains coming off the tracks.

2.3.1.5. Gangsaw machine center

The two main activities that occur at the gangsaw include:

1. Aligning a log with the saws,
2. The actual processing of the log.

The timing of the processing activities of the gangsaw machine center began when the gangsaw operator unloaded a single log from the conveyor preceding the gangsaw. Timing stopped when the second feed roller on the out feed side of the gangsaw was lowered. The processing times for 159 red oak logs varying in length between eight and sixteen feet were sampled.

Although two activities occur at the gangsaw machine center, it was not as important to record the time for each activity as was done at the headrig. This is due, in part, to the fact multiple boards are produced simultaneously at the gangsaw. At the headrig machine center, multiple boards can be produced but a number of activities occur between the sawing of a board.

Of the machine centers modeled, the gangsaw had the least amount of delays due to material handling problems. The main interruption at this machine center was due to routine maintenance that the operator had to perform on the machine several times daily. For the most part, the operator was able to schedule this routine maintenance when there were no logs available to be processed or when there was enough space available on an overflow conveyor to store logs.

2.3.1.6. Edger machine center

The edger at the large volume sawmill was an optimizing edger that utilized visual scanning technology to determine the optimal amount of wane to be removed from each board. The edger required minimal human input to do the actual edging but did require an operator to control a system of conveyors that moved boards to the edger machine center. It was the operator's responsibility to ensure that each board was wane side up before being scanned by the edger optimizer. The operator would also occasionally have to adjust settings to the computer program to compensate for extremely large or misshapen pieces of lumber.

The processing times of twenty-four pieces of red oak lumber varying in length between eight and twelve feet were sampled. The timing began when an individual piece of lumber was seized by a set of mechanical clamps. Timing stopped when the board first appeared from the out feed side of the edger. As with the band resaw machine center, the velocity and holding capacities of the conveyors before and after the edger machine center were important factors in accurately modeling the edger machine center.

There were few observed failures or delays during the timing of the defined process activity at the edger. Mechanical failures appeared to be very minimal at this machine center but material handling problems were quite evident. The majority of delays at the edger machine center occurred due to the operator of the edger having to manually align pieces of lumber correctly on the edger conveyor, prior to being feed into the edger. These delays were classified as unscheduled downtime for the edger machine center.

2.3.1.7. Trimmer machine center

The processing of lumber at the trimmer machine center was observed to be determined by the speed at which the operator was able to properly align boards on the conveyor leading to the trim saws. Once properly aligned on the conveyor, boards were passed through the trim saws at a constant rate. Therefore, the processing function at this machine center was based upon the elapsed time an operator spent handling individual boards. Twenty-five timings were recorded of the time it took the operator to align pieces of red oak lumber. It was also observed that some boards did not have to be aligned and were not handled by the trimmer operator. The percent of boards that did not have to be handled by the operator was estimated to be five percent. Unscheduled downtime at the trimmer was observed to be caused by:

1. The lumber inspectors downstream from the trimmer signaling for the trimming operation to be stopped.
2. Lumber jammed at the out feed of the trimmer.
3. The trimmer operator having to unscramble lumber at several conveyors leading up to the trimmer machine center.

2.3.1.8. Lumber inspectors

The inspection and grading of lumber at the large volume sawmill is done by two personnel without the assistance of any mechanical equipment such as an automatic board flipper. Twenty-two timing measurements were collected from the two lumber inspectors. The timing measurements encompassed the total time that it took an inspector to flip a board and write a symbol on the board that identified the lumber grade.

Downtime and failure data was not collected for the lumber inspection process because interruptions in this process were observed to not affect the majority of machine centers at the sawmill. It was however observed that the rate at which the trimmer processed boards sometimes exceeded the rate and capacity of the inspectors to grade the lumber. In the actual system, when the capacity and rate of the inspection process was exceeded the operator of the trimmer machine center was signaled to halt the trimming process, until the inspectors had processed the extra capacity. The capacity of the lumber inspectors was observed to be correlated to the number of boards on the green chain between the trimmer station and where the lumber inspectors were located. A description of how this interaction was modeled is described in more detail in SECTION III.10.

2.3.2. Medium volume sawmill

To avoid the redundancy of describing the same machine centers used in the large volume sawmill, the descriptions of the machine centers present in the medium volume sawmill will be abbreviated and only differences in the definitions of the processing functions will be highlighted. As illustrated in Figure II-6, the medium volume sawmill does not utilize a band resaw or a cant positioner, and has fewer conveyors.

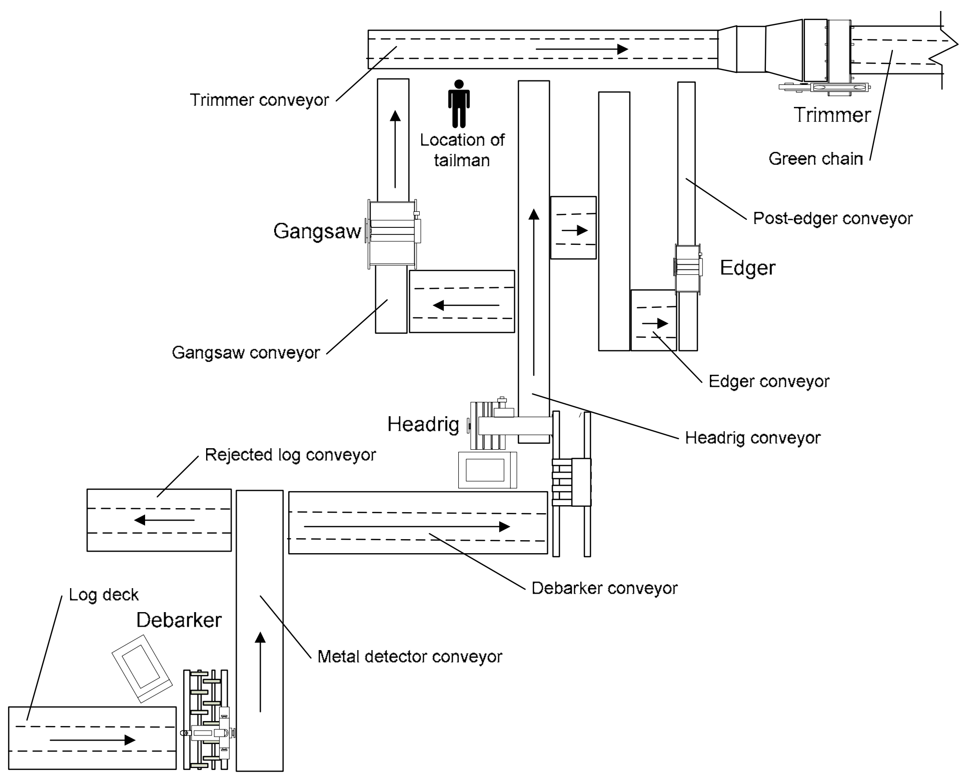


Figure II-6. Machine and conveyor layout at the medium volume sawmill Machine and conveyor layout at the medium volume sawmill

2.3.2.1. Debarker machine center

The debarker was of the same type as found at the large volume sawmill and there was no difference in the manner of determining starting and ending points of the timing process. Unlike the debarker at the large volume sawmill, unscheduled downtimes for the debarker at the medium volume sawmill occurred more randomly and were due in large part to trivial mechanical problems. The number of data points used to assess processing time consisted of 39 red oak logs varying in length between eight and fourteen feet.

2.3.2.2. Headrig machine center

In regards to headrig operation, the main difference between the two sawmills was that at the medium volume sawmill only two clear sides of a log were sawn as opposed to four. However, on large size logs with scaling diameters of 19 inches and greater, the headrig operator would saw four sides of the log in order to match the dimensional limitations of the gangsaw. The activities that occurred at the headrig machine of the medium volume sawmill were:

1. Loading and positioning the log on the carriage
2. Move the carriage forward to the saw
3. The actual sawing process of the log passing through the saw
4. Returning the carriage to set up for a cut without rotating log
5. Returning the carriage to the original log loading position
6. Rotating the log 180°
7. Unloading the log onto the headrig conveyor

8. Returning the carriage to the original position after unloading the log onto the headrig conveyor

The timing measurements for each of the above activities were taken from red oak logs varying in length between eight and fourteen feet in length and of various diameters. Procedures for collecting the timing data was the same as outlined in SECTION II.2.3.1.2 for the collection of timing data relevant to the large volume sawmill. The number of timing measurements recorded for each activity at the headrig machine center is summarized in Table II-3.

Table II-3. Number of timing measurements collected for each activity of the headrig machine center at the medium volume sawmill

Activity	**Number of timing measurements**
Loading and positioning the log on the carriage	44
The actual sawing process of the log passing through the saw	44
Returning the carriage to set up for a cut without rotating the log	44
Returning the carriage to the original log loading position	42
Rotating the log 180°	44
Unloading the log onto the headrig conveyor	8
Returning the carriage to the original position after unloading the log on the headrig conveyor	42

In error, the activity of *moving the carriage towards the saw* was not timed. To compensate for this error the data from the timings recorded for the *return carriage to original log loading position* activity was used in place of the missing dataset. Through the model validation procedure, described in SECTION IV.14.2, this error was found to be inconsequential.

2.3.2.3. Gangsaw machine center

The gangsaw operator at the medium volume sawmill was required to manually handle each log, unlike the operator at the larger sawmill who had the benefit of electrically powered positioning conveyors. However, the timing procedure remained similar. Timing began when the operator would manually load and position the cant on the infeed conveyor of the gangsaw. The timing would stop when the second feed roller on the outfeed of the gangsaw dropped down. A total of 126 timing measurements were taken from red oak logs ranging in length from eight to twelve feet.

The majority of unscheduled downtime occurrences at the gangsaw machine center were due to the gangsaw operator having to leave his station and walk approximately fifteen yards to maintain the flow of materials to the chipper. A chipper machine center is used to convert unusable wood; slabs, edgings, and trimmings into small wood chips. These delays occurred randomly and along with other observed delays were later used as unscheduled downtime statistics for the gangsaw machine center. Other types of delays included the operator having to replace belts that had fallen off rollers, aligning logs on the log storage conveyor preceding the gangsaw, and waiting for the tailman to clear debris out of the gangsaw. Tailman is a term used for sawmill personnel who manually handle lumber for the purpose of maintaining an efficient flow of materials through a sawmill. In most instances, when the gangsaw operator had a delay or breakdown, the tailman would have to stop one of the conveyors leading to the trimmer and assist the gangsaw operator. This phenomenon was modeled in the simulation model.

2.3.2.4. Edger machine center

The edger at the medium volume sawmill did have the same type of automation as the large volume sawmill. The decision of how much wane to remove from each board was made by one operator. Lumber also had to be manually moved from a conveyor and then be fed into the edger. The specific activities that occurred at the edger, in sequence, were:

1. Manual placement of an individual board on the infeed rollers of the edger
2. Adjustment of the location of the floating saw on the arbor of the edger
3. Feeding an individual board into the edger

The elapsed time it took for the edger operator to perform the above three activities was recorded for 49 red oak boards ranging in length from six to fourteen feet in length. Failures at this machine center were not able to be recorded because they occurred infrequently. The method of how failures and downtime at this machine center was modeled is discussed in SECTION IV.7.

2.3.2.5. Trimmer machine center

The trimmer at the medium volume sawmill operated in approximately the same manner as the one at the larger sawmill. The types of delays also were similar. The number of data points used to assess processing time consisted of 23 pieces of red oak lumber ranging in length between eight and sixteen feet.

2.4. Measuring scheduled and unscheduled machine downtime

At both of the sawmills studied, scheduled and unscheduled downtimes occurred at the machine centers. The scheduled downtimes occurred in fifteen and thirty-minute time intervals, at fixed frequencies. Information on the frequency and duration of the scheduled breaks was able to be collected from sawmill personnel. Because neither of the sawmills kept accurate records of unscheduled machine downtime, the frequency and duration of unscheduled downtime was directly measured at the machine centers.

The procedure used to measure unscheduled downtime of the sawmill machine centers was identical between both of the sawmills studied. The frequency of unscheduled machine downtime was quantified based upon the number of items, logs or lumber, that were processed before an instance of unscheduled downtime occurred.

Duration of the unscheduled downtime was measured with a stopwatch, starting when an instance of unscheduled downtime occurred and stopping when the respective machine center process resumed. The steps of analyzing the frequency and duration of the unscheduled downtime timings are detailed in SECTION II.3.3. The number of unscheduled downtime measurements collected at the machine center, for the large and medium volume sawmills, are presented in Table II-4, and Table II-5 respectively.

Table II-4. Number of unscheduled downtime measurements collected at the large volume machine center by machine center

Machine center	Number of measurements
Debarker	5
Headrig	4
Band resaw	14
Cant positioner	5
Gangsaw	0
Edger	16
Trimmer	9

Table II-5. Number of unscheduled downtime measurements collected at the medium volume sawmill by machine center

Machine center	Number of measurements
Debarker	5
Headrig	4
Gangsaw	10
Edger	0
Trimmer	15

The edger machine center at the medium volume sawmill and the gangsaw machine center at the large volume sawmill did not have any unscheduled downtime during the time period when the unscheduled downtime statistics were being collected. As a result, no unscheduled downtime information was collected. Despite the absence of downtime data for two machine centers, all of the machine centers were assigned specific downtime statistics in the simulation models. The procedures used to generate the unknown downtime statistics are outlined in SECTION III.14 and SECTION IV.12.

2.5. Measuring the velocity and capacity of conveyors

In both of the sawmills studied, movement of logs and lumber between machine centers was done using a series of conveyors. Figure II-7 illustrates the three types of conveyors used in the large and medium volume sawmills. Conveyors that move material perpendicular to the material's length are referred to as chain conveyors. Roller conveyors carry logs and lumber parallel to the length dimensions. Both chain and roller type conveyors are designed to move multiple boards simultaneously. Lug-type conveyors however, are designed to regulate the number of items that are being conveyed from one area to another. Typically, lug-type conveyors are located before machine centers where it is necessary to evaluate each item individually. These machine centers include trimmers, edgers, and the beginning of green chains. For the three types of conveyors, the speed rate does vary between conveyors, but when active the conveyors move at a constant rate. In addition, many of the conveyors are not always active and simply accumulate and hold material until the material is needed.

The speed of all the conveyors, regardless of type or design, was estimated by timing how long it took an individual item to travel a certain distance. Approximately 20 timings were done for each conveyor. Average foot per minute speed rates for the conveyors were calculated by dividing the distance an item traveled over the time it took the material to travel between two locations. The calculated average foot per minute rate, was then used as the velocity rate of the each respective conveyor.

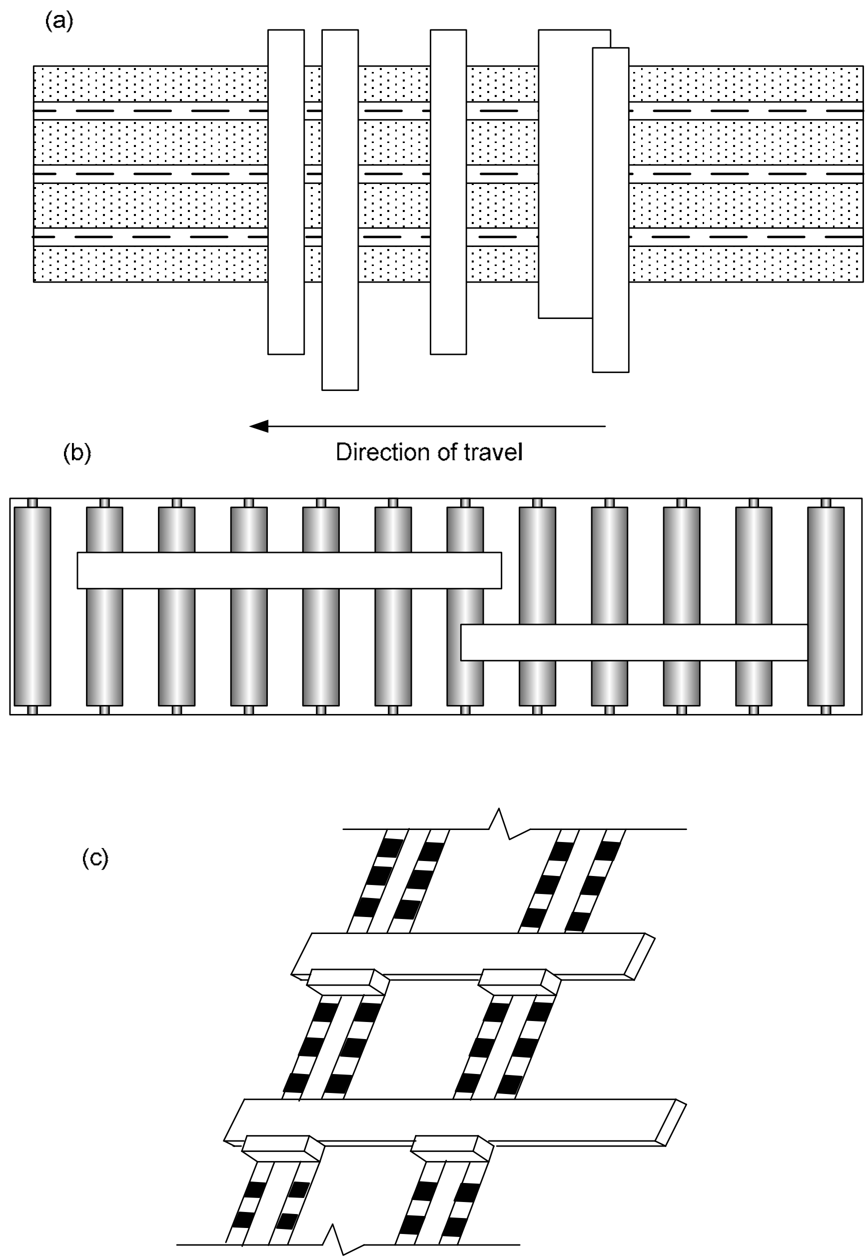


Figure II-7. Examples of sawmill conveyors that transport lumber perpendicular to the lengthwise section (a), parallel the lengthwise section (b), and a lug-type conveyor (c)

The capacity of the individual conveyors was observed to be largely dependant upon the physical size of the material that is moved on the conveyor and the conveyor type. However, it was also observed that some conveyors were kept below maximum capacity as dictated or controlled by operators of the machine centers. Because of this, the capacity levels of the conveyors was measured largely in part by observing how many items could occupy a conveyor when at maximum capacity and also what the typical or preferred capacity was. For lug-type conveyors, capacity was determined by observing the number of boards that could fit into each individual lug. The total number of lugs on the conveyor then determined how many boards could fit into this type of conveyor. In addition, it was also observed what factors or actions caused the individual conveyors to be deactivated or activated.

2.6. Transporters

Along with conveyors, humans also are used to move lumber in hardwood sawmill systems. The green chain is where the majority of lumber is manually transported. Another area where lumber is moved manually is at the tailman position, located at the outfeed of the gangsaw. The task of the green chain employees, termed stackers, is to separate the lumber into packs that are organized by lumber grade, length and thickness. It was observed that the stackers on average only handle one board at a time. Because the green chain does not stop when the lumber is offloaded, instances do occur when the stacker cannot keep up with the pace of the green chain. In these cases the green chain is temporarily stopped. Depending on the duration of time, the green chain is inactive, processes upstream such as lumber grading and trimming may also have to be stopped.

Transporters in the simulation models required a velocity rate to model the time required to transport items between the various machine centers. An estimate of the velocity rate for the lumber stackers at one of the sawmills was made by first recording the time required for a stacker to offload and place a piece of lumber into a pack of lumber. A total of eight timing measurements were collected. The average time value was then divided by the distance between the green chain and the lumber pack to calculate the average velocity of a lumber stacker. This value was used in the simulation models as the velocity of all lumber stackers for both sawmills.

The second type of transporters used in hardwood systems are front-end loaders. Front-end loaders are used to transport logs around the log yard. In particular, the front-end loader is responsible for supplying logs to the debarker. The number of logs the front-end loaders could transport was similar between both sawmills. However, the tasks that the front-end loaders had to perform were different.

The loader operator at the medium volume sawmill could only place three logs at a time on the conveyor leading to the debarker, due to the setup of the conveyor. Because of this loading limitation, the loader operator used a staging area for logs. The loader operator would transport 10 logs approximately fifty yards from a main log pile to the staging area. The loader operator would then transport three logs approximately five yards from the staging area to the log deck. The loader operator at the large sawmill did not have to build a staging area and was able to simply transport logs from the main log pile directly to the log deck. The distance from the main log pile to the debarker conveyor at the large sawmill was approximately eighty to 100 yards.

The velocity of both front-end loaders was determined using land speed specifications for a John Deere 644J front-end loader, which is similar in size to the front-end loaders used by both of the sawmills studied. Based upon the specifications for the John Deere 644J front-end loader, the average velocity rate for the loaders at both sawmills was estimated to be 495 ft/min or 5.6 miles/hour (Deere and Company 2004).

3. Data analysis

This section describes how the data collected from the sawmills was analyzed, for input into the simulation models. The statistical approach to analyzing the lumber yield from the sawmill machine centers was based upon the published work of Meimban (1991). Analysis of the machine center processing data and unscheduled downtime data followed guidelines outlined in the publications of Law and Kelton (1991) and Kelton et al. (2004)

3.1. Lumber yield from sawmill machine centers

The goal of the analysis was to be able to predict lumber grade and volume yield from the logs sampled at the sawmills. It was also desired that the material flow patterns of the logs sampled could be predicted. This was accomplished by:

1. Grouping the logs into one inch scaling diameter categories by log grade and length.
2. For each log group, cumulative density functions (CDF) were constructed to predict:
    a. Distribution of lumber grade yield by machine center
    b. Lumber volume based upon lumber grade
    c. Material flow patterns based upon lumber volume and lumber grade

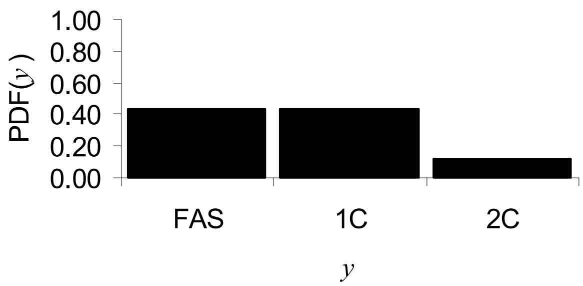
The information collected from three, eighteen-inch logs of identical grade and length classification will be used as an example of how lumber grade yield, lumber volume yield, and material flow probabilities were calculated for the band resaw machine center. The material flow probabilities are in relation to predicting which boards will be sent directly to the trimmer and which are routed to the edger.

In Table II-6 the grade and volume of each board that was sawn from three logs at the band resaw is presented. All of the volume figures represent the volume of nominal 1-inch thick lumber. The first step was to combine both columns of data in Table II-6 and calculate the probability density function (PDF) statistics of the grade lumber that was produced. This was done using the computer program JMPIN Ver. 4.0.4 distributed by SAS Institute Inc. (Sall et al. 2001). For this example, the JPMIN `Distribution` programming script was used to calculate the PDF statistics of the lumber grades produced from three eighteen-inch logs of identical grade and length classification (Sall et al. 2001). The PDF statistics calculated by the JPMIN software is presented in Figure II-8.

Table II-6. Grade and volume of boards that were sent to either the edger or trimmer

Grade and volume of boards sent to the edger [A]	**Grade and volume of boards sent directly to the trimmer**
FAS (6)	FAS (8)
FAS (6)	FAS (8)
FAS (13)	FAS (8)
FAS (12)	FAS (9)
FAS (15)	FAS (10)
1C (6)	FAS (10)
1C (7)	FAS (11)
1C (9)	FAS (13)
1C (11)	FAS (13)
1C (11)	1C (10)
1C (13)	1C (10)
2C (6)	1C (10)
2C (7)	1C (12)
2C (9)	1C (12)
	1C (12)
	1C (12)
	1C (12)
	2C (9)

[A]Values in parenthesis are lumber volume values in bd.ft.



y	Count	$p_Y(y)$
FAS	14	0.43750
1C	14	0.43750
2C	4	0.12500
Total	32	1

Figure II-8. Probability density function (PDF) statistics calculated by the JPMIN software

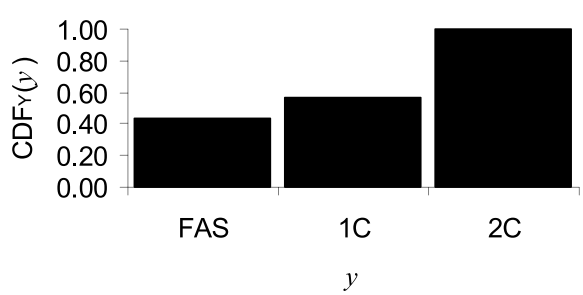
Interpretation of Figure II-8 is that of the lumber produced at the band resaw, from an eighteen-inch diameter log of a particular grade and length classification, 43.7 percent will be FAS, 43.7 percent will be 1C, and 12.5 percent will be 2C. Cumulative distribution function statistics were then constructed with the PDF information, by use of Equation II-2. The CDF statistics of each lumber grade relevant to this example dataset are presented in Figure II-9.

$$CDF_Y(y) = P(Y \leq y) = \sum p_Y(k) \text{, sum over } k \leq y \qquad \textbf{Equation II-2}$$

where:

y = the k^{th} lumber grade

Y = the outcome of a single draw



y	$p_Y(y)$	$CDF_Y(y)$
FAS	0.43750	0.43750
1C	0.43750	0.5625
2C	0.12500	1

Figure II-9. Cumulative density function (CDF) statistics for each lumber grade

The same procedure as described above was used to construct CDF statistics correlating lumber volume attributes to the individual lumber grades. Correlating lumber volume to lumber grade is necessary to accurately model the process of sawing lumber from logs, if information on lumber volume is of interest (Meimban 1991). Randomly assigning volume attributes to the lumber, without regards for lumber grade would have been ignoring the direct relationship between the quality or grade of a board and its position relative to the center or core of a log (Malcolm 2000). In addition, the direct relationship between the volume of a board and its position relative to the center of a log also must be accounted for (Meimban 1991).

To illustrate how the lumber volume and lumber grade relationship was quantified, Table II-7 contains CDF statistics that were calculated using Equation II-2 from the values in Table II-6. The CDF statistics in Table II-7 are the cumulative probability values that a specific lumber grade will produce a board with a volume of y.

Table II-7. Cumulative density statistics for lumber volumes by lumber grade

Lumber grade								
FAS			**1C**			**2C**		
y^A	$p_Y(y)$	$CDF_Y(y)$	y^A	$p_Y(y)$	$CDF_Y(y)$	y^A	$p_Y(y)$	$CDF_Y(y)$
6	0.133	0.133	6	0.067	0.067	6	0.250	0.250
8	0.217	0.350	7	0.066	0.133	7	0.250	0.500
9	0.083	0.433	9	0.084	0.217	9	0.500	1
10	0.134	0.567	10	0.216	0.433			
11	0.066	0.633	12	0.484	0.917			
12	0.067	0.700	13	0.083	1			
13	0.233	0.933						
15	0.067	1						

[A] y = lumber volume in bd.ft.

Table II-8, illustrates how material flow probabilities were calculated and contains the same information from Table II-6, but the values have been sorted by lumber grade and material flow pattern.

Table II-8. Grade and volume of boards that were sent to either the edger or trimmer separated by grade and arranged in increasing numerical order by volume

Grade and volume of boards sent to the edger[A]			**Grade and volume of boards sent directly to the trimmer**		
FAS (6)	1C (6)	2C (6)	FAS (8)	1C (10)	2C (9)
FAS (6)	1C (7)	2C (7)	FAS (8)	1C (10)	
FAS (12)	1C (9)	2C (9)	FAS (8)	1C (10)	
FAS (13)	1C (11)		FAS (9)	1C (12)	
FAS (15)	1C (11)		FAS (10)	1C (12)	
	1C (13)		FAS (10)	1C (12)	
			FAS (11)	1C (12)	
			FAS (13)	1C (12)	
			FAS (13)		

[A]Values in parentheses are lumber volume values in bd.ft.

From Table II-8 it is evident that boards of the FAS grade with volumes of 6, 12, and 15 board feet in this instance were all sent to the edger from the band resaw. Likewise, boards of the FAS grade that had volumes of 8, 9, 10, and 11 board feet were all routed directly to the trimmer. However, two 13 board foot FAS grade boards were sent directly to the trimmer and one board with the same grade and volume was sent to the edger. Therefore, for this dataset, the material flow analysis reveals that 66.7 percent of 13 bd.ft. FAS boards will be sent directly to the trimmer and 33.3 percent of these boards will be routed to the edger from the band resaw.

The analysis procedures described in this section were used to evaluate all of the logs sampled from both of the sawmills. How the results of these analyses were used in the development of the simulation models, is detailed in SECTION III and SECTION IV.

3.2. Machine center processing times

Probability distributions for the processing times were generated using the Input Analyzer software (Version 7.01.00) by the Rockwell Software company (Rockwell Software Inc. 2002). The Input Analyzer software is able to fit a distribution to raw data, estimate a distribution's parameters, and test the distribution's fit using the chi-square and Kolmogorov-Smirnov (K-S) goodness-of-fit hypothesis tests (Kelton et al. 2004).

For each dataset, the Input Analyzer software generated multiple probability distributions. The fit of each probability distribution was evaluated by using the distribution's mean square error and the K-S goodness-of-fit test. The distribution with the lowest mean square error value was used in the simulation model. Benefits of using the K-S goodness-of-fit test over the chi-square method are that small sample sizes are valid, and the raw data does not have to be placed in class intervals (Law and Kelton 1991). In addition, the K-S test is recommended when evaluating the fit of distributions for non-integer data, which was characteristic of the processing time data (Rockwell Software Inc. 2002). The probability distributions as calculated by the ARENA Input Analyzer for each machine center, by sawmill, are presented in the Appendix sections under Table IX-1 and Table IX-9.

3.3. Unscheduled machine downtime

As discussed in SECTION II.2.4, the frequency of unscheduled downtime for each machine center was quantified based upon the number of items, logs or lumber, that were processed before an unscheduled downtime occurred. For all but one of the machine centers, the frequency that unscheduled downtimes occurred was modeled using a Poisson distribution, where the λ parameter was the average number of items processed before a downtime occurred. Initial testing of the simulation models demonstrated that the Poisson distribution produced more realistic values, based upon the information collected, than continuous theoretical distributions.

However, for the debarker machine center at the large volume sawmill, the frequency of unscheduled downtimes was modeled using a Uniform distribution, where the minimum parameter was 25, and the maximum parameter was 30. The majority of unscheduled downtimes at the debarker were due to the operator having to remove barcode tags from the ends of logs, prior to being debarked. Observation of the debarking process illustrated that the barcode tags had to be removed after a certain number of logs were processed. The number of logs or frequency of the unscheduled downtime was quantified to be between 25 and 35 logs. For all of the other machine centers, the frequency of unscheduled downtime was modeled using the Poisson distribution.

The Input Analyzer software was used to fit distributions to the information collected on the duration of unscheduled downtimes for each machine center (Kelton et al. 2004). The same procedure, as described, in SECTION II.3.2 was used to evaluate the fit of the distributions generated by the Input Analyzer software.

4. References

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SECTION III. MODEL LOGIC OF THE LARGE VOLUME SAWMILL

1. Introduction

The description of the simulation model presented in this section was developed from information collected from a hardwood sawmill that produces approximately 35 MMBF of hardwood lumber annually. Based upon the volume of lumber produced annually by this sawmill, it is considered to be a high production sawmill (Bowe et al. 2001, Anonymous 2001). The sawmill is operational 80 hours per week with two fully staffed work shifts. For the simulation model of this sawmill, only the day shift was modeled. Red oak lumber produced at this sawmill was sorted into five grades: FAS, 1C, 2C, 3A, and 3B. Standard 3 ½ x 6 inch pallet cants are also produced during the production of red oak lumber.

2. Generation of entities

Logs and pieces of lumber were modeled using entities. In the ARENA modeling environment, entities are dynamic objects that move through modules and affect the state of the system (Kelton et al. 2004). Entities were generated by using the *Create*, *Separate,* and *Arrivals* modules. Modules are the building blocks of simulation models and are used to drive the creation, control, and movement of entities (Kelton et al. 2004). More specifically, modules can be classified as either flowchart modules or data modules. Flowchart modules are places or nodes that control how entities move through the model. Additionally, flowchart modules are also used to define the parameters or attributes of entities. Data modules are used as look-up tables where the characteristics of entities and resources are referenced by the flowchart modules. Characteristics such as log grade or downtime statistics for a specific machine center are stored in data modules.

At simulation time zero in the model of the large volume sawmill, a *Create* flowchart module was programmed to generate one set of 20 entities. The 20 entities served as a catalyst for other events to start in the simulation model. These initial 20 entities began the generation of other entities through a *Separate* flowchart module. A *Separate* module can be used to split an existing batch of entities or to replicate entities. The logic of how logs enter the system and were replicated using a *Separate* module is summarized in Figure III-1. In the simulation model, the rate at which other entities were generated by way of the *Separate* module depended on system conditions such as availability of transporters and the current capacity of conveyors. In addition to the *Create* module, six *Arrival* Element modules were used to generate entities at simulation time zero.

Element modules provide access to the SIMAN programming language and can be used when the standard ARENA modules do not provide a needed operation or function (Kelton et al. 2004). The *Arrival* Element module functions much like the *Create* modules, but do not need to be connected to adjacent flowchart modules. In contrast to the *Create* modules, the *Arrival* Element modules offer greater flexibility in determining where entities are generated (i.e. queues). Entities generated by the *Arrival* Element modules were used to model the work in process inventory of logs that are present in the large volume sawmill at the beginning of each workday.

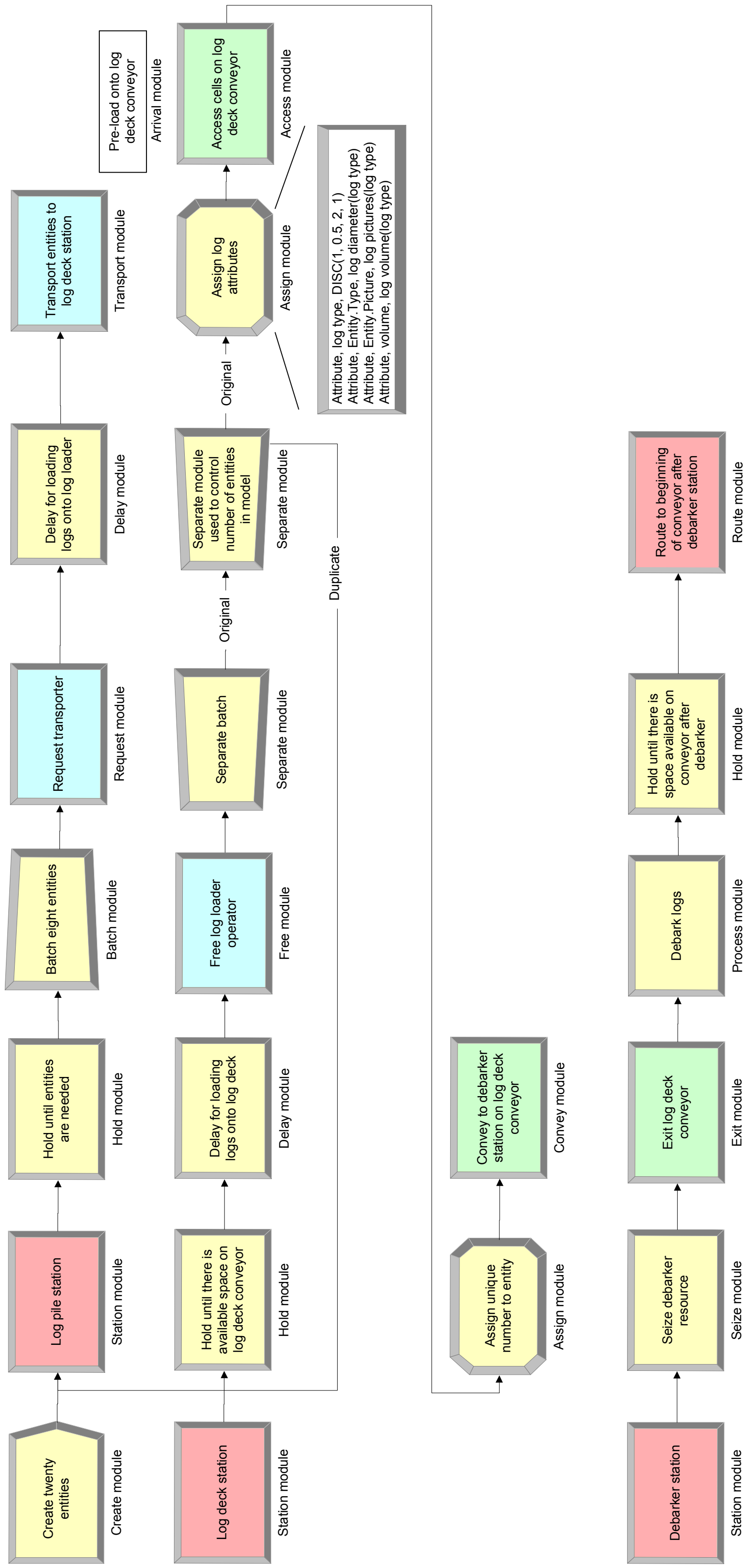

Figure III-1. Model logic illustrating how entities enter the system and were assigned attributes to create logs

3. Creating Logs

Entities representing logs were assigned log type attributes, log diameter attributes, picture attributes, and volume attributes by means of an *Assign* flowchart module. *Assign* modules enable the allocation of specific characteristics or attributes to entities. The attributes assigned to an entity enables differentiating between entities. Attributes are also used to control the movement of entities through a model. When numerous attributes must be assigned, a *Set* data module can be used as a lookup table that is referenced by the value of one or several of the attributes. An example of the data used in the *Assign* modules for allocating diameter and picture attributes to the log type entities is listed in Table III-1 and diagrammed in Figure III-1. The reference that the Set data module uses in assigning the attributes is the value of the log type attribute.

The log type attribute is an integer that identifies the grade, diameter, and length of a log. The value of the log type attribute controls the grade and volume of the lumber that will be produced from the entity. In addition, the log type attribute dictates the material flow patterns of entities.

Log type attributes were assigned using a discrete probability function by an *Assign* module. By manipulating the discrete probability function, the percentage of each log type in the simulation was able to be controlled. Controlling the percentage of each log type in the model enabled examining how the dynamics of the model changes as a function of log diameter, grade, and length parameters.

The attribute values in Table III-1 reference a look-up table in a *Set* data module. An example of members of a *Set* data module is presented in Table III-2.

Entity pictures corresponding to log diameters were designed using Microsoft Visio. Unique entity pictures were used for each log diameter to visually differentiate between entities during simulation animations. The entity pictures facilitated in verifying the simulation model by visually observing how the different entities moved through the model.

Table III-1. Example of the data input into the Assign module used to create entities representing logs

Prompt	Entry
Name	`Assign log types`
Type	`Attribute`
Attribute Name	`Log type`
Value	`DISC(0.33,1,0.66,2,1,3)` [A]
Type	`Attribute`
Attribute Name	`Entity.Type`
Value	`Log diameter(Log type)` [A]
Type	`Attribute`
Attribute Name	`Entity.Picture`
Value	`Log pictures(Log type)` [A]
Type	`Attribute`
Attribute Name	`Volume`
Value	`Log volume(Log type)` [B]

[A] Entries for these prompts reference values in a look-up table. The values in the look-up table are defined in Table III-2
[B] Entries for this prompt reference value in a look-up table. The values in the look-up table are defined in Table III-3

Table III-2. Prompts and entries of the Set module related to assigning log diameter, and log picture attributes

Prompt	Entry
Name	`Log diameter`
Type	`Entity.Type`
Members	`12 diam`
	`13 diam`
	`14 diam`
Name	`Log pictures`
Type	`Entity.Picture`
Members	12 diameter log
	13 diameter log
	14 diameter log

The log volume attribute was assigned to the entities by using an *Expression* data module. An *Expression* data module assigned the appropriate log volume attribute based upon the value of the log type attribute from a look-up table. The *Set* data module was not used to assign volume attributes because *Set* data modules have limitations as to the type of attributes that can be assigned. An *Expression* data module does not have the same limitations. Log volume attributes assigned to the entities were based upon log volume values from the Doyle Log Scale (Martin and Savage 1996). An example of the members of the *Expression* data module used to assign log volume attributes are illustrated in Table III-3.

Table III-3. Prompts and entries for the Expression data module used to assign the log volume attribute

Prompt	Entry
Name	`Log volume`
Expression values	`48`
	`61`
	`75`

4. Debarker logic

Entities arriving at the debarker station first had to seize the debarker resource, by means of a *Seize* module, before an entity could exit the log deck conveyor. The *Seize* module allocated the debarker resource (operator of the debarker) to an entity. If a previous entity had already seized the debarker resource then all following entities remained on the log deck conveyor until the debarker resource was released. This is a modeling technique termed blocking (Kelton et al. 2004). The entities are blocked from proceeding to the next module until the blockage is resolved. Entity blocking was used to model the capacity limitations of the conveyors in the actual system. Figure III-2 illustrates how the *Station*, *Seize*, and *Access* modules were used to invoke the entity blocking technique. A *Station* module defines the physical location of a machine center relative to a conveyor or travel route of a transporter, i.e. a forklift. The *Access* flowchart modules are used to allocate space on a conveyor to an entity and an *Exit* module removes entities from conveyors.

In this instance, the debarker resource must be released, by means of a *Release* module, before the next entity could seize the debarker resource. A *Release* module relinquishes a resource (machine operator) from an entity. The release of the debarker resource was dependant upon the processing time assigned to the process and the availability of space on the conveyor after the debarker station.

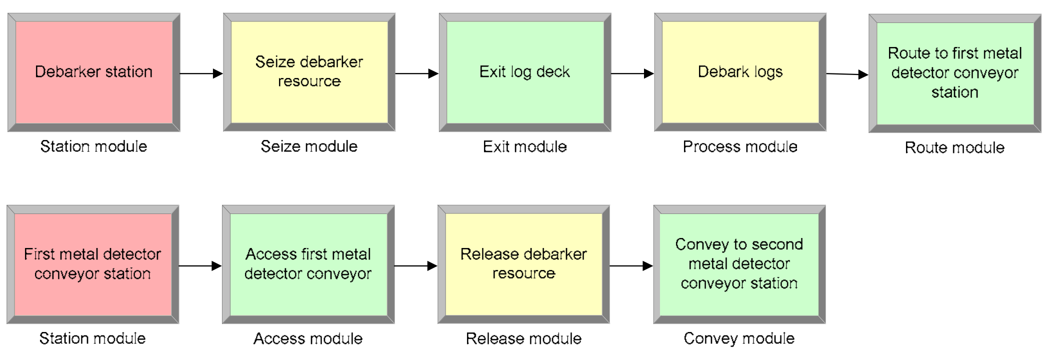

Figure III-2. Example of how the Seize, Release, and Access modules were used to block releasing an entity before there is available space on a conveyor

The *Process* module, in Figure III-2, was used to model the time it takes to debark a log. At *Process* modules and *Delay* modules, entities are impeded from moving to the next module for a specific amount of time. For the model of the large volume sawmill system, the processing time distributions calculated using the procedure described in SECTION II.3.2, determined the amount of time an entity was impeded. The processing time distribution for the debarker resource is defined in

Table IX-1 of Appendix A. From the debarker station, entities move to the headrig station by means of a series of conveyors.

5. Headrig logic

Because of the large amount of individual activities and processing decisions that occur at the headrig machine center, substantially more modules were required to model the headrig machine center, than were used to model the debarker machine center. A general overview of the activities and decisions an operator of the headrig machine center at the large volume sawmill performs are presented in Figure III-3.

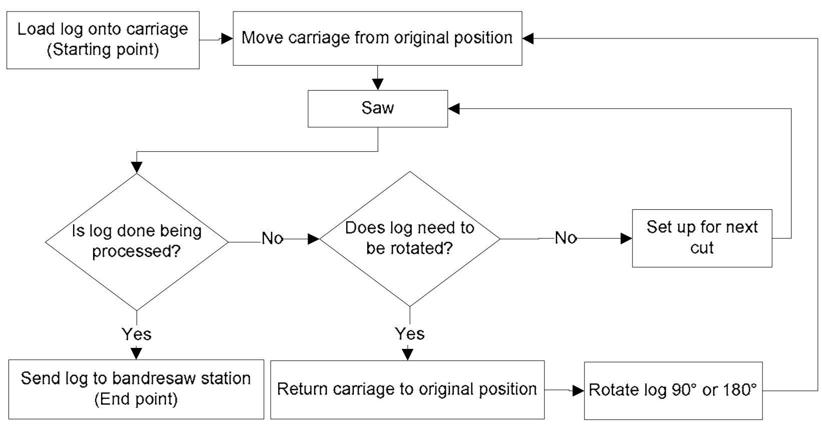

Figure III-3 Activities and decisions that occur at the headrig machine center

As with the debarker station, an entity arriving at the headrig station could not exit the debarker conveyor until the entity was able to seize the headrig resource (sawyer). The debarker conveyor refers to the conveyor that precedes the headrig station and transports debarked logs. When an entity seized the headrig resource, two attributes named “cuts” and “log rotations” were assigned as illustrated in Figure III-4.

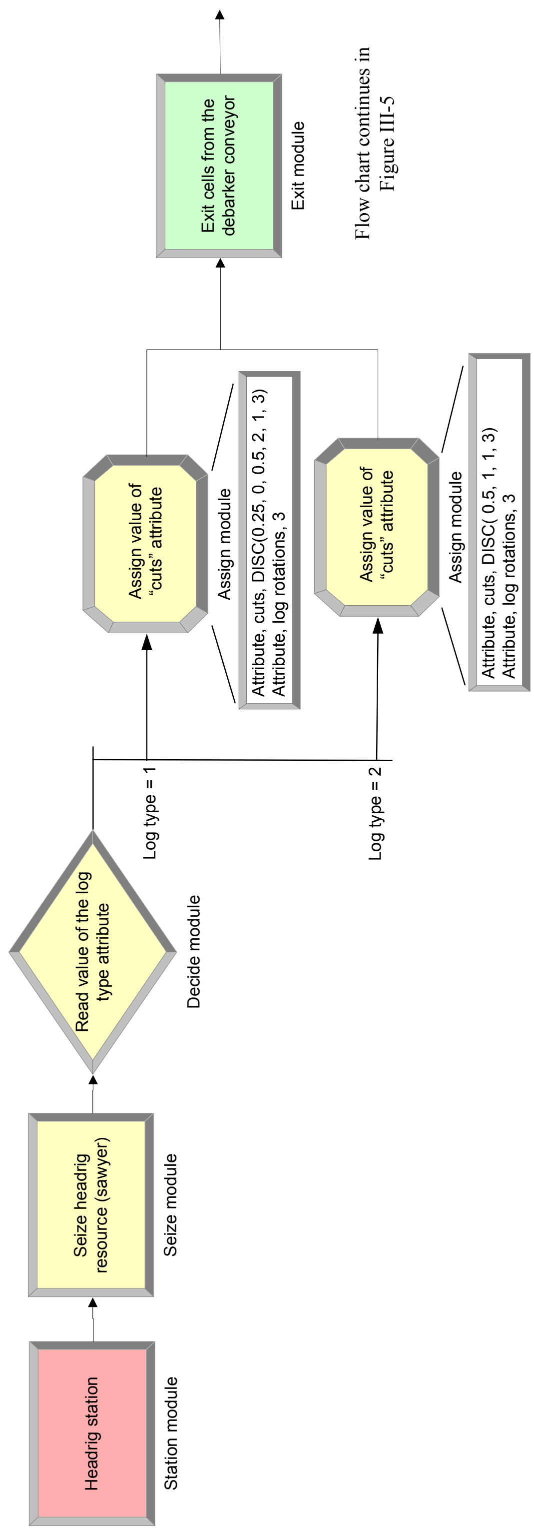

Figure III-4. Illustration of the logic used to assign the "cuts" and "no. of log rotations" attributes

The *Assign* module that the entity was routed to depended upon the value of the “log type” attribute. At the *Assign* module, an attribute named “cuts” was assigned. The “cuts” attribute refers to the number of boards that the log entity will produce. This attribute was assigned using a discrete probability distribution, calculated from the log sampling procedure described in SECTION II.3.1. In addition, a “log rotations” attribute was also assigned to the entity. The “log rotations” attribute referred to the number of times that an entity would be delayed, by the use of a *Delay* module that represented the time required to rotate a log. The “log rotations” attribute was set to a value of three for all entities. In the actual system, logs must be rotated three times so that four faces (sides) of a log can be sawn. Four faces of each log are sawn to create four flat surfaces, which is a requirement for logs to be processed at the band resaw machine center.

After the “log rotations” and “cuts” attribute had been assigned, an entity then passed through two *Delay* modules (Figure III-5). The first *Delay* module represented a log being loaded on the carriage and the second *Delay* module represented the carriage being moved toward the saw blade. The entity then passed through a *Hold* module that retains the entity until less than two entities were accumulated on the headrig conveyor. A *Hold* flowchart module enables stopping the movement of entities through the model logic until specific system conditions become true. The headrig conveyor is the conveyor immediately after the headrig station that transports lumber and logs, which have been four-sided at the headrig.

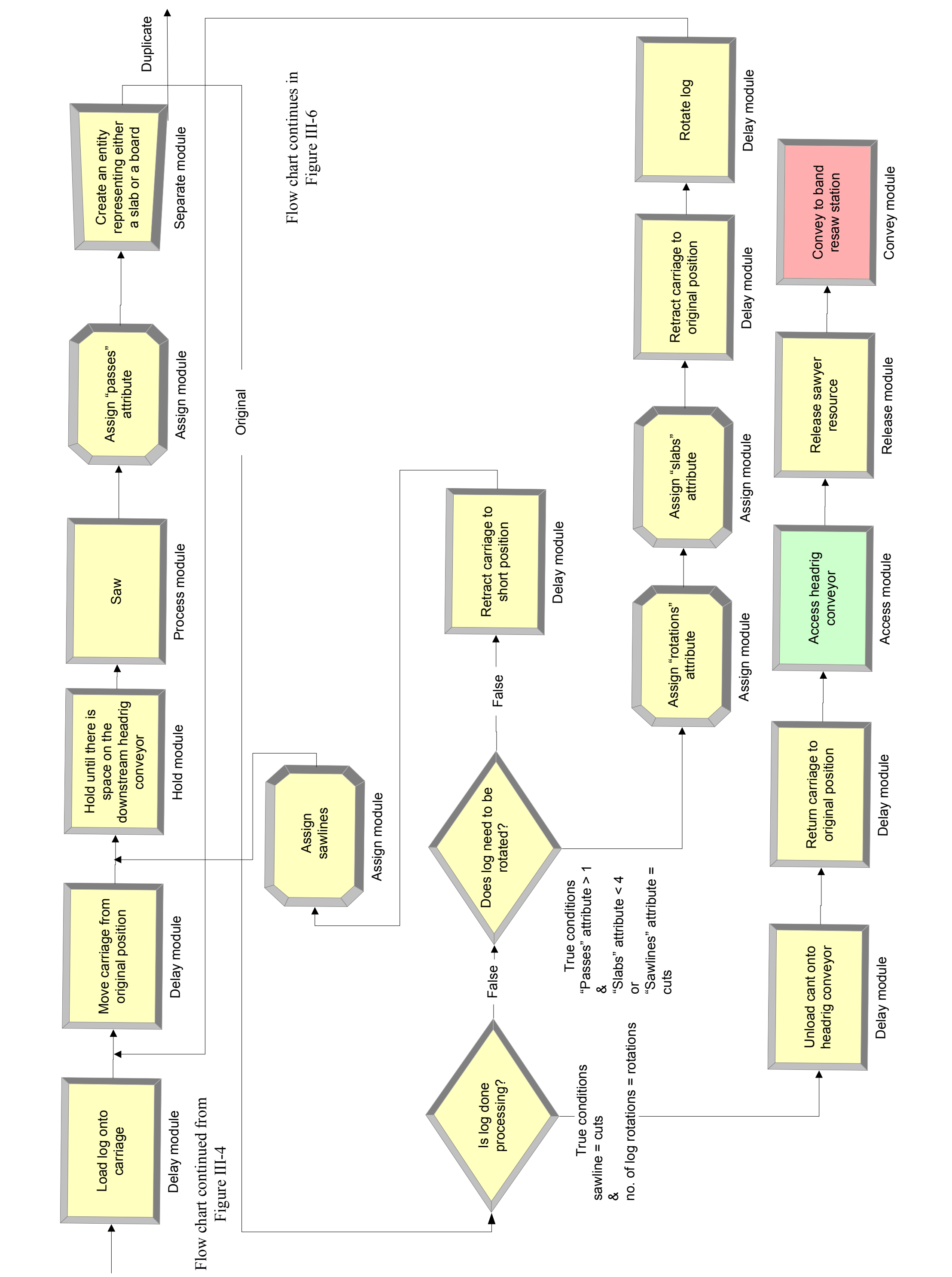

Figure III-5. Logic used to model the operation of the headrig machine center

After the *Hold* module, an entity was then delayed at a *Process* module that represented the amount of time it took a log to travel through the saw blade. Each time an entity passed through the *Process* module it also had to pass through an *Assign* module where an attribute named “passes” was assigned.

The “passes” attribute is an integer value that increased by a value of one each time an entity encountered the “passes” *Assign* module. The “passes” attribute was used by *Decide* modules to determine if duplicated entities should represent a slab or a board (Figure III-6). A *Decide* flowchart module can be used to control where entities move based upon system conditions and entity attributes. At one of the *Decide* modules used to the model the headrig, the “passes” attribute was also evaluated determine if an entity needed to be routed to a *Delay* module that represented the log rotating process. If an entity did go through the log rotation process, the value of the “rotations” attribute was increased by a factor of one. The value of the “rotations” attribute was one variable that determined if an entity exited the group of modules related to the headrig process. The second factor that determined the flow logic at the headrig was the value of the “sawline” attribute, which corresponded to the number of times an entity had gone the *Process* module without going through the log rotation process. The *Process* module represented the log passing through the saw.

After the attribute “passes” had been assigned, an entity was then duplicated by means of a *Separate* module. This duplication procedure represented a slab or board being sawn from a log. Next, the original entity and the duplicated entity were routed in different directions to *Decide* modules (Figure III-6). One *Decide* module evaluated the attributes of the duplicated entity to determine if it should become a board or a slab. The other *Decide* module evaluated the attributes of the original entity to determine if the processing sequence at the headrig station was finished. Conditions that had to be true for a log entity to exit the headrig sawing process were:

1. Value of the “sawline” attribute equaled the value of the “cuts” attribute
2. Value of the “number of log rotations” attribute equaled the value of the “log rotations” attribute

Using a *Decide* module, the value of the “sawline” attribute was used to evaluate if the duplicated entity became a board or a slab. If the duplicated entity had all of the following attribute values, then it was routed to an *Assign* module and was assigned the attributes of a board:

1. “Sawline” attribute value equaled zero,
2. “Slab” attribute value equaled one,
3. “Number of log rotations” attribute value equaled zero

If not all three of these conditions were true then the duplicated entity represented a slab and left the system by way of a *Dispose* module. A *Dispose* flowchart module is how entities exit the boundaries of the simulation model and become inactive (Kelton et al. 2004). This is the only part of the model where the production of waste by-products from the log sawing process was simulated. The volume of slabs produced was not recorded, and was only modeled to accurately replicate the number of processes that occur at the headrig machine center.

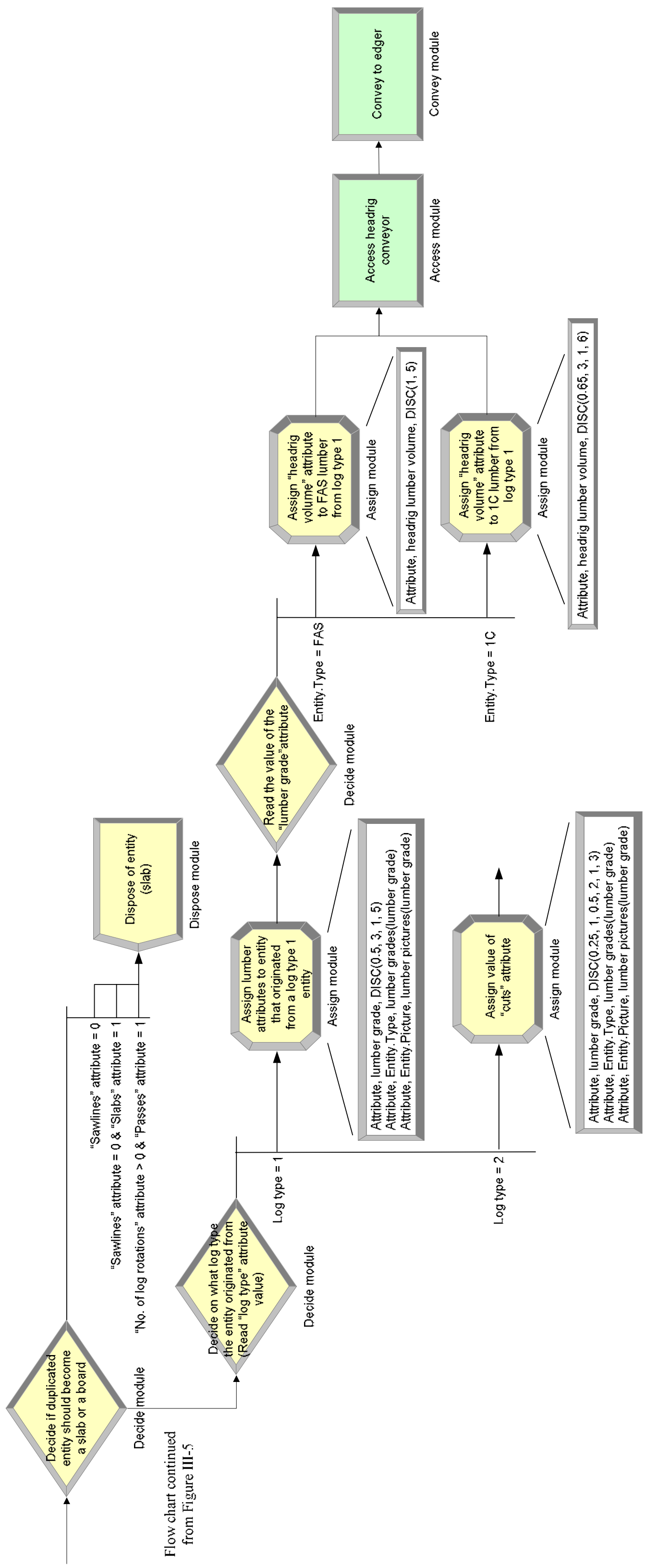

Figure III-6. Logic used to assign lumber volume and lumber grade attributes to entities

Duplicated entities with attribute values that meet the conditions of being a board were routed through a series of *Assign* modules where "lumber grade" and "lumber picture" attributes were assigned. The specific *Assign* module to which an entity was routed depended upon the value of an entity's "log type" attribute value. Lumber grade, and picture attributes were assigned to the entities using a *Set* data module. The logic behind the *Set* data module used for assigning diameter and picture attributes is defined in Table III-4. The corresponding members of the *Set* data module are presented in Table III-5. The "lumber grade" attribute was assigned based upon a discrete probability function relevant to the value of the log type attribute. A description of how this probability statistic was calculated is outlined in SECTION II.3.1.

Table III-4. Example of the data input into the Assign module used to create entities representing boards

Prompt	Entry
Name	`Assign lumber grades for type 1 log`
Type	`Attribute`
Attribute Name	`Lumber grade`
New Value	`DISC(0.25,1,0.5,1,3)` [A]
Type	`Attribute`
Attribute Name	`Entity.Type`
New Value	`Lumber grades(Lumber grade)` [A]
Type	`Attribute`
Attribute Name	`Entity.Picture`
New Value	`Lumber pictures(Lumber grade)` [A]

[A] Entries for these prompts reference values in a look-up table.
The values in the look-up table are defined in Table III-5

Table III-5. Prompts and entries of the Set module related to assigning lumber grade and lumber picture attributes

Prompt	Entry
Name	`Lumber grades`
Type	`Entity.Type`
Members	`FAS`
	`1C`
	`2C`
Name	`Lumber pictures`
Type	`Entity.Picture`
Members	FAS
	1C
	2A

Before any volume attributes could be assigned to an entity, it first had to pass through a *Decide* module to evaluate what lumber grade would be assigned to the entity. The hierarchy of *Decide* modules, illustrated in Figure III-6, ensured that realistic volume values were assigned to the entities as a function of lumber grade and log characteristics. In the actual sawmill system; lumber volume and lumber grade are directly correlated, as previously discussed in SECTION II.3.1.

Table III-6 presents the logic of the *Assign* module used to allocate the “headrig lumber volume” attribute to the lumber type entities. To differentiate between the lumber type entities generated at the headrig, band resaw, and gangsaw machine centers, the name of the lumber volume attributes included the names of the machine centers; i.e. headrig lumber volume, band resaw lumber volume, gangsaw volume.

Table III-6. Prompts and entries of the Assign module related to assigning lumber volume attributes

Prompt	Entry
Name	`Assign headrig volume attribute to FAS lumber from log type 1`
Type	`Attribute`
Attribute Name	`Headrig lumber volume`
New Value	`DISC(1,5)`

After being assigned a “headrig lumber volume” attribute value, entities representing boards had to access cells on the headrig conveyor and were sent to the beginning of the edger conveyor. All of the lumber entities produced at the headrig were sent to the edger, as is done in the actual system.

Entities representing logs that had completed the loop of *Delay*, *Decide*, and *Process* modules, that defined the sawing process, also had to access cells on the headrig conveyor before leaving the headrig station. However, before this occurred the entity had to pass through several *Delay* modules that represented the sawyer unloading a four-sided log and returning the carriage to the original log loading position. Once the entity had successfully accessed cells on the headrig conveyor, the headrig resource was released and a new entity seized the headrig resource.

6. Band resaw logic

As with the headrig station, entities arriving at the band resaw station were first assigned an attribute that was used to control how many duplicated entities were to be created. The duplicated entities represented the boards sawn from a log. The name given to this attribute was “band resaw cuts”, and an example of the data used for this attribute is presented in Table III-7. The value of this attribute was defined using a discrete probability function based upon an entity’s “log type” attribute value. The same type of model logic for assigning the “cuts” attribute at the headrig station, as diagrammed in Figure III-4, was used for assigning the “band resaw cuts” attribute.

Table III-7. Prompt and entry used assign the band resaw cuts attribute

Prompt	Entry
Name	`Assign band resaw cuts for 12 diam log`
Type	`Attribute`
Attribute Name	`Band resaw cuts`
New Value	`DISC(0.5,6,1,9)`

The sawing process at the band resaw station was modeled using a *Process* module to delay an entity's movement for a specified amount of time. The distribution used for the band resaw sawing process is presented in Table IX-1 of Appendix A. Immediately after the *Process* module was an *Assign* module and a *Separate* module (Figure III-7). The duplicated entity generated at the *Separate* module represented a single board sawn from the original "log type" entity. At the *Assign* module, the attribute "band resaw sawline" was added to the original "log type" entity. The "band resaw sawline" was an integer value that increased by a value of one, every time an entity encountered this *Assign* module. A *Decide* module determined if the entity was done going through the collection of modules that defined the band resaw station. Conditions that had to be true for the entity to leave the band resaw station were that the "bandsaw cuts" attribute value had to equal the "band resaw sawline" attribute value.

If these conditions were found to be true then an entity would access cells on the band resaw conveyor and be conveyed to the gangsaw conveyor. The band resaw conveyor is located directly after the band resaw station and the gangsaw conveyor is located immediately before the gangsaw machine station.

Duplicated entities, representing boards, passed through a series of *Assign* modules that allocated "lumber grade" and "band resaw volume" attribute values

(Figure III-7). Numerous *Decide* modules were employed to allocate the “lumber grade” and “band resaw volume” attributes based upon “log type” and “lumber grade” attribute values, in a manner similar to that used at the headrig station.

However, unlike the headrig station where all boards were routed to the edger, boards produced at the band resaw had the possibility of being sent to either the edger or trimmer machine centers. In the actual system, the probability of which machine center the boards were routed to was measured to be a function of the grade and volume of the board. These probabilities were calculated in the procedure outlined in SECTION II.3.1. The probabilities were implemented into the simulation by using numerous *Decide* modules (Figure III-8).

The duplicated entities sent to the edger, were routed to the beginning of the edger conveyor. Entities sent directly to the trimmer had to access cells on the trimmer conveyor. The trimmer conveyor is large conveyor that conveys boards to the trimmer machine center.

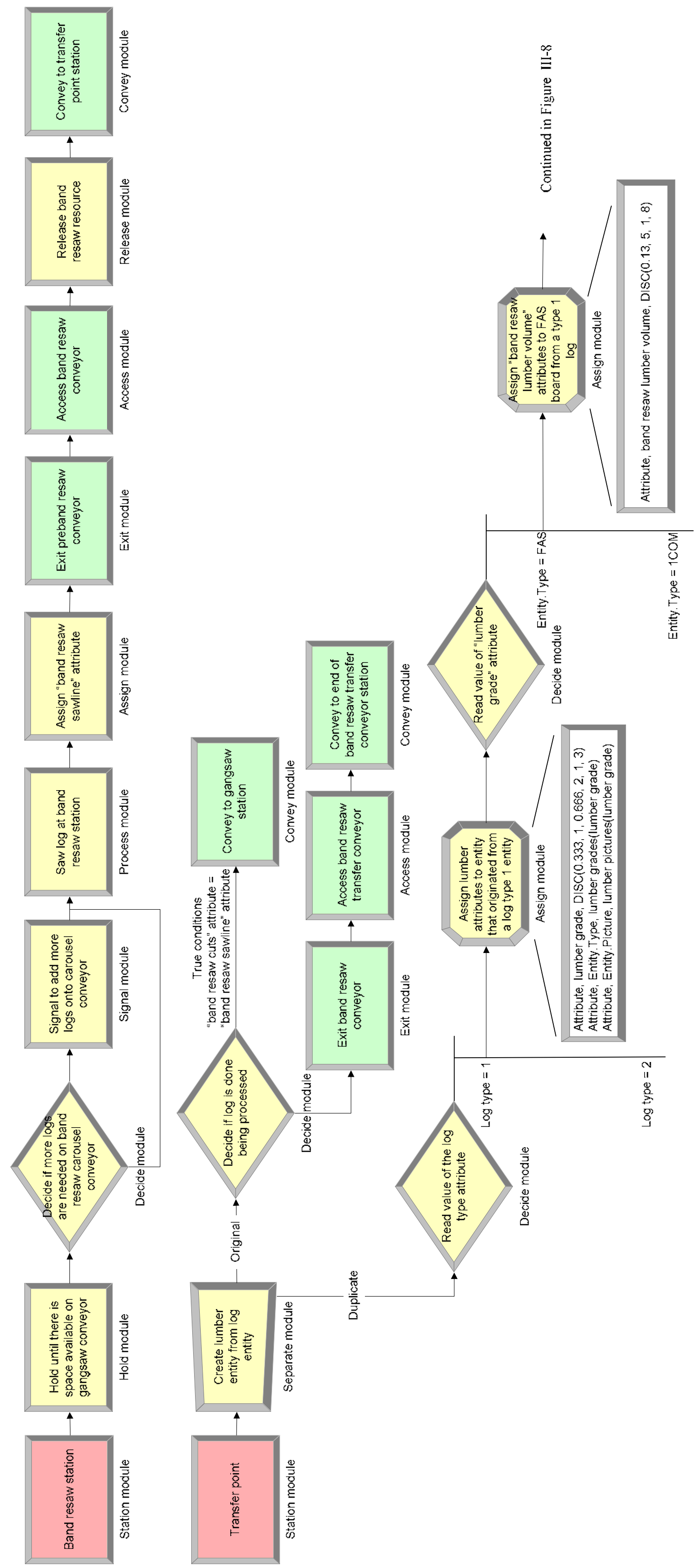

Figure III-7. Model logic of the band resaw station

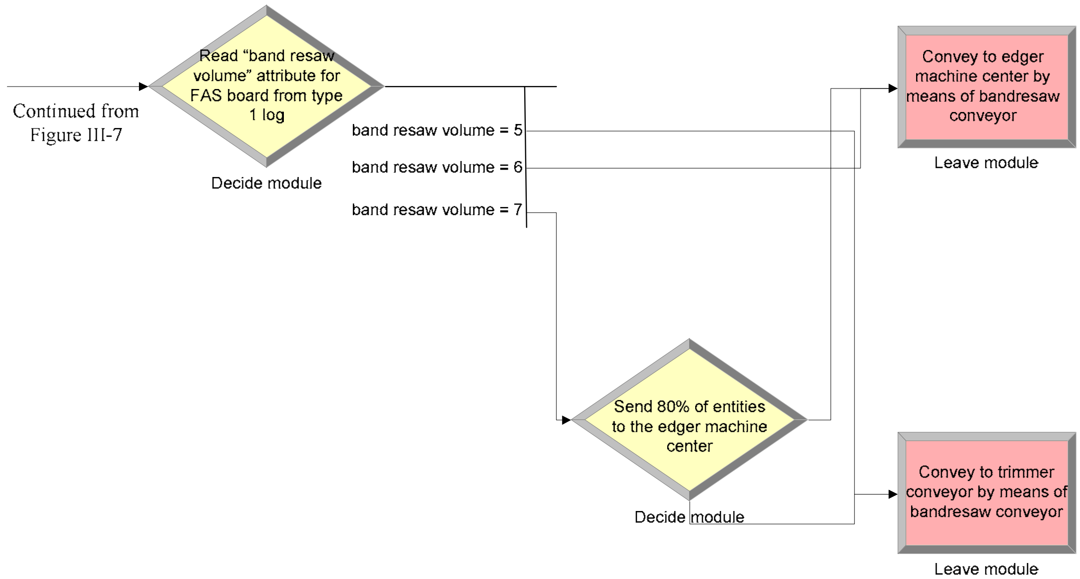

Figure III-8. Illustration of the model logic used to control material flow paths from the band resaw machine center

7. Cant flipper logic

In the actual sawmill system; the purpose of the cant flipper station is to rotate each log so that the best face is orientated toward the saw on the band resaw. This is a time saving operation for the band resaw operator, who then only has to align the log with the saw blade.

Entities arriving at the cant flipper station first had to seize the cant flipper resource before exiting the band resaw carousel conveyor. The flipping or rotating of a log at the cant flipper station was modeled using a *Process* module. The *Process* module delayed each entity for a specified amount of time before accessing cells on the third band resaw carousel conveyor. Entities first had to be able to access conveyor cells on the third band resaw carousel conveyor before the cant flipper resource was released. In the actual system, the third band resaw carousel conveyor is used to move logs from the cant positioner machine center to the band resaw machine center.

8. Gangsaw logic

Entities representing logs, that were done being processed by the band resaw machine center, moved from the band resaw to the gangsaw machine center by means of the band resaw conveyor. At the gangsaw machine center, a *Process* module delayed the entities for a specific amount of time, representative of the time it takes for a log to be sawn at the gangsaw. After the *Process* module, an entity had to access cells on the post gangsaw conveyor. The post gangsaw conveyor is a conveyor located directly after the gangsaw machine station that conveys material to the trimmer conveyor. Entities had to first successfully access cells on the post gangsaw conveyor before the gangsaw resource was released.

At the end of the post gangsaw conveyor, a *Separate* module created a specific number of duplicate entities. The exact number of duplicate entities created depended upon on the value of an entity's "log type" attribute. A *Decide* module was used to evaluate the "log type" attribute value of the entities. At the *Separate* module, a discrete probability function defined the number of duplicate entities that were to be generated. The programming input used for the *Separate* module is presented in Table III-8. An illustration of the model logic used for the gangsaw machine center is presented in Figure III-9.

Table III-8. Prompt and entries used to create duplicate entries at the gangsaw machine center

Prompt	Entry
Name	`Create entities from type 1 log at gangsaw`
Type	`Duplicate entity`
Percent cost to duplicates	`0`
# of duplicates	`DISC(0.5,3,1.0,4)`

The original "log type" entity was routed to an *Assign* module where the attribute values representative of a pallet cant were assigned. The attributes used to define a pallet cant was a numerical value termed "cant volume" and a picture attribute (Table III-9). For the "cant volume" attribute, a value of 14 or 21 was assigned to the entities that had been generated to represent pallet cants. The 14 and 21 "cant volume" attribute values correspond to the volume in board feet of a pallet cant sawn from an eight-foot log and a twelve-foot log, respectively. All entities created at the gangsaw station were conveyed directly to the trimmer station by way of the trimmer conveyor.

Table III-9. Prompts and entries used to assign pallet cant attributes to the entities

Prompt	Entry
Name	`Assign cant volume 14`
Type	`Attribute`
Attribute Name	`Cant volume`
New Value	`14`[A]
Type	`Attribute`
Attribute Name	`Entity.Picture`
New Value	`Cant`

[A]Log type entities representing 12-foot logs were assigned a cant volume attribute value of 21

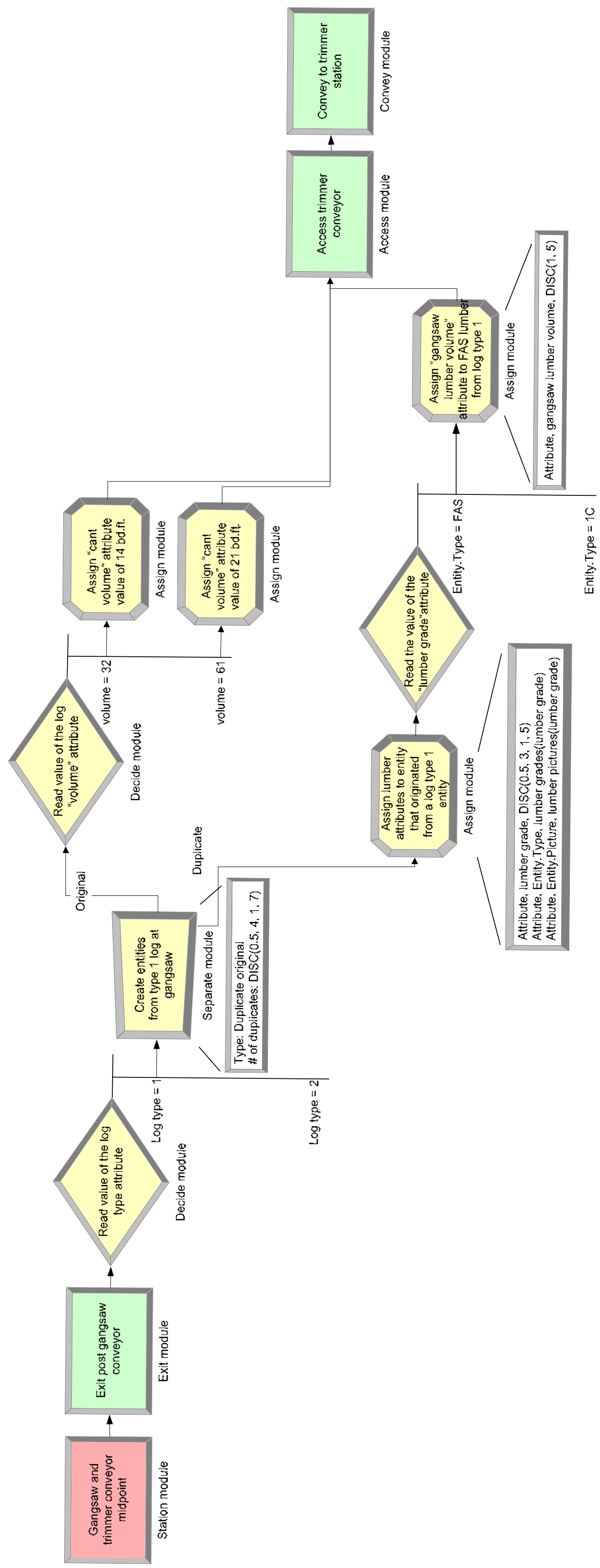

Figure III-9. Model logic of how entities were duplicated at the gangsaw machine center

9. Edger logic

Entities routed to the edger station first had to seize the edger resource before exiting the edger conveyor. The edging procedure was modeled using a *Process* module where an entity was delayed for a specific amount of time. The edger resource was not released until an entity could access cells on the post edger conveyor. The post edger conveyor is located immediately behind the edger machine center. From the post edger conveyor an entity was conveyed to the trimmer conveyor.

10. Trimmer logic

As with the other machine centers, *Seize* and *Release* modules were used for blocking entities from exiting conveyor cells until they could seize a resource. However, unlike the other machine centers a *Process* module was used to delay entities based entirely on material handling time, and not on a compilation of material handling and machine processing time. Careful observations of the real system illustrated that boards pass through the trim saws on a conveyor at a constant rate. However, before entering the conveyor the trimmer operator had to ensure that the boards were aligned perpendicular to the trim saws. The alignment of boards to the trim saws activity was modeled with a *Process* module. The arrangement of modules used to model the trimmer machine center is presented in Figure III-10.

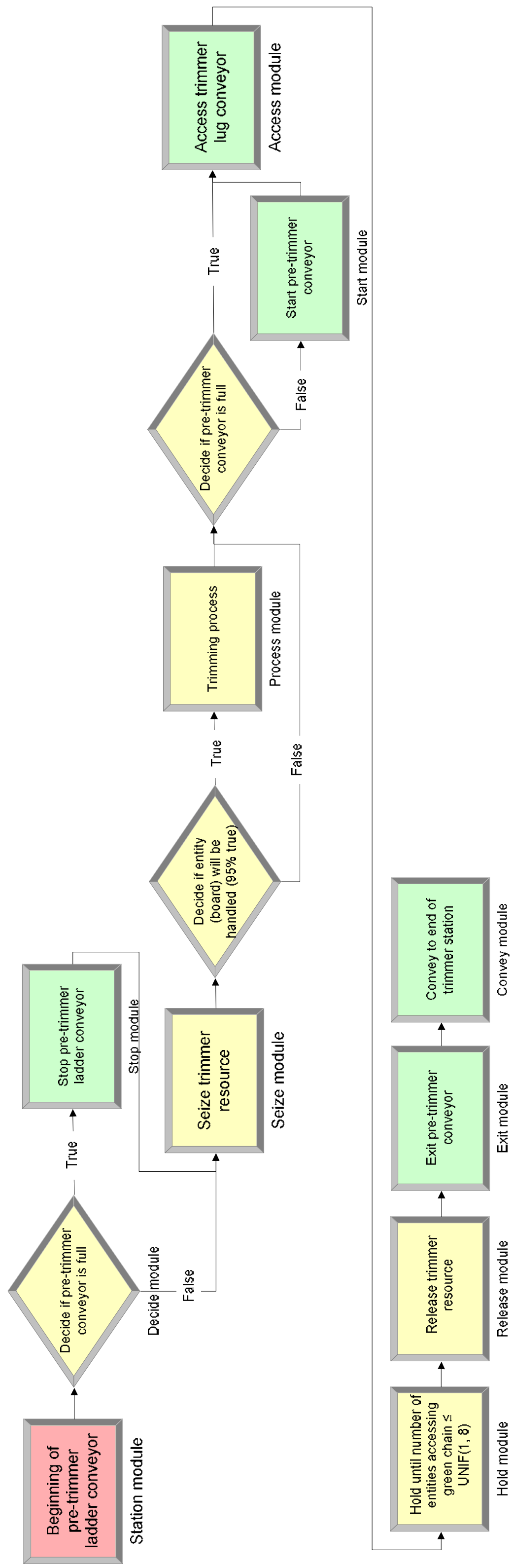

Figure III-10. Logic used to model the trimmer machine center

In the actual system, a limiting constraint of the trimming process is the rate at which the lumber inspectors on the green chain can grade boards. To model this constraint, a *Hold* module was used to prevent entities from releasing the trimmer resource until there were less than a specific number of entities attempting to access the green chain. The specific number of entities was determined by a value generated from a Uniform distribution, where the minimum parameter was one and the maximum parameter was eight. The values of the parameters used for the Uniform distribution were determined based upon observations of the actual sawmill system.

When an entity did release the trimmer resource, cells on the pre-trimmer conveyor became available for other entities, and the entity that had released the trimmer resource was conveyed to a *Station* module. The *Station* module corresponded to the end of the pre-trimmer conveyor and the beginning of the trimmer lug conveyor. The trimmer lug conveyor is used to move lumber through the bank of saws that make up the trimmer machine center.

11. Logic used to model the lumber inspectors

At the large volume sawmill, two lumber inspectors grade boards on the green chain conveyor after the trimmer machine center. To share the workload equally, the inspectors alternate between grading each board. To model the workload sharing, a *Decide* module sent every other entity to one of the lumber inspectors (Figure III-11).

Unlike the other processes that were modeled, the entities do not exit a conveyor before being processed. To model the inspection of lumber on the green chain, two *Station* modules and two *Process* modules were used (Figure III-11). The absence of an *Exit* module, before the lumber inspection *Station* and *Process* modules, caused entities to reside on the green chain conveyor while the lumber inspection process took place.

After entities were delayed at the *Process* module, a *Decide* module read the value of the “lumber grade” attribute and routed the entity to a specific “lumber stacking” station on the green chain. The “lumber stacking” stations represented areas on the green chain where lumber is moved off the green chain by a lumber stacker. In the actual system, the location where lumber is removed from the green chain is based upon lumber grade and length. In the model, only the lumber grade parameter was used to control which station the lumber entities were routed to on the green chain. Due to limitations in the data collection procedures, described in SECTION II.2.2, the sorting of the lumber entities by grade and length could not be modeled.

No unscheduled downtime statistics were assigned to the lumber inspection process. The manner in which the trimmer machine center was modeled took into account unscheduled downtime for the lumber inspectors. The net effect was that unscheduled downtime for the lumber inspectors could occur but was dependent upon the model logic of the trimmer machine center.

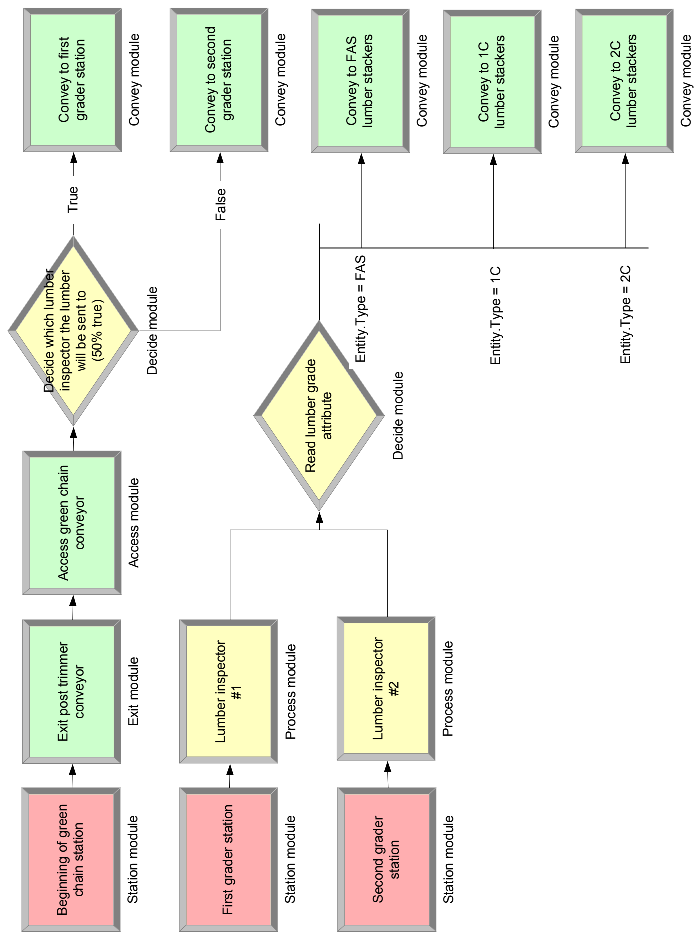

Figure III-11. Logic used to model the lumber inspectors

12. Conveyor logic

Modeling the conveyors involved using *Conveyor* and *Segment* data modules along with *Access*, *Convey*, and *Exit* flowchart modules. Information on conveyor velocity, conveyor type, and cell size of the conveyors were stored in the *Conveyor* data module. The *Segment* data module was used to define the distance between machine centers that sent or received material on a conveyor.

The ARENA simulation program identifies conveyors as accumulating or non-accumulating. When an entity on an accumulating conveyor is blocked from exiting the conveyor, other entities accumulate behind the blocked entity.

Accumulating conveyors remain active unless a specific command renders them inactive. When an entity is blocked from exiting a non-accumulating conveyor the conveyor becomes inactive, which stops the progress of other entities on the conveyor. The majority of conveyors, in the simulation model, were specified as accumulating. Lug-type conveyors, which are used in the sawmill to regulate the number of items that are being conveyed from one area to another, were specified as non-accumulating.

Before an entity could enter a conveyor, it first had to access cells on a conveyor by means of an *Access* module. The *Access* module was used to define the number of cells that an entity would occupy on a conveyor. The size of each cell was defined within the *Conveyor* data module. Manipulation of the cell size for each conveyor enables controlling the number of entities that can be on a conveyor at any one given time.

For the simulation model, conveyors that moved boards lengthwise had a cell size of twelve and conveyors that moved boards edgewise had a cell size of one. Conveyors that moved logs had a cell size of two to model the size of logs. A cell size of twelve is equivalent to twelve feet of conveyor length and a cell size of one is equivalent to one foot of conveyor length.

13. Transporter logic

The log loader, lumber forklift, and lumber stackers were all modeled as transporters. Creating transporters in ARENA involves using the *Transporter* and *Distance* data modules along with *Request*, *Transport*, *Free*, *Enter*, and *Leave* flowchart modules. The *Transport* data module defined the name, the capacity, and the velocity of a transporter. Distances between the stations, that the transporters serviced, were defined using the *Distance* data module.

Transporters are inactive until an entity requests a transporter by way of a *Request* module. The *Request* module specifies which transporter becomes active. A *Transport* module then defines which station the entity will be moved to. The velocity of the transporter and the distance between stations defines the time required to transport an entity from one station to another. A *Free* flowchart module is used to release the transporter resource, enabling the transporter to service the next request.

The *Request* and *Free* modules were used primarily to model the log loader because they offered greater modeling flexibility than the *Enter* and *Leave* modules. The *Enter* and *Leave* modules were used when modeling the lumber stackers and the lumber forklift. The *Leave* module is a combination of the *Request* and *Transport* modules. The *Enter* module was used to simultaneously define a station and to free a transporter. The primary reason the *Enter* and *Leave* modules were not used when modeling the log loader is because the modules did not facilitate blocking entities from freeing a transporter before cells on a conveyor were able to be accessed.

14. Modeling scheduled and unscheduled downtime

At the beginning of an eleven-hour workday, the debarker and headrig machines start operating one half hour before the other machine centers. One half hour before the end of a workday, the headrig, and debarker machine centers shut down while the other machine centers continue to operate. The band resaw machine center goes offline fifteen minutes before the end of a workday. During the workday, all of the machine centers stop for two fifteen minute breaks and one thirty minute break. To model the work schedule a *Schedule* data module was used. The *Schedule* data module enabled controlling the operating schedule of each machine center resource.

As shown in Table III-10 the capacities and durations for three work schedules (Headrig, Band resaw, and Mill) were input into the *Schedule* data module. The Headrig schedule controlled the availability of resources for the headrig and debarker machine centers. Control of the operating schedules for the band resaw and cant positioner machine centers was done using the parameters of the Band resaw schedule. The operating schedule for the rest of the machine centers was controlled by the capacity and duration values specified in the Mill schedule.

Table III-10. Prompts and entries for the Schedule data module

Prompt	Entry					
Name	Headrig schedule		Band resaw schedule		Mill schedule	
Format type	Duration		Duration		Duration	
Type	Capacity		Capacity		Capacity	
Time units	Hours		Hours		Hours	
Scale factor	1.0		1.0		1.0	
Duration	Capacity	Duration	Capacity	Duration	Capacity	Duration
	1	3.00	0	0.50	0	0.50
			1	2.50	1	2.50
	0	0.25	0	0.25	0	0.25
	1	2.25	1	2.25	1	2.25
	0	0.50	0	0.50	0	0.50
	1	2.50	1	2.50	1	2.50
	0	0.25	0	0.25	0	0.25
	1	1.75	1	2.00	1	2.25
	0	0.50	0	0.25		

Unscheduled downtime (machine breakdowns) for each machine center resource was controlled using the *Failure* data module (Table III-11). The duration and frequency statistics used for each machine center was collected from the actual system, as described in SECTION II.2.4.

Table III-11. Prompts and entries for the Failure data module

Prompt	Entry
Name	`Debarker failure`
Type	`Count`
Count	`UNIF(25,30)`
Down time	`UNIF(48,126)`
Down time units	`Seconds`
Name	`Headrig failure`
Type	`Count`
Count	`POIS(49)`
Down time	`6 + 42 * BETA(0.303, 0.456)`
Down time units	`Seconds`
Name	`Band resaw failure`
Type	`Count`
Count	`POIS(96)`
Down time	`5 + WEIB(15.8, 0.716)`
Down time units	`Seconds`
Name	`Cant positioner failure`
Type	`Count`
Count	`POIS(89)`
Down time	`UNIF(10, 21)`
Down time units	`Seconds`
Name	`Gangsaw failure`
Type	`Count`
Count	`POIS(49)`
Down time	`6 + 42 * BETA(0.303, 0.456)`
Down time units	`Seconds`
Name	`Edger failure`
Type	`Count`
Count	`POIS(51)`
Down time	`3 + LOGN(34.6, 88)`
Down time units	`Seconds`
Name	`Trimmer failure`
Type	`Count`
Count	`POIS(200)`
Down time	`8 + 46 * BETA(0.392, 0.65)`
Down time units	`Seconds`

Unscheduled downtime statistics were not able to be collected for the gangsaw machine center because none occurred during the collection of this information. In place of the missing data, the unscheduled downtime statistics for the headrig machine center were used. By visually examining the movement of entities through the simulation model, the duration and frequency of breakdowns at the gangsaw appeared to be similar to the actual system.

15. Model verification

The purpose of model verification is to ensure that logic used to create the model was correctly input into the model and that the model is reading the input logic properly. Using a high level of animation facilitated the verification process by enabling the viewing of how entities moved through the system. The entities could be viewed moving between machine centers and waiting in queues to access conveyors or seize resources.

In addition, the ARENA software automatically reports logical errors at the beginning of each simulation and as they arise when the simulation model is running. Common errors detected at startup included unconnected modules and resources that had been animated but not defined. A common error detected by ARENA when the simulation was being run is that entities were leaving the model (by way of *Dispose* modules) without first exiting conveyor cells.

The one aspect of the model that was not easily viewed through the animation or capable of being detected by the ARENA software was the logic used to assign lumber grade and volume attributes to entities. Because the purpose of building the simulation model was to examine product costs it was imperative that the correct lumber grade and volume attributes were being assigned to the entities.

As part of the verification process the proportion of each lumber grade generated by log type for each machine center was compared to the data collected from the sawmill. Specifically, the data collected on the lumber yield from the sawmill machine centers, described in SECTION II.2.2, was used for the comparison. The comparison was a nonempirical evaluation of the difference between the input values and the output values of the model. For the comparison, the output data from ten replications of the simulation model was used. The percentage of the total lumber volume produced at the headrig machine center for each lumber grade by log parameter is shown in Table III-12. Comparisons of the input and output proportions for the band resaw, gangsaw, and edger machines center are presented in Table III-13 to Table III-15, respectively. The values in the tables indicate that the data collected from the large volume sawmill was correctly programmed into the model and that the model was reading the information correctly.

Table III-12. Verification of input values relating to the volume and grade of lumber produced at the headrig machine center

	Log parameters [A]		Percentage of total volume produced [B]				
Grade	**Length (ft.)**	**Diameter (in.)**	**FAS**	**1C**	**2C**	**3A**	**3B**
Prime	8	14	60.0(57.1)	40.0(42.9)	0(0)	0(0)	0(0)
Select	8	12	0(0)	0(0)	59.3(57.1)	0(0)	40.7(42.9)
Select	8	13	43.5(45.5)	0(0)	0(0)	0(0)	56.5(54.5)
Select	8	14	0(0)	29.3(32.0)	47.1(48.0)	0(0)	23.5(20.0)
Select	8	15	0(0)	100(100)	0(0)	0(0)	0(0)
Select	8	18	0(0)	41.1(50.0)	58.9(50.0)	0(0)	0(0)
Select	8	19	0(0)	100(100)	0(0)	0(0)	0(0)
Prime	12	13	0(0)	60.7(55.6)	39.3(44.4)	0(0)	0(0)
Prime	12	14	41.3(41.2)	58.7(58.8)	0(0)	0(0)	0(0)
Prime	12	15	0(0)	82.3(80.0)	0(0)	0(0)	17.7(20.0)
Prime	12	18	79.9(78.9)	20.1(21.1)	0(0)	0(0)	0(0)
Prime	12	19	46.8(50.0)	34.8(34.6)	18.4(15.4)	0(0)	0(0)
Prime	12	20	0(0)	77.8(76.7)	22.2(23.3)	0(0)	0(0)
Select	12	12	0(0)	79.7(77.8)	20.3(22.2)	0(0)	0(0)
Select	12	13	0(0)	39.6(43.8)	60.4(56.3)	0(0)	0(0)
Select	12	14	0(0)	79.0(72.7)	0(0)	0(0)	21.0(27.3)
Select	12	15	0(0)	28.1(28.6)	16.8(17.1)	0(0)	55.1(54.3)
Select	12	18	20.9(17.4)	79.1(82.6)	0(0)	0(0)	0(0)
Select	12	19	0(0)	64.2(63.0)	0(0)	0(0)	35.8(37.0)
Select	12	20	0(0)	60.5(61.5)	19.8(19.2)	0(0)	19.8(19.2)

[A]Prime grade equates to four clear log faces. Select grade refers to two clear log faces
[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

Table III-13. Verification of input values relating to the volume and grade of lumber produced at the band resaw machine center

Log parameters [A]			Percentage of total volume produced [B]				
Grade	Length (ft.)	Diameter (in.)	FAS	1C	2C	3A	3B
Prime	8	14	75.2(77.5)	15.3(14.1)	9.5(8.5)	0(0)	0(0)
Select	8	12	22.6(25.9)	45.3(43.1)	25.5(24.1)	0(0)	6.7(6.9)
Select	8	13	15.3(16.1)	36.3(39.1)	12.2(12.6)	0(0)	36.2(32.2)
Select	8	14	17.4(17.1)	34.8(33.3)	37.4(40.0)	4.8(4.8)	5.5(4.8)
Select	8	15	46.8(46.5)	42.4(41.9)	10.8(11.6)	0(0)	0(0)
Select	8	18	26.3(25.6)	25.5(27.5)	43.7(42.5)	4.5(4.4)	0(0)
Select	8	19	29.6(30.9)	46.8(47.4)	15.1(13.4)	0(0)	8.5(8.2)
Prime	12	13	63.4(64.7)	31.4(30.3)	5.2(5.0)	0(0)	0(0)
Prime	12	14	65.4(67.4)	31.0(28.6)	3.6(4.0)	0(0)	0(0)
Prime	12	15	83.0(79.3)	17.0(20.7)	0(0)	0(0)	0(0)
Prime	12	18	84.4(84.0)	10.0(10.0)	5.7(6.0)	0(0)	0(0)
Prime	12	19	50.6(49.0)	32.1(34.8)	16.1(15.0)	0(0)	1.1(1.1)
Prime	12	20	80.2(79.1)	13.1(12.3)	3.6(5.5)	2.0(2.2)	1.1(1.0)
Select	12	12	27.3(28.1)	34.3(36.4)	22.1(19.0)	4.0(5.0)	12.3(11.6)
Select	12	13	14.8(14.3)	40.8(37.8)	39.2(42.9)	0(0)	5.2(5.1)
Select	12	14	29.1(30.2)	51.8(50.3)	19.1(19.5)	0(0)	0(0)
Select	12	15	33.1(32.6)	38.7(39.5)	17.6(18.6)	0(0)	10.6(9.3)
Select	12	18	47.8(45.8)	42.3(44.2)	9.8(10.0)	0 (0)	0(0)
Select	12	19	28.9(29.0)	29.9(29.6)	29.4(29.6)	11.8(11.8)	0(0)
Select	12	20	41.7(41.2)	53.2(53.3)	0(0)	1.9(2.4)	3.1(3.1)

[A] Prime grade equates to four clear log faces. Select grade refers to two clear log faces

[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

Table III-14. Verification of input values relating to the volume and grade of lumber produced at the gangsaw machine center

Log parameters [A]			Percentage of total volume produced [B]				
Grade	Length (ft.)	Diameter (in.)	FAS	1C	2C	3A	3B
Prime	8	14	34.9(33.3)	0(0)	0(0)	0(0)	65.1(66.7)
Select	8	12	20.4(20.8)	11.2(11.1)	21.2(20.8)	21.5(19.4)	25.7(27.8)
Select	8	13	21.0(19.6)	19.1(15.7)	0(0)	0(0)	59.9(64.7)
Select	8	14	18.1(18.2)	18.1(18.2)	27.8(27.3)	17.9(18.2)	18.1(18.2)
Select	8	15	0(0)	49.4(50.0)	16.0(16.7)	0(0)	34.7(33.3)
Select	8	18	0(0)	16.3(14.3)	0(0)	11.4(14.3)	72.3(71.4)
Select	8	19	0(0)	19.7(20.0)	20.7(20.0)	20.7(20.0)	40.0(40.0)
Prime	12	13	30.6(28.7)	0(0)	23.9(23.8)	0(0)	45.5(47.5)
Prime	12	14	27.4(25.4)	23.4(25.4)	16.2(15.9)	0(0)	33.0(33.3)
Prime	12	15	17.9(19.4)	0(0)	25.2(25.0)	0(0)	56.9(55.6)
Prime	12	18	0(0)	0(0)	0(0)	0(0)	100(100)
Prime	12	19	37.7(40.0)	0(0)	10.5(10.0)	11.7(10.0)	40.0(40.0)
Prime	12	20	4.6(4.8)	14.5(14.4)	4.4(4.8)	0(0)	76.5(76.0)
Select	12	12	21.5(22.2)	6.3(7.4)	31.2(29.6)	7.1(7.4)	33.8(33.3)
Select	12	13	0(0)	23.4(26.3)	23.0(21.1)	0(0)	53.6(52.6)
Select	12	14	24.6(25.0)	18.6(16.7)	27.1(25.0)	0(0)	29.8(33.3)
Select	12	15	0(0)	0(0)	13.7(13.3)	0(0)	86.3(86.7)
Select	12	18	0(0)	34.1(34.2)	14.5(15.8)	8.4(7.9)	43.0(42.1)
Select	12	19	0(0)	9.5(11.0)	0(0)	0(0)	90.5(89.0)
Select	12	20	0(0)	10.8(10.0)	0(0)	29.3(30.0)	59.8(60.0)

[A] Prime grade equates to four clear log faces. Select grade refers to two clear log faces

[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

Table III-15. Verification of input values relating to the volume and grade of lumber produced at the edger machine center

Log parameters [A]			Percentage of total volume produced [B]				
Grade	Length (ft.)	diameter (in.)	FAS	1C	2C	3A	3B
Prime	8	14	71.1(71.6)	19.6(19.4)	9.3(9.0)	0(0)	0(0)
Select	8	12	6.9(9.1)	47.2(45.5)	33.9(32.7)	0(0)	12.0(12.7)
Select	8	13	8.7(8.3)	37.2(41.7)	6.3(6.7)	0(0)	47.8(43.3)
Select	8	14	5.2(5.7)	38.4(44.8)	48.0(43.7)	0(0)	8.4(5.7)
Select	8	15	48.3(48.8)	40.5(39.0)	11.1(12.2)	0(0)	0(0)
Select	8	18	16.1(14.9)	39.2(40.4)	36.9(37.2)	7.9(7.4)	0(0)
Select	8	19	21.1(26.7)	64.2(60.0)	0(0)	0(0)	14.7(13.3)
Prime	12	13	46.9(44.7)	40.5(42.1)	12.6(13.2)	0(0)	0(0)
Prime	12	14	48.1(48.7)	51.9(51.3)	0(0)	0(0)	0(0)
Prime	12	15	63.0(64.6)	33.7(32.3)	0(0)	0(0)	3.4(3.1)
Prime	12	18	93.7(93.8)	6.3(6.3)	0(0)	0(0)	0(0)
Prime	12	19	42.1(40.4)	43.3(44.7)	12.7(13.0)	0(0)	1.9(1.9)
Prime	12	20	70.8(70.9)	17.6(15.8)	6.4(8.1)	3.4(3.6)	1.8(1.6)
Select	12	12	28.9(29.2)	55.3(53.9)	4.3(4.5)	5.6(6.7)	6.0(5.6)
Select	12	13	12.5(12.3)	40.6(38.6)	42.6(44.7)	0(0)	4.4(4.4)
Select	12	14	29.1(30.4)	40.5(38.3)	28.1(28.7)	0(0)	2.3(2.7)
Select	12	15	24.0(24.6)	36.6(37.3)	14.0(14.9)	0(0)	25.3(23.1)
Select	12	18	35.3(29.9)	53.4(56.9)	11.3(13.2)	0(0)	0(0)
Select	12	19	26.1(26.7)	35.5(35.2)	34.0(33.9)	0(0)	4.4(4.2)
Select	12	20	20.0(21.2)	68.8(67.5)	3.7(3.3)	3.8(4.6)	3.7(3.3)

[A] Prime grade equates to four clear log faces. Select grade refers to two clear log faces
[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

The second part of the verification process was to examine how the model responded when unscheduled downtime occurred at the machine centers. When the capacity of a machine resource is set to zero, by means of the *Resource* data module, the resource cannot seize entities. This manipulation of the *Resource* data module essentially shuts down a machine center for the entire duration that the simulation model is programmed to run. By setting the capacity of a machine resource to zero, it could be observed if the other machine centers and conveyors behaved as intended, because of the offline machine center. Numerous simulation runs were done, where for each run a specific machine center was taken offline. The verification process illustrated that the logic programmed into the model was correct and that the model performed as anticipated.

16. Model validation

16.1. Validation of model assumptions

The two general types of assumptions that must be validated for simulation models are structural assumptions and data assumptions (Law and Kelton 1991). Structural assumptions are related to differences between the way the actual system operates and the manner in which the system is modeled (Banks et al. 2001). Often, structural assumptions are necessary because many details of the actual system do not need to be modeled in order to satisfy the purpose of the simulation study. Data assumptions are associated with the collection and analysis of the input data. More specifically, data assumptions address random sampling issues and distribution fitting. For the sawmill simulation models, the most important data assumption concern was the analysis of the log sampling data, and machine processing data.

16.1.1. Structural assumptions

16.1.1.1. State of model at startup

One of the structural assumptions is that at startup (simulation time zero) there are already logs on several of the conveyors. The conveyors, where log entities are present at startup are the:

1. Log deck conveyor that services the debarker machine center.

2. Debarker conveyor connecting the debarker and the headrig machine centers.
3. Band resaw holding conveyor, where logs routed from the headrig wait for processing at the band resaw.
4. Short band resaw holding conveyor, which is the overflow conveyor when the band resaw holding conveyor becomes filled to capacity.
5. Band resaw carousel conveyor, which moves logs directly to the band resaw machine center.
6. Gangsaw conveyor where logs are held until processing at the gangsaw machine center.

Through numerous observations of the actual system and conversations with the machine operators, it was determined that these conveyors are typically holding some logs at startup, but the number varies greatly. The simulation method used to model the variation was to use six *Arrival* modules and a Uniform distribution.

The *Arrival* modules created a number of entities at the *Access* queues for each of the six conveyors described above. How many entities were created depended upon the minimum and maximum parameter of the Uniform distribution. For each *Arrival* module, the minimum parameter of the Uniform distribution was set at one. The maximum parameter of the Uniform distribution depended upon the capacity of the conveyor where the entities were created. By using the Uniform distribution the number of logs present in the sawmill at startup was able to be accurately modeled based upon the conversations with the sawmill personnel.

16.1.1.2. Remanufactured lumber

Another structural assumption is that remanufactured lumber does not enter the system from the green chain. In the actual system, lumber that has to be remanufactured is constantly being routed back into the sawmill at the edger machine center, from either the green chain or the trimmer machine center.

One of the reasons that lumber is sent back into the sawmill, is that the lumber inspectors, on the green chain, decide that the edging process was not properly done or not done at all. Often the operator of the trimmer machine center is able to identify boards that need to be remanufactured before they reach the lumber inspectors. Boards, identified by the trimmer operator, as having to be remanufactured are routed back to the edger machine center through a series of conveyors.

From observing the sawmill operation, it was evident that the primary cause of boards having to be remanufactured is the limited capacity of the edger conveyor. When unscheduled downtime occurs at the edger machine, the edger conveyor quickly fills to maximum capacity. At maximum capacity, a mechanism that moves boards from the band resaw conveyor to the edger conveyors fails to function properly. As a result, the operator of the band resaw machine center routes boards that need edging directly to the trimmer conveyor. The scenario of the band resaw operator changing the material flow pattern of boards, based upon the status of the edger conveyor is represented in the simulation model. Lumber being routed from the trimmer to the edger machine center for the purpose of being remanufactured is also modeled.

However, the situation where lumber is sent from the green chain to the edger machine center for remanufacturing is not represented in the simulation model. The proportion of boards that the trimmer operator failed to identify as needing to be remanufactured before they reached the green chain was not quantified. Neglecting to model the remanufactured lumber sent from the green chain to the edger, was considered to have a negligible effect on system operation, since it is modeled that boards needing to be remanufactured are sent to the edger from the trimmer machine center.

16.1.1.3. Assigning lumber grade attributes as a function of time

The model is also not capable of precisely assigning grade and volume attributes to the lumber entities in the order that a board would actually be produced from a log. Conventional knowledge states that the grade of the lumber sawn from an individual log will decrease incrementally as boards are removed from the log (Malcolm 2000). In addition, there is a time component associated with this phenomenon since producing lumber from a log involves a series of steps or activities that occur along a timeline. In general, the grade of an individual board produced at time x, by a headrig or band resaw machine center, will be of a higher grade than a board that is produced at time $x + 1$ from the same log. This lumber grade and time relationship could not be modeled because the methodology of the lumber yield sampling procedure did not facilitate recording the numerical order that boards were produced from a log. Such a sampling procedure was cost prohibitive in terms of time and money budgeted for this project. This assumption is only relevant to the headrig and band resaw machine centers because they are multiple pass machine centers. In particular, this assumption is most relevant at the band resaw machine center because this is where the majority of lumber is produced.

To fully understand how this assumption affects the goals of this research project, it must be explained that for the system being modeled, the number of entities in a queue and the total time an entity is in a queue changes dynamically. If the system did not have failures and scheduled breaks, the total time an entity is in a queue would change dynamically as a function of log input parameters. However, since there are failures and scheduled breaks, the total time an entity is in a queue changes dynamically at discrete points in time, thus quickly losing any relationship to log input parameters. Where this assumption most directly affects the goals of this research project is the precision of allocating costs to the individual boards based upon time in queues. The potential exists that the total time a board is modeled as being in a queue will not be representative of the actual time that a specific grade of lumber is held in a queue. If the system being modeled did not have failures and scheduled breaks, this assumption would perhaps be of greater importance. However since these events do occur in the actual system and are not a function of lumber grade this assumption will not significantly affect the precision that costs can be assigned to individual boards based upon time in queues.

16.1.1.4. Relation of processing time distributions to log parameters

When observing the log and lumber processing activities it was evident that the cycle times of the machine centers were not entirely correlated to log and lumber parameters. Other variables such as material handling time appeared to be a significant factor in affecting processing times. Human and mechanical handling of lumber and logs was observed to be wrought with mistakes and time delays. Because of this, the processing of logs and lumber at machine centers was not modeled to be a direct function of log and lumber parameters. Rather the processes that occur at each machine center were modeled using distributions that encompassed processing time data collected from a wide variety of log and lumber parameters at the individual machine centers.

The relevance of this modeling approach is most important at the headrig and band resaw machine centers since collectively they drive the production rate of the sawmill. Using data collected from the actual system, a two-sample Welch *t*-test was used to empirically test if there was a statistically significant difference in cycle times at the headrig between 8-foot and 12-foot red oak logs of similar diameter. For logs with scaling diameters between 12 and 15 inches the Welch *t*-test failed to reject the null hypothesis that the average headrig cycle time between 8 and 12-foot logs is equal ($p = 0.69$) at an alpha level of 0.05. The dataset that was used to perform the statistical analysis consisted of headrig cycle times for 24 logs, that were 8 and 12-foot in length. Normal material handling delays were included in the recording of the cycle times. Based upon the results of the statistical analysis, it is evident that neglecting log length, as a factor in modeling the headrig machine center is valid based upon the information that was collected.

As described in SECTION III.5, the log diameter parameter is indirectly included in the modeling of logs being sawn at the headrig. Cycle time of the headrig as a function of log diameter was modeled based upon the number of boards produced, and the number of times the log is rotated. In general, the data from the lumber recovery studies illustrated that as log diameter increases more boards are produced at the headrig.

A two-sample Welch *t*-test was also used to test for differences in the cycle times between 8-foot and 12-foot logs at the band resaw. The statistical test failed to reject the null hypothesis that the average band resaw cycle time between 8 and 12-foot logs is equal ($p = 0.08$) at an alpha level of 0.05. The cycle times did not include normal material handling delays and only represented the elapsed time from when the saw entered a log to when it exited.

16.1.2. Data assumptions

16.1.2.1. Assumptions of the lumber yield data analysis

As stated in SECTION II.3.1, the lumber statistics were calculated based upon 1-inch nominal lumber thickness. However, during the data collection process at the large sawmill, some of the information was gathered when the target nominal thickness was 1.25 or 1.5 inches. While this would not affect the accuracy of the volume calculations, the potential exists to introduce errors in predicting the number of boards sawn from individual logs. This potential error is due to the fact that as the target nominal thickness of the lumber increases, the number of boards sawn from each log decreases. A statistical analysis was done to determine if the differences in thickness would affect the accuracy of predicting the number of boards produced.

The statistical analysis involved comparing the variance in the number of boards produced from groups of logs where mixed lumber thicknesses were sawn to groups of logs where only one lumber thickness was sawn. Only the boards produced at the band resaw machine center were used in the statistical analysis for the following reasons:

1. In comparison to the primary log processing machine centers, i.e. the headrig and gangsaw machine center, the band resaw produces the largest number of boards.

2. Including the data from the gangsaw machine center would inject a noise factor into the statistical analysis. The number of boards produced at the gangsaw machine center is more dependant upon if pallet cants are produced than on target lumber thickness.

Table III-16 presents the largest difference in number of boards produced at the band resaw by sawing scenario. Each data point per sawing scenario is from logs with identical diameter, grade, and length parameters.

Table III-16. The largest difference in the number of boards produced at the band resaw by sawing scenario

Sawing scenario	Largest difference in number of boards sawn													
Two lumber thicknesses were sawn	1	3	2	5	3	4	0	6	1	3	8	1	2	3
One lumber thickness was sawn	3	3	4											

The null hypothesis for the statistical analysis was that the variance in number of boards produced between both groups was equal at an alpha level of 0.05. The alternative hypothesis was that the variances between the groups were not equal. A two-tailed test of the variance ratio was performed using the SAS `proc ttest` command (SAS Institute Inc. 2004). The statistical test failed to reject the null hypothesis that the variances between the two log groups were equal ($p = 0.13$). The results of the statistical test on the data collected for this project do not illustrate that prediction bias for the number of boards produced at the band resaw, will result in any practical significance.

16.1.2.2. Reliability of the processing time data

An important data assumption for this model was that the raw data used to calculate the machine processing time distributions was homogenous and uncorrelated. These conditions must be true for the statistical analysis procedures used to calculate the fit of the machine center processing time distributions to be valid (Law and Kelton 1991). More specifically the curve fitting procedure of ARENA's Input Analyzer software is based upon maximum-likelihood estimators, which assumes that the individual observations in the data sets are independent and uncorrelated (Law and Kelton 1991, Rockwell Software 2003).

16.1.2.2.1. Tests for homogeneity

The Kruskal-Wallis hypothesis test for homogeneity was used to assess the homogeneity of each data set collected from the actual system. Because some of the processing times were collected on different days, the potential exists that statistically, the collected data may not be from the same parent population. The Kruskal-Wallis hypothesis test for homogeneity is a nonparametric one-way ANOVA test (Law and Kelton 1991, SAS Institute Inc. 2004). The test statistic for the Kruskal-Wallis homogeneity test is defined in Equation III-1 (Law and Kelton 1991).

$$T = \frac{12}{n(n+1)} \sum_{i=1}^{k} \frac{R_i^2}{n_i} - 3(n+1)$$

Equation III-1

where:

$$n = \sum_{i=1}^{k} n_i$$

$$R_i = \sum_{j=1}^{n_i} R(X_{ij}) \text{ for } i = 1, 2, \ldots, k$$

X_{ij} denotes the i$^{\text{th}}$ sample of size n_i

The null hypothesis of the test is that all of the population distribution functions are identical against the alternative hypothesis that at least one of the populations tends to yield larger observations (Law and Kelton 1991). The null hypothesis is rejected at level α if $T > \chi^2_{k-1,1-\alpha}$. This test was done using the SAS `npar1way` procedure (SAS Institute Inc. 2004).

The specific raw data tested for homogeneity was the processing times of the band resaw and gangsaw machine centers. Testing the homogeneity of the other timing measurements was not needed because they were all collected on a single day. Results of the Kruskal-Wallis test failed to reject the null hypothesis, at an alpha level of 0.05, that the population distribution functions were identical for the information relating to the processing times for the band resaw machine center (p = 0.50). The processing time information collected from the gangsaw machine center was also judged to be homogenous (p = 0.53).

16.1.2.2.2. Tests for independence

To examine the assumption that observations used to generate input distributions for simulation models are independent and uncorrelated Kelton and Law (1991) suggest using either graphical; i.e. correlation plots, scatter plots, or nonparametric statistical testing techniques. The independence of the observations used to generate the processing time distributions for this model was assessed using autocorrelation plots. Autocorrelation plots allow for a graphical representation of the correlation between observations in the same dataset that are *k* observations apart in time (Sall et al. 2001). The number of *k* observations apart in time is referred to as the lag.

To construct an autocorrelation plot for each dataset, the individual observations were arranged in the order that they were collected over time. The autocorrelation of the k^{th} lag was calculated with the JPMIN (Version 4.04) statistical analysis software package. The JPMIN `Time Series` programming script was used to calculate the autocorrelation values (Sall et al. 2001).

Autocorrelation plots of each dataset, used to generate processing time distributions for this model, are presented sequentially from Figure III-12 to Figure III-22. The number of lags used for each analysis was 25 percent of the number of observations in the original ordered datasets as recommended by Sall et al. (2001). Solid bars in the correlation plots illustrate the autocorrelation at the k^{th} lag and the continuous thin lines are ± 2 standard errors from the baseline of zero for the k^{th} lag. Observations in a data series are considered independent if the autocorrelation values are near zero (Kelton and Law 1991).

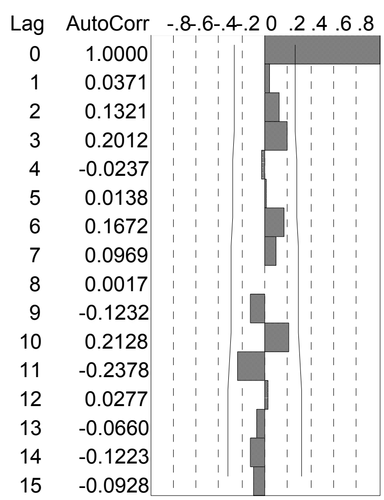

Figure III-12. Autocorrelation plot for the band resaw processing time dataset

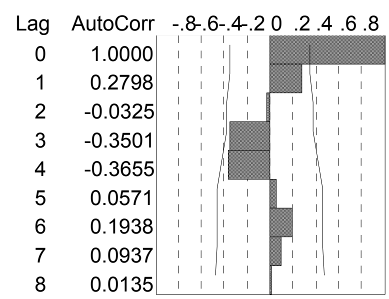

Figure III-13. Autocorrelation plot for the log sawing time at the headrig dataset

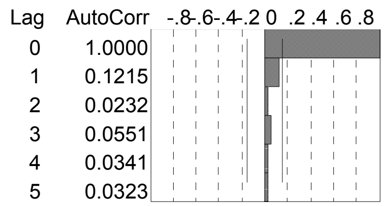

Figure III-14. Autocorrelation plot for the return carriage to original position time at the headrig dataset

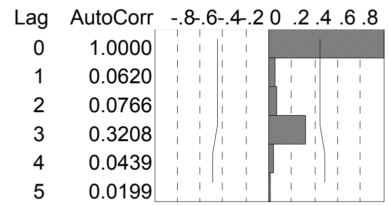

Figure III-16. Autocorrelation plot for the return carriage to short position dataset

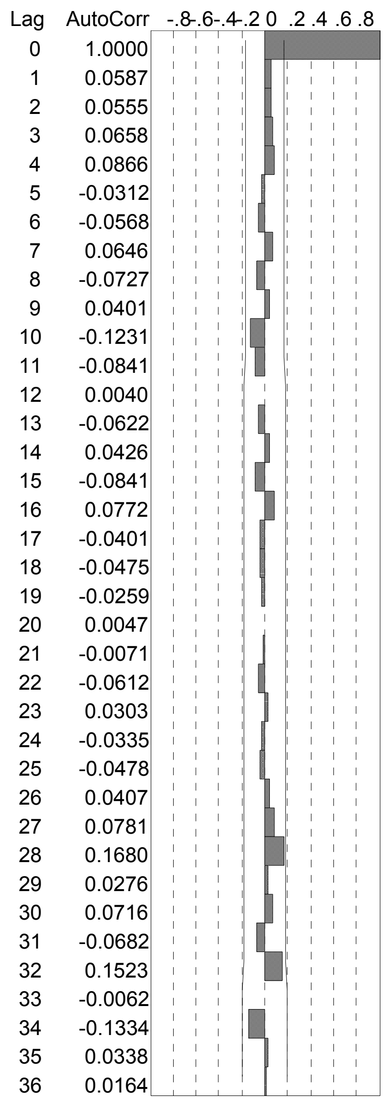

Figure III-15. Autocorrelation plot for the log loading time at the headrig dataset

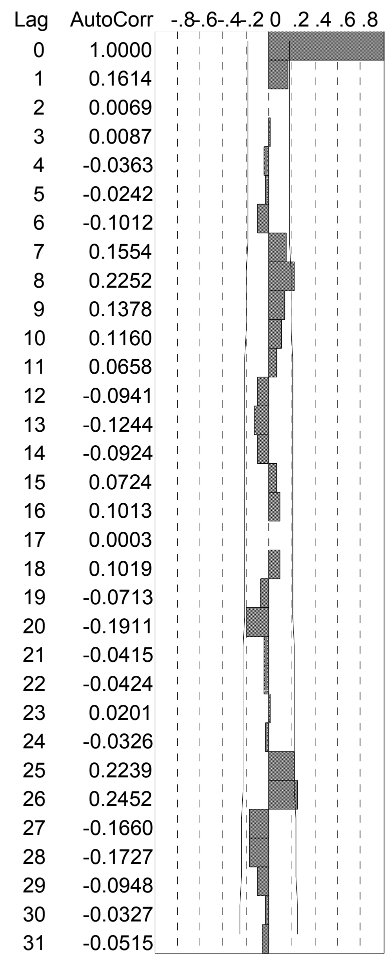

Figure III-17. Autocorrelation plot for the log rotating time at the headrig dataset

Lag	AutoCorr
0	1.0000
1	0.1215
2	0.0232
3	0.0551
4	0.0341
5	0.0323
6	0.0928
7	0.0915
8	0.0383
9	-0.0249
10	-0.0623
11	0.0570
12	-0.0070
13	0.0839
14	-0.0758
15	-0.0270
16	-0.0034
17	0.0919
18	-0.0512
19	0.0129
20	0.1352
21	-0.1197
22	-0.0082
23	0.0034
24	-0.1272
25	-0.0197
26	0.0615
27	0.0746
28	0.0437
29	0.0366
30	0.0413
31	0.0530
32	0.1060
33	0.1418
34	-0.0578
35	0.0057
36	0.0399
37	0.0912
38	0.0113
39	-0.0039
40	0.0662
41	-0.0461
42	0.0095

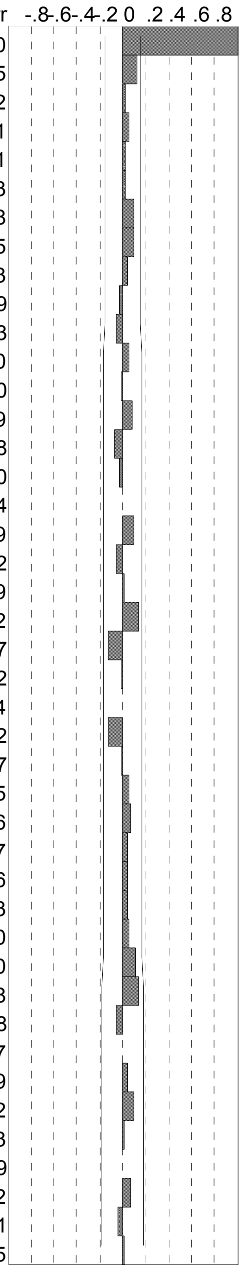

Figure III-18. Autocorrelation plot for the move carriage forward time at the headrig dataset

Lag	AutoCorr
0	1.0000
1	-0.0696
2	-0.1395
3	-0.0872
4	0.0071
5	-0.0041
6	0.0603
7	0.0065
8	0.1011
9	-0.1376
10	0.1801
11	0.1810
12	-0.0019
13	-0.0829
14	-0.2197
15	0.0692
16	0.0568

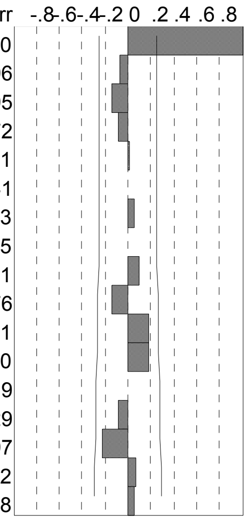

Figure III-19. Autocorrelation plot for the return carriage to original position after dropping off cant dataset

Lag	AutoCorr
0	1.0000
1	-0.1029
2	-0.1033
3	-0.0794
4	-0.0646
5	-0.1354
6	-0.0806
7	0.0327
8	-0.0317
9	-0.0738
10	0.2123
11	-0.0173
12	-0.0531
13	0.0938
14	0.0121
15	-0.0362

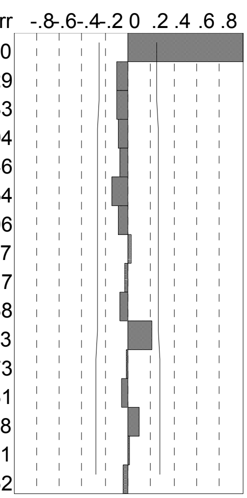

Figure III-20. Autocorrelation plot for the debarker processing time dataset

Lag	AutoCorr
0	1.0000
1	0.0918
2	0.1692
3	0.0948
4	-0.0371
5	0.0432
6	-0.0440
7	0.0717
8	0.0451
9	0.0896
10	0.0079
11	0.0868
12	-0.0106
13	0.0040
14	0.0857
15	0.1534
16	0.0707
17	0.1826
18	0.0667
19	0.1231
20	0.0589
21	-0.0518
22	0.0063
23	-0.0245
24	0.0081
25	-0.0297
26	0.0144
27	0.0948
28	-0.0253
29	0.0554
30	0.0695
31	0.0178
32	0.0812
33	0.0810
34	0.1659
35	0.0445
36	0.0871

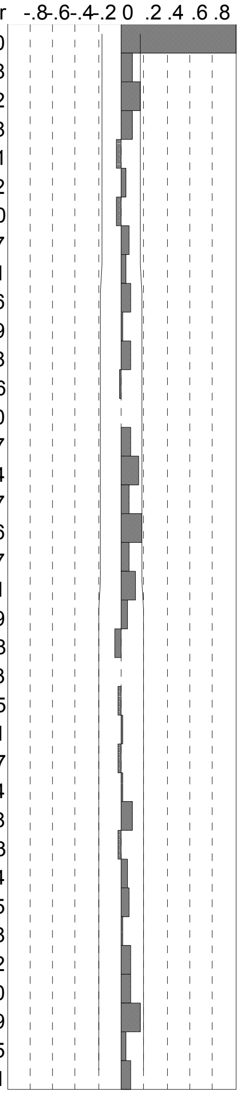

Figure III-21. Autocorrelation plot for the gangsaw processing time dataset

Lag	AutoCorr
0	1.0000
1	0.2365
2	0.3210
3	0.0882
4	-0.1155
5	0.0040
6	-0.2524

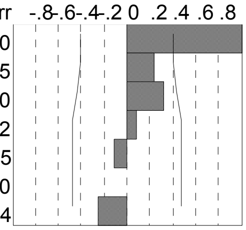

Figure III-22. Autocorrelation plot for the edger processing time dataset

Lag	AutoCorr
0	1.0000
1	0.3509
2	0.0551
3	-0.0768
4	-0.0797
5	-0.1018

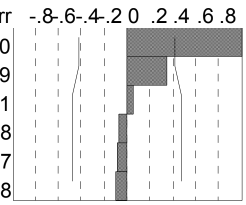

Figure III-23. Autocorrelation plot for the log unloading time at the headrig dataset

Lag	AutoCorr
0	1.0000
1	0.1794
2	-0.0163
3	-0.0747
4	-0.1075

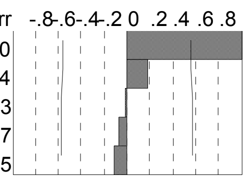

Figure III-24. Autocorrelation plot for the trimmer processing time dataset

The observations used to generate processing time distributions for this model were determined to be independent based upon the autocorrelation plots in Figure III-12 to Figure III-22. This conclusion was based upon the criterion that autocorrelation values were close to zero. Therefore, the assumption that the observations in the datasets used to generate the processing time distributions are independent was validated.

16.2. Comparison of simulation output data to actual system observations

16.2.1. Methods

The output data from ten replications of the simulation model was used for the model validation procedure. Volume of lumber produced per hour and the number of logs processed per hour were the output variables used to evaluate the accuracy of the model. In addition, the cycle times of entities at the headrig and band resaw machine centers were compared to cycle time measurements from the actual system.

The volume of lumber produced per hour, and number of logs processed per hour are both monitored by the management of the actual sawmill system. These production measurements provided benchmarks for evaluating the accuracy of the simulation model. Eight production reports from the actual system, on days when the sawmill was producing red oak lumber, were obtained. Since the sawmill management team did not collect information on the cycle times of the headrig and band resaw machine centers, this information was collected directly from the individual machine centers.

The headrig and band resaw machine centers were chosen to be part of the validation process because they are the two main machine centers that drive production at the sawmill. It was found through the validation process that changing only one time distribution in the modules that make up these machine centers dramatically alters the output variables generated by the model. Thus, it was very important that the time distributions input into the model were accurately representing the machine center processing times.

Each replication run modeled a full eleven-hour workday, with specific starting and stopping times, i.e. a terminating simulation. By using ten statistically independent replications, the relative error (γ) of the confidence intervals for the output data remained below 0.15. The relative error value of a confidence interval, defined in Equation III-2, communicates the precision of the confidence interval.

$$\gamma = \frac{(\overline{X} - \mu)}{\mu}$$ **Equation III-2**

where:

γ = the relative error of a confidence interval

$\overline{X}$ = the half-width of a confidence interval

μ = the average calculated value

Lower relative error values relate to smaller, more precise confidence intervals. For simulation models, the precision of confidence intervals can typically be increased by performing more replications of the model. Law and Kelton (1991) recommend performing enough replications so the relative error of a confidence interval is less than or equal to 0.15.

The statistical independence of the replications was controlled by using different initial seed values to produce random number streams. By default the 7.01.00 version of the ARENA software uses the initial seed values of 14561, 25971, 31131, 22553, 12121, 32323, 19991, 18765, 14327, and 32535 to generate random number streams for the first ten replications, respectively (Rockwell Software 2003). The data from one replication of the simulation model would have been neither independent nor identically distributed, due to the manner in which the ARENA software generates random numbers (Kelton et al. 2004).

A discrete empirical distribution was used to control the probability of each log type being created in the simulation model. Twenty different log types, representing logs with different grade, diameter, and length parameters, were able to be modeled. The value of the discrete empirical distribution that was used, allowed for equal probability of any log type being created. For the actual system, the input of logs into the sawmill is also random and not controlled based upon log grade, diameter, or length characteristics.

It should also be noted that for the validation process, the *Preempt* rule for scheduled breaks and failures was used. The *Schedule* and *Failure* rules used in the ARENA modeling environment control the manner in which entities seize and release resources when there is a scheduled break or failure. Specifically, the *Preempt* rule will not allow an entity to be released until the time assigned for the scheduled break or failure has elapsed (Kelton et al. 2004). The *Preempt* rule most closely models the manner in which entities are handled during scheduled breaks and failures in the actual sawmill system.

For each of the production measurements, a two-sample Welch *t*-test was used to determine if the differences between the actual system values and the simulation model values were statistically significant.

16.2.2. Results

The SAS `ttest` procedure was used to implement two-sample Welch *t*-tests at an alpha level of 0.05 (SAS Institute Inc. 2004). For each test, the null hypothesis was that the outputs from the simulation model were equal to the values from the production reports. The alternative hypothesis was that the values were not equal.

For the average volume of lumber produced per hour production measurement, the result of the two-sample Welch *t*-test was to reject the null hypothesis (p = 0.02), in favor of the alternative. The average volume of lumber produced per hour value from the simulation was not equal to the average value from the actual system, at an alpha level of 0.05. Table III-17 presents the statistics from the test. The null hypothesis was also rejected when the average number of logs processed per hour values from the simulation model were compared to the actual system values (p = 0.03). The statistics from the test are presented in Table III-18.

Table III-17. Two-sample Welch t-test on the average volume of lumber produced (bd.ft.) per hour by the actual system and the output from model of the large volume sawmill

Variable	n [A]	Range [B] Min	Max	Two-sample Welch t-test 95% Confidence intervals for μ	p-value[C]
System data	8	6,138	7,725	6,994 ± 570 (6,424 , 7,564)	0.02
Simulated data	10	5,955	7,567	6,198 ± 348 (5,851 , 6,546)	

[A]n = number of data points or replications
[B]Values are reported in units of board feet/hour
[C]$\alpha = 0.05$

Table III-18. Two-sample Welch t-test on the average number of logs processed per hour by the actual system and the output from the model of the large volume sawmill

Variable	n [A]	Range [B] Min	Max	Two-sample Welch t-test 95% Confidence intervals for μ	p-value[C]
System data	8	53	73	62 ± 6 (56 , 68)	0.03
Simulated data	10	53	58	56 ± 1 (55 , 57)	

[A]n = number of data points or replications
[B]Values are reported in the units number of logs processed/hour
[C]$\alpha = 0.05$

One possible explanation that the values from the simulation model were less than the values of the actual system can be attributed to changes in the operation of the sawmill. When the data used to calculate the material flow probabilities was collected, it was standard operating procedure to send small diameter logs (12 – 15 inches) from the headrig to the band resaw machine center. However, the production reports that were used as benchmarks for the validation procedure were from a time period when small diameter logs were being sent to the gangsaw machine center directly from the headrig. The change in operating procedure could have resulted in a greater production rate, which would explain why the values from the actual system are greater than the values from the simulation model. Overall, the differences in the production measurements between the actual system and the model were not considered to be of practical consequence.

Altering the simulation model to replicate the new operating procedure was not feasible. The distributions used to assign lumber grade and volume attributes were based upon information that had been collected when the logs were routed to the band resaw from the headrig. Simply changing the material flow patterns of entities in the model would not be a valid representation of the system because of differences in lumber grade and volume yield between the band resaw and gangsaw machine centers.

Cycle times (elapsed processing times) of entities at the headrig and band resaw machine centers were recorded from the simulation model using several *Read/Write* modules. The *Read/Write* modules were used to write data from the simulation model to a Microsoft Excel file.

The number of individual data points from each replication ranged from 650 to over 1000. For each replication, an average value was calculated. The hypothesis that the average values from the replications equaled the average value of the timing data from the actual system was tested at an alpha level of 0.05. Timing data from the actual system used for the statistical analysis was specific to measurements taken during the processing of red oak. The SAS `ttest` procedure was used to perform the statistical analysis.

For the headrig machine center data, the statistical test failed to reject the null hypothesis (p = 0.13), indicating that the headrig cycle times from the simulation were not significantly different from the values of the actual system (Table III-19). When the data for the band resaw cycle times were analyzed with the two-sample Welch t-test, the null hypothesis was rejected in favor of the alternative hypothesis. The cycle times for the band resaw machine center obtained from the simulation model were significantly different than the values from the actual system at an alpha level of 0.05. As presented in Table III-20, the values from the simulation model are approximately one second less than the actual system values. This small difference was viewed as not practically significant to invalidate the model. Based upon the numerous statistical tests performed on the production measurements and machine center cycle times, it was concluded that the simulation model suitably represented the actual system.

Table III-19. Two-sample Welch t-test on the average headrig cycle times recorded at the actual system and the output from model of the large volume sawmill

		Range [B]		Two-sample Welch t-test	
Variable	n [A]	**Min**	**Max**	**95% Confidence intervals for μ**	p**-value** [C]
System data	70	22.65	86.40	46.82 ± 2.83 (43.99 , 49.65)	0.13
Simulated data	10	48.73	49.33	49.00 ± 0.12 (48.88 , 49.12)	

[A] n = number of data points or replications
[B] Values are reported in units of seconds
[C] $\alpha = 0.05$

Table III-20. Two-sample Welch t-test on the average band resaw cycle times recorded at the actual system and the output from the model of the large volume sawmill

Variable	***n*** [A]	**Range** [B] **Min**	**Max**	**Two-sample Welch *t*-test 95% Confidence intervals for μ**	***p*-value** [C]
System data	299	8.69	13.89	8.69 ± 0.16 (8.53 , 8.85)	< 0.0001
Simulated data	10	7.89	7.95	7.93 ± 0.02 (7.91 , 7.95)	

[A] n = number of data points or replications
[B] Values are reported in units of seconds
[C] $\alpha = 0.05$

16.3. Face validity

The purpose of examining the face validity is to determine if the model appears realistic at "face value" to either the model user or experts who know and understand the actual system (Law and Kelton 1991). To evaluate the face validity of the sawmill simulation model, a sensitivity analysis was performed. The sensitivity analysis involved examining model responses when the distribution of the log type input was systematically changed. More specifically, the sensitivity analysis involved modeling how the system would respond when only 19-inch diameter logs or 13-inch diameter logs were sawn during an eleven-hour workday. Model response was measured using the output variables; (1) number of logs processed, (2) total volume of logs processed, and (3) total volume of lumber produced. The output variables were compared against the values when all of the available logs, that were able to modeled, were input into the model. The output values from the two sensitivity analysis tests are presented in Table III-21.

Table III-21. Comparison of output values when only 19 or 13-inch diameter logs are sawn to the model output when all logs are sawn

Log input scenario	Number of logs processed	Total volume of logs processed (bd.ft.) [A]	Total volume of lumber produced (bd.ft.)
	- - - - - - - - - - - - - 95% Confidence intervals for μ[B] - - - - - - - - - - - - - -		
19-inch diameter logs	382 ± 14	57,515 ± 2,120	58,402 ± 353
13-inch diameter logs	654 ± 12	35,115 ± 807	55,563 ± 281
All available log diameters	535 ± 14	52,445 ± 1,367	61,984 ± 3,472

[A]The volume of logs processed values are reported in board feet from the Doyle log scale
[B]Confidence intervals were calculated using data from ten replications of the simulation model

The output values from the sensitivity analysis test were as expected. As illustrated in Table III-21 when only 19-inch diameter logs were processed the number of logs processed value was less than for the scenario where only 13-inch diameter logs were input into the model. When processing only 19-inch diameter logs the band resaw machine center, and not the headrig, becomes the limiting constraint of the system. In comparison to 13-inch diameter logs, 19-inch diameter logs require more sawcuts at the band resaw. The increased number of sawcuts consequently reduces the throughput rate of the band resaw. Because of the decreased throughput rate, the conveyors that supply logs to the band resaw from the headrig quickly fill to maximum capacity. When the conveyors that supply logs to the band resaw reach maximum capacity, the headrig machine center is forced to shutdown until space on the conveyors becomes available. The decreased throughput rate of the band resaw machine center is the reason why the total volume of lumber produced is not largely different between the two scenarios.

In comparison to the scenario where only 19-inch diameter logs were processed, the volume of logs processed value was less when only 13-inch logs were input. This is due to the fact that a single 19-inch diameter log has more volume than a 13-inch diameter log. Overall, the simulation model has been demonstrated to have high face validity based upon how the output values of the simulation model changed as expected when different input variables were used.

17. References

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SECTION IV. MODEL LOGIC OF THE MEDIUM VOLUME SAWMILL

1. Introduction

The description of the simulation model presented in this section was developed from information collected from a hardwood sawmill that produces approximately 7 MMBF of hardwood lumber annually. Based upon the volume of lumber produced annually by this sawmill, it is considered to be a medium production sawmill (Bowe et al. 2001, Anonymous 2001). The sawmill is operational 40 hours per week and employees one work shift. Red oak lumber produced at this sawmill was sorted into three grades: FAS, 1C and, 2C. Lumber graded as 2C included all grades of lumber below the 2C grade. Standard 3 ½ x 6 inch pallet cants are also produced during the production of red oak lumber.

2. Generation of entities

A *Create* module generated one batch of twenty entities at simulation time zero. Additional entities were generated through *Separate* and *Arrival* modules. Two *Arrival* modules put entities into the system that represented logs on conveyors at the start of each workday. The entities from the *Arrivals* module enter the system at queues for the log deck and debarker conveyor.

3. Creating Logs

Entities representing logs were assigned log type attributes, log diameter attributes, picture attributes, and volume attributes to differentiate them from entities symbolizing pieces of lumber. Values of the attributes were allocated using *Assign* modules that referenced the look-up tables of *Set* modules. The procedure was similar to the method used for creating log type entities in the model of large volume sawmill.

4. Debarker logic

With the exception of different processing times and conveyor lengths, the logic used to model the debarker was similar to the description of the debarker machine center of the large volume sawmill, that is discussed in SECTION III.4.

5. Headrig logic

Unlike the four sided sawing pattern used at the large sawmill the headrig at the medium sawmill typically only saws two faces of a log before sending it to the gangsaw. The exception being large logs (≥ 19-inches scaling diameter) where four sides (faces) of the log are sawn in order to meet the dimensional specifications of the gangsaw machine center. Because a band resaw machine center is not used at the medium size sawmill, logs are routed to a gangsaw after the headrig.

Essentially the logic for the headrig was the same as in the large sawmill but with different time distributions, used to model delays and process of the sawing sequence. The decision rules that control the number of times a log is rotated was also different because some logs have four faces sawn, while other logs only have two faces sawn.

The number of times a log is rotated is directly related to the number of faces that are sawn on the log. Entities with a log diameter attribute value of less than 19-inches were modeled as being rotated twice and only two faces of the log were sawn.

In relation to the overall cycle time of the headrig machine center this means that it takes a longer time to saw logs that are equal to or greater than 19-inches in diameter. Thus the number of logs, equal to or greater than 19-inches in diameter, input into the model will directly affect the number of logs processed and overall production related output values.

Along with log diameter, the productivity of the headrig machine center in the actual system is also affected by breakdowns (unscheduled downtime) at the gangsaw machine center. The length of the breakdown is the critical component because the queue or holding area before the gangsaw is limited to only four logs. Overall, this means that if a breakdown at the gangsaw machine center exceeds the amount of time that it takes the headrig operator to saw four logs, operations at the headrig must also stop or route the logs somewhere else.

In the actual system, the headrig operation will stop sawing if a breakdown at the gangsaw is minor. If a major catastrophic breakdown occurs at the gangsaw, the headrig operator has the option to completely breakdown the log to a pallet cant, or send the log to a carousel conveyor. Logs sent to the carousel conveyor are routed outside the sawmill and reenter the sawmill at the gangsaw machine center. The carousel conveyor was not modeled because major catastrophic breakdowns were not modeled. However, a scenario can occur in the model where the headrig operation is blocked due to a breakdown at the gangsaw machine center. Blocking was modeled by not allowing an entity to release the headrig resource until there were available cells on the conveyor immediately before the gangsaw machine center.

When logs that are equal to or greater than 19-inches diameter are sawn at the headrig, a proportion of the boards do not need to be edged and are sent directly to the trimmer. Sending boards directly to the trimmer from the headrig is a material flow pattern that does not occur at the large volume sawmill. A series of Decide modules that read the attribute values of the log and lumber entities controlled the material flow pattern (Figure IV-1). The logic of the *Decide* modules that determined the material flow patterns is based upon statistics calculated from the information collected at the sawmill. A description of the data collection procedure is detailed in SECTION II.2.2 and the statistical analysis procedures are presented in SECTION II.3.1

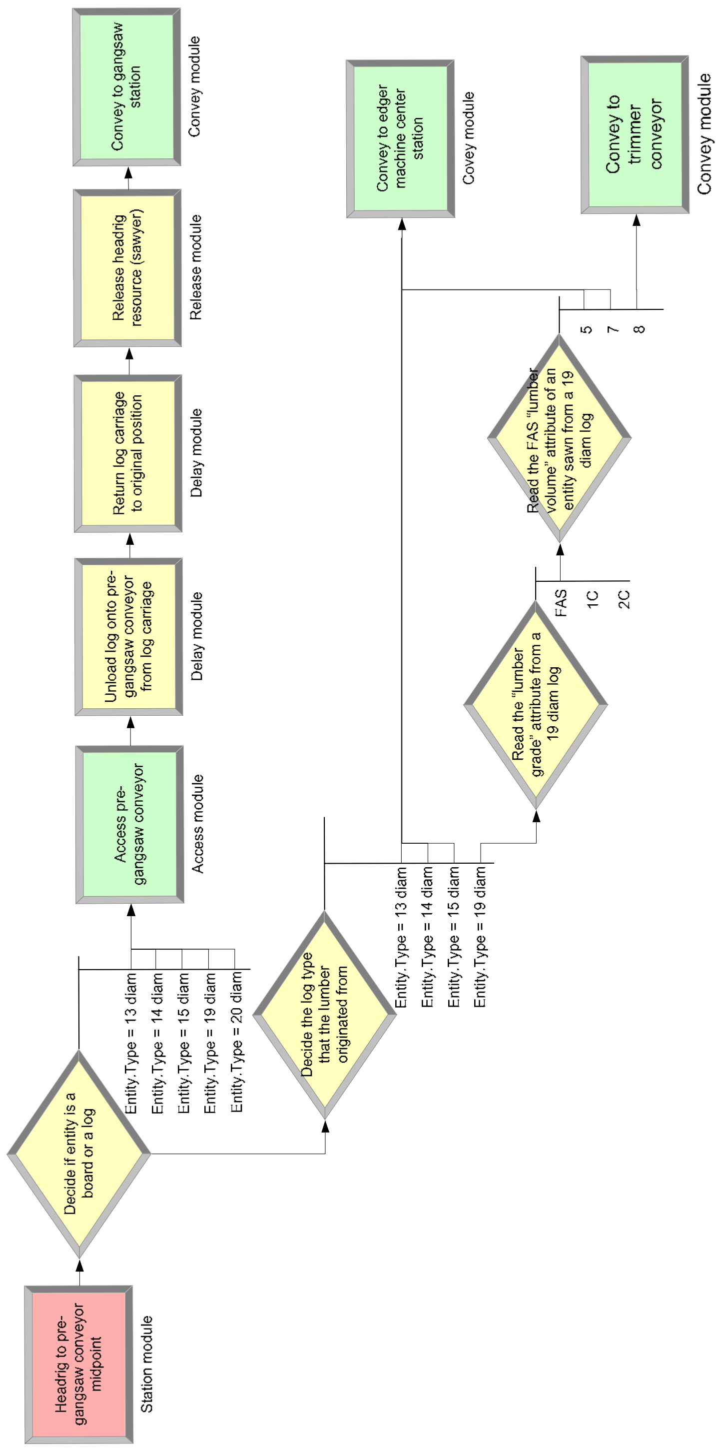

Figure IV-1. Model logic used to control material flow from the headrig to either the edger or trimmer machine centers

6. Gangsaw logic

Because the medium volume sawmill does not utilize a band resaw, log are routed to a gangsaw machine center after being processed at the headrig. When arriving at the gangsaw, two or four faces of a log may have already been sawn at the headrig, depending on the diameter of the log. After being processed at the gangsaw, some of the lumber produced from a log where only two faces are sawn, would have to be sent to the edger machine center. Sending boards from the gangsaw to the edger is also a material flow pattern unique to the medium volume sawmill.

Boards that had been processed at the gangsaw machine center and needed to be edged were transferred to the edger by way of a transporter. The transporter represented the gangsaw tailman. At a *Station* module on the conveyor used to move boards toward the trimmer machine, the attributes of the entities were evaluated by several *Decide* modules. Depending on the value of the attributes, an entity would either be routed to the trimmer machine center or taken off the conveyor and sent to the edger by way of a transporter. The same type of model logic governing material flow from the headrig (Figure IV-1) was used for the gangsaw machine center, except a transporter was used to move boards to the edger.

Representing the gangsaw tailman, the transporter moved entities off the trimmer conveyors to a *Station* module, where cells on the edger conveyor were accessed. When an entity was able to access cells on the edger conveyor, the transporter was released.

7. Edger logic

The time required to edge a board was modeled using a *Process* module. Blocking of entities from seizing the edger resource was done by using *Seize* and *Release* modules. The edger resource could not be released until the postedger conveyor; that links the edger machine center to the trimmer conveyor; could be accessed. The postedger conveyor had a maximum capacity of one entity.

8. Trimmer logic

Because of the configuration of the conveyor system, the trimmer operator is forced to manually move and align every board perpendicular to the bank of trim saws. In comparison, the trimmer operator at the large volume sawmill did not have to handle each individual board. The time required to manually reposition every board before the trim saw conveyor, was modeled using a *Process* module. A *Seize* and *Release* module controlled the flow of entities from the trimmer conveyor to the green chain.

At the medium volume sawmill the close proximity of the trimmer to the lumber inspector and the shorter length of the green chain required the trimmer operator to more closely regulate the flow of materials through the trimmer. A *Hold* module prevented an entity from releasing the trimmer resource until the following conditions were satisfied:

1. The number of entities in the “access green chain” queue equaled zero.
2. The number of entities in queue for the lumber inspection process equaled zero or one.
3. The number of entities in the “access green chain ladder conveyor” queue equaled zero.

The green chain ladder conveyor connects the trimmer machine center to the green chain. Once the three system conditions described above, were found to be true, the trimmer resource was released and a new entity seized the resource. Compared to the large volume sawmill the system conditions for releasing the trimmer resource in the model of the medium volume sawmill were much more stringent. Entities moved from the trimmer station to the beginning of the green chain by means of two ladder conveyors. At the end of the second ladder conveyor (green chain ladder conveyor), boards were graded by a single lumber inspector.

9. Logic used to model the single lumber inspector

Lumber grading at the medium volume sawmill is done by one lumber inspector where the boards remain on the green chain conveyor. The logic used to model the lumber grading process was very similar to that utilized at for the large volume sawmill. One exception being that there was only one lumber inspector, so a *Decide* module was not needed to split the workload between two inspectors. The second exception was the probability distribution used to model the time delay associated with the lumber grading process was also different. A single *Process* module was used to seize, delay, and release the lumber inspector resource. After the lumber inspection station, entities were conveyed on the green chain to lumber stacker stations. At each station, a transporter was requested to remove the entity from the green chain conveyor.

10. Conveyor logic

In comparison to the large volume sawmill, a smaller number of conveyors were utilized for moving lumber at the medium volume sawmill. One reason that fewer conveyors are used is the absence of a band resaw and that remanufactured lumber does not enter the system. The lengths of the conveyors that are used to move logs and lumber from similar machine centers, was also less for the medium volume sawmill. Shorter conveyors and less machine centers equated to faster throughput times but the production per hour rate was still less than that of the large volume sawmill. The presence of the band resaw machine center at the large volume sawmill probably accounts for the larger production per hour values.

As with the large volume sawmill, *Access*, *Convey*, and *Exit* flowchart modules were used to model the conveyors for the medium volume sawmill. The lengths and velocity rates of the individual conveyors utilized at the medium volume sawmill were entered into the *Conveyor* and *Segment* data modules. Most of the conveyors were defined in the *Conveyor* data module as being accumulating. The lug-type conveyors used at the trimmer machine center were defined as the non-accumulating type.

11. Transporter logic

At the large volume sawmill the gangsaw tailman does not have a vital role in movement of material between machine centers and thus was not modeled. However, at the medium volume sawmill the gangsaw tailman is directly responsible for moving boards from the outfeed of the gangsaw to the edger machine center. In addition, the gangsaw tailman also controls the movement of the conveyor that transports lumber to the trimmer machine center. Because of the many system dynamics that are affected by the gangsaw tailman, the position was included in the simulation model of the medium volume sawmill and was modeled as a transporter.

All of the entities generated at the gangsaw machine center were routed on a conveyor to a *Station* module that represented the location of the gangsaw tailman in relation to the beginning and ending of the conveyor. At the *Station* module, the operating state of the gangsaw machine resource was evaluated by a *Decide* module. The operating state of a resource is a numerical value that communicates if a resource is idle (-1), busy (-2), inactive (-3), or failed (-4) (Kelton et al. 2004). If the *Decide* module evaluated the gangsaw resource as being in a failed state, the conveyor that moved lumber to the trimmer was stopped. As illustrated in Figure IV-2, a *Hold* module restricted entities from starting the trimmer conveyor until the gangsaw resource became idle, busy, or inactive. In the actual system when the gangsaw has unscheduled downtime, the tailman will stop the trimmer conveyor and assist the gangsaw operator in repairing the machine.

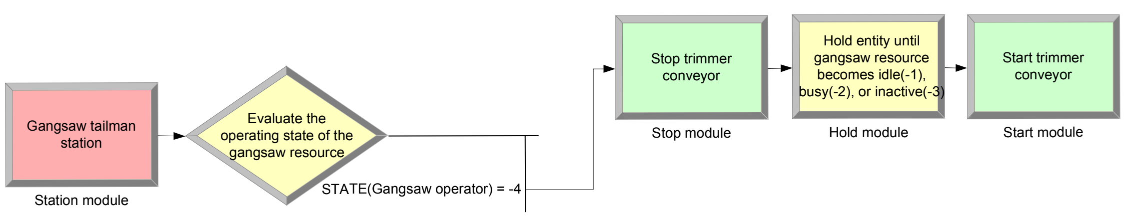

Figure IV-2. Logic used to stop the trimmer conveyor when the gangsaw resource was in a failed state

Other transporters modeled include a log loader and six lumber stackers. The technique to model the lumber stackers was the same as that used in the model of the large volume sawmill. However, the log loader that transports logs from the log yard to the log deck had to be modeled in a slightly different manner.

The design of the log deck conveyor system at the large volume sawmill facilitated the direct loading of logs from the log yard. At the medium volume sawmill, logs loaded onto the conveyor leading to the debarker machine center, have to be aligned with three supports that hold up the conveyor. Through observations of the actual system, if logs were not placed in a certain position, they would fall off the log deck conveyor. To ensure that logs are properly loaded onto this conveyor, logs are placed on the log deck in batches of three by the log loader. To optimize the transportation of logs from the log yard to the debarker, the log loader transports logs in batches of ten. Logs taken from the log yard are placed in a staging area near the debarker. From the staging area, logs in batches of three are then loaded onto the log deck.

In the simulation model, a *Station* module was used to represent the staging area for logs (Figure IV-3). At the staging area station, entities from the log yard were batched and held in queue until the number of entities being conveyed or accumulated on the log deck reached a specific number. The specific number of entities was determined by a value generated from a Uniform distribution with a minimum parameter of one and a maximum parameter of fourteen. The parameters of the Uniform distribution were chosen based upon the maximum capacity of the log deck as measured in the actual system. When the number generated from the Uniform distribution equaled the current conditions of the log deck conveyor, the log loader was requested to transport logs to the beginning of the log deck.

The beginning of the log deck conveyor was modeled as a *Station* module. Another *Hold* module was then used to prevent the entities from being unloaded onto the log deck until a specific number of entities were present on the log deck conveyor. Determination of the number of entities that could be present on the log deck conveyor before the transporter would be released was based upon a value generated by the Uniform distribution with a minimum parameter of one and a maximum parameter of fourteen. Using the Uniform distribution in two different modules to specify parameters for the log deck conveyor was done to model the randomness of the log loader. From observing the log loader at the sawmill, there appeared to be no set rules or parameters, that were followed governing when to put logs onto the log deck. The only exception being that logs could not be loaded if the conveyor was at maximum capacity.

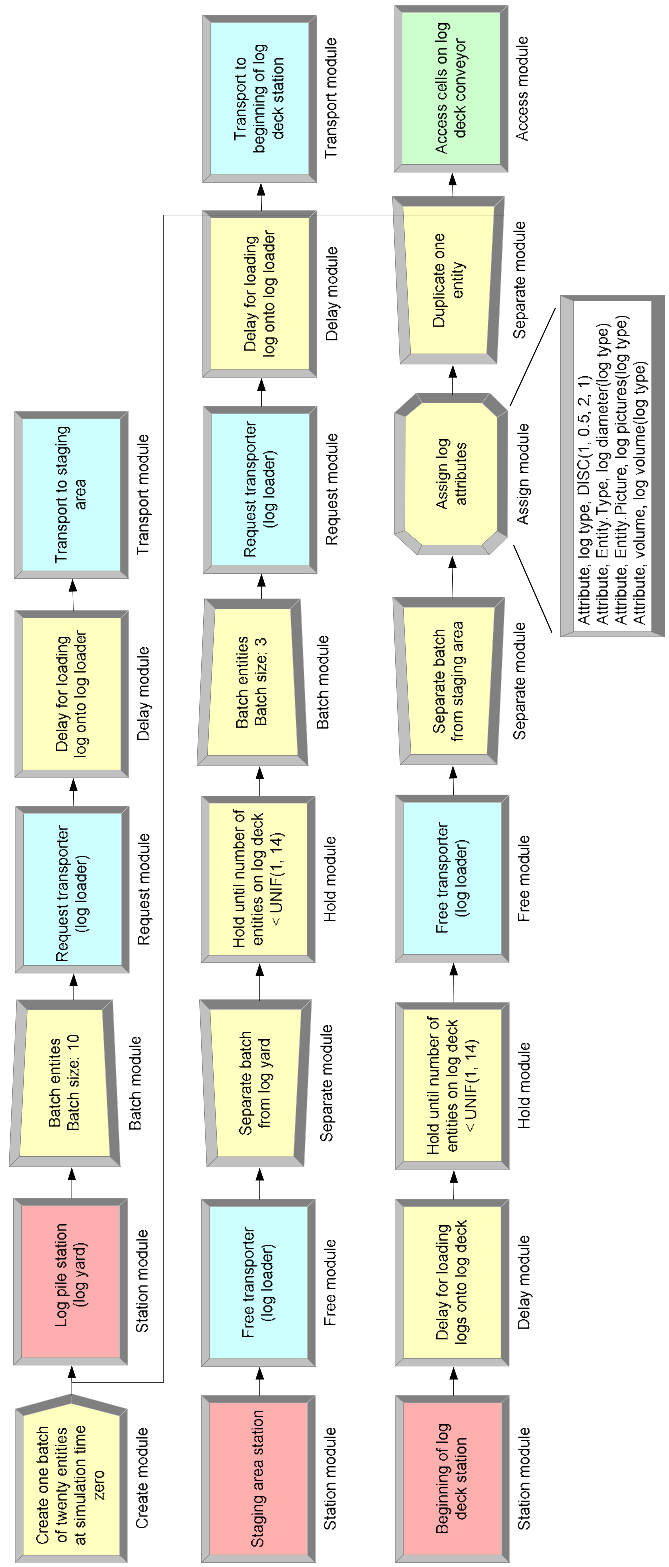

Figure IV-3. Logic used to model the movement of the log loader transporter from the log yard, staging area, and log deck stations

12. Modeling scheduled and unscheduled downtime

Information on scheduled downtime for each machine center was able to be obtained from the management of the sawmill. At the beginning of a ten-hour workday, all of the machine centers begin working. Two fifteen minute breaks and one thirty minute break are scheduled each day and occurred at fixed times from the start of the workday. The *Schedule* data module controlled the frequency and duration of the scheduled downtimes (Table IV-1). Because all of the machine centers began and stopped operating at the same time, only one workday schedule was needed. In contrast, the *Schedule* data module for the large volume sawmill required three different workday schedules to model how the machine centers began and stopped operating at different times.

Table IV-1. Prompts and entries for the Schedule data module

Prompt	Entry	
Name	Mill schedule	
Format type	Duration	
Type	Capacity	
Time units	Hours	
Scale factor	1.0	
Duration	Capacity	Duration
	1	2.50
	0	0.25
	1	2.25
	0	0.50
	1	2.50
	0	0.25
	1	1.75

The unscheduled downtime statistics that had been collected for each machine center from the sawmill were input into a *Failure* data module (Table IV-2). Unscheduled downtime statistics for the edger machine center were not collected, because this machine center did not have an instance of unscheduled downtime on the day, downtime statistics were being recorded. The unscheduled downtime statistics of the headrig machine center were used in place of the missing information for the edger machine center. The frequency and duration of breakdowns by visual examination of the simulation model appeared similar to observations of the actual system.

Table IV-2. Prompts and entries for the Failure data module

Prompt	Entry
Name	`Debarker failure`
Type	`Count`
Count	`POIS(9)`
Down time	`16 + WEIB(42.5, 0.69)`
Down time units	`Seconds`
Name	`Headrig failure`
Type	`Count`
Count	`POIS(17)`
Down time	`UNIF(6, 37)`
Down time units	`Seconds`
Name	`Gangsaw failure`
Type	`Count`
Count	`POIS(21)`
Down time	`7 + LOGN(62.5, 178)`
Down time units	`Seconds`
Name	`Edger failure`
Type	`Count`
Count	`POIS(17)`
Down time	`UNIF(6, 37)`
Down time units	`Seconds`
Name	`Trimmer failure`
Type	`Count`
Count	`POIS(28)`
Down time	`1 + LOGN(5.01, 8.53)`
Down time units	`Seconds`

13. Model verification

As part of the verification process the capacity of machine center resources were systematically set to zero and the system response was visually observed, through the animation of the model. Numerous simulation runs were done, where by, for each run a specific machine center was taken offline. This part of the verification process illustrated that the logic programmed into the model produced the expected results.

Another part of the verification process was to compare the proportion of each lumber grade produced by the simulation model to the yield data collected from the sawmill. This comparison was done by log type and machine center. A specific percentage of each lumber grade was expected to be modeled as being produced by the headrig, and gangsaw machine centers. In addition, a specific proportion of each lumber was expected to be routed to the edger machine center. The expected percentage values were compared to the values generated from ten replications of the simulation model. Output from the simulation model and the expected values for the headrig and gangsaw machine centers are presented in Table IV-3 and Table IV-4, respectively. The proportion of each lumber grade modeled as being processed by the edger machine center and the expected values is presented in Table IV-5. Overall, the verification process illustrated that the logic programmed into the model was correct and that the model performed as anticipated.

Table IV-3. Verification of input values relating to the volume and grade of lumber produced at the headrig machine center

Grade	Log parameters[A] Length (ft.)	Diameter (in.)	Percentage of total volume produced[B] FAS	1C	2C and lower
Prime	8	13	0(0)	19.7(20.6)	80.3(79.4)
Prime	8	14	30.2(30.4)	52.9(52.2)	16.9(17.4)
Prime	8	15	0(0)	57.1(58.0)	42.9(42.0)
Select	8	13	8.1(7.8)	56.1(56.9)	35.8(35.3)
Select	8	14	0(0)	50.0(48.1)	50.0(51.9)
Select	8	15	0(0)	52.2(52.0)	47.8(48.0)
Prime	12	13	29.1(30.2)	52.0(50.9)	18.9(18.9)
Prime	12	14	30.7(30.6)	65.5(65.3)	3.8(4.1)
Prime	12	15	33.3(34.7)	27.3(28.5)	39.3(36.8)
Select	12	13	15.7(13.8)	24.5(23.8)	59.8(62.5)
Select	12	14	9.8(10.5)	16.4(15.8)	73.8(73.7)
Select	12	15	18.1(18.3)	42.0(40.9)	39.9(40.9)
Select	12	19	39.5(40.2)	46.6(45.1)	13.9(14.6)
Select	12	21	0(0)	78.5(79.1)	21.5(20.9)

[A]Prime grade equates to four clear log faces. Select grade refers to two clear log faces

[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

Table IV-4. Verification of input values relating to the volume and grade of lumber produced at the gangsaw machine center

	Log parameters[A]		Percentage of total volume produced[B]		
Grade	**Length (ft.)**	**Diameter (in.)**	**FAS**	**1C**	**2C and lower**
Prime	8	13	0(0)	15.3(16.3)	84.7(83.7)
Prime	8	14	29.8(29.6)	11.9(11.1)	58.4(59.3)
Prime	8	15	0(0)	51.5(56.6)	48.5(43.4)
Select	8	13	0(0)	24.4(25.7)	75.6(74.3)
Select	8	14	0(0)	8.2(8.2)	92.2(91.8)
Select	8	15	0(0)	29.4(27.6)	70.6(72.4)
Prime	12	13	19.8(20.7)	46.8(45.1)	33.4(34.1)
Prime	12	14	11.7(11.3)	34.4(35.5)	53.9(53.2)
Prime	12	15	25.4(23.3)	23.8(24.7)	50.8(52.1)
Select	12	13	0(0)	21.6(22.4)	78.4(77.6)
Select	12	14	0(0)	4.7(4.8)	95.3(95.2)
Select	12	15	0(0)	20.8(20.4)	79.2(79.6)
Select	12	19	14.3(14.1)	21.0(21.2)	64.7(64.7)
Select	12	21	16.3(17.1)	32.7(31.4)	50.9(51.4)

[A]Prime grade equates to four clear log faces. Select grade refers to two clear log faces
[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

Table IV-5. Verification of input values relating to the volume and grade of lumber produced at the edger machine center

	Log parameters[A]		Percentage of total volume produced[B]		
Grade	**Length (ft.)**	**Diameter (in.)**	**FAS**	**1C**	**2C and lower**
Prime	8	13	0(0)	19.7(20.6)	80.3(79.4)
Prime	8	14	30.2(30.4)	52.9(52.2)	16.9(17.4)
Prime	8	15	0(0)	57.1(58.0)	42.9(42.0)
Select	8	13	6.3(6.2)	44.0(44.6)	49.7(49.2)
Select	8	14	0(0)	45.8(43.9)	54.2(56.1)
Select	8	15	0(0)	52.2(52.0)	47.8(48.0)
Prime	12	13	25.7(26.2)	52.3(50.8)	22.1(23.0)
Prime	12	14	30.0(29.8)	66.3(66.1)	3.7(4.0)
Prime	12	15	31.9(33.3)	26.1(27.3)	42.0(39.3)
Select	12	13	14.6(12.8)	27.5(26.7)	57.9(60.5)
Select	12	14	9.0(9.6)	20.2(19.3)	70.8(71.1)
Select	12	15	17.4(17.5)	42.0(41.2)	40.6(41.2)
Select	12	19	46.1(46.5)	42.1(40.8)	11.8(12.7)
Select	12	21	0(0)	72.9(73.6)	27.1(26.4)

[A] Prime grade equates to four clear log faces. Select grade refers to two clear log faces
[B] Values in parenthesis are the true or expected values. Values may not sum to 100% due to rounding

14. Model validation

14.1. Validation of model assumptions

The structural and data assumptions of the simulation model were validated using techniques described by Law and Kelton (1991) and Banks et al. (2001). For the most part, the structural and data assumptions for the model of the large volume sawmill and the model of the medium volume sawmill were similar. The major difference being the number of conveyors where log type entities are pre-loaded at the beginning of each simulation run.

14.1.1. Structural assumptions

14.1.1.1. State of model at startup

At simulation time zero, between one and fourteen log type entities are occupying the cells of the log deck conveyor and debarker conveyor. The log deck conveyor holds logs for processing at the debarker machine center and the debarker conveyor brings logs into the sawmill after debarking. Two *Arrival* modules were used to generate entities that represented logs loaded onto the conveyors during the previous workday and had not yet been processed. A Uniform distribution, with a minimum parameter of one and a maximum parameter of fourteen, controlled the number of entities present in the conveyors at startup. The maximum parameter for the Uniform distribution corresponds to the maximum number of logs that each conveyor can hold. A Uniform distribution was used because observations of the actual system demonstrated that the number of logs present on the conveyors at startup varied and were not fixed.

14.1.1.2. Assigning lumber grade attributes as a function of time

As with the model of the large sawmill, the limitations of the lumber yield collection procedure did not allow for recording the numerical order that boards were produced from a log. Because of this, the model is not capable of precisely assigning grade and volume attributes to the lumber entities in the order that they would be produced from a log. The main concern of not being able to model the relationship between lumber grade and time, was that the product costs would not be accurately assigned based upon the time an entity is in a queue. However, since the throughput of material through the system occurs very quickly, the time an entity is in queue may have a negligible affect on product costs. A more thorough explanation of the problems associated with not modeling lumber grade production as a function of time is presented in SECTION III.16.1.1.3.

14.1.1.3. Relation of processing time distributions to log parameters

For the simulation model, the processing time distributions were not modeled as being specific to log or lumber parameters. Observations of the actual system illustrated that regardless of log or lumber parameters, delays associated with material handling occurred at all of the machine centers. The material handling delays appeared to occur randomly and were included in the timing of the individual processes at each machine center.

When viewed in its entirety, the course of action for sawing lumber at the headrig involves numerous processes. The process of moving the log through the saw, in most instances, requires incrementally more time as the length of a log increases. In the instances where a jacket board or a slab is being sawn, log length is not a factor because the saw does not travel the entire length of the log. However, because moving the log through the saw is only one process that occurs at the headrig, the effect of log length of total processing time may not be significant. In modeling the headrig processes for the simulation model the effect of log length on total processing time was not considered to be a factor that would dramatically affect the processing time.

A two-sample Welch *t*-test was conducted to test the assumption that log length does not have a significant effect on the processing time of the headrig machine center. The data for the statistical test was collected from the medium volume sawmill and encompassed the total processing times for red oak logs varying in scaling diameter from eight to twelve inches. Of the forty-seven measurements recorded, fourteen were from logs eight-foot in length and the remaining thirty-three data points were from twelve-foot long logs. From the statistical test there was no significant difference (p=0.52) in the total processing times between eight and twelve foot long logs at an alpha level of 0.05. Since the headrig machine center controls the production at the sawmill, the significance of material length on the processing times of the other machine centers was not examined.

14.1.2. Data assumptions

For the model of the large volume sawmill there was an assumption made about the analysis of the lumber yield data in regards to lumber thickness. The assumption was that ability to predict lumber yield, would be biased since the lumber yield data had been collected under sawing conditions when two lumber thicknesses were being simultaneously being sawn. The same assumption is not relevant for the lumber yield data from the medium volume sawmill since all of the data was collected when the target nominal lumber thickness was one inch.

14.1.2.1. Reliability of the processing time data

14.1.2.1.1. Tests for homogeneity

Only the dataset for the debarking process was tested for homogeneity because it was the only dataset that contained information collected at different time periods. All of the other datasets used to calculate processing time distributions for the machine centers had been collected on a single day. The 33 data points relevant to the debarking processing had been collected on three separate days. The SAS `npar1way` procedure was used to perform the Kruskal-Wallis test for homogeneity. Results of the test were to reject the null hypothesis that the population distribution functions are identical for the debarker processing times dataset (p = 0.02). A thorough description of the Kruskal-Wallis test is presented in SECTION III.16.1.2.2.1.

Despite the null hypothesis of the homogeneity test being rejected, the values were still considered to be representative of the debarking process. One explanation that the null hypothesis was rejected is that more material handling delays occurred on one of the days when the information was being collected. The difference in the timing values from the different days would be statistically different if the material handling delays did not occur uniformly between the different days.

14.1.2.1.2. Tests for independence

Autocorrelation plots were constructed for each dataset that was used to calculate the distributions for the processing times of each machine center. For each dataset, the autocorrelation of the k^{th} lag was calculated with the JMPIN statistical software package (Sall et al. 2001). Autocorrelation plots of each dataset are presented consecutively from Figure IV-4 to Figure IV-14. The solid bars of the autocorrelation plots represent the autocorrelation value for the k^{th} lag. The thin continuous lines are located ± 2 standard errors from the baseline of zero for the k^{th} lag. Since the autocorrelation values of each dataset were near zero, each dataset was considered to be independent.

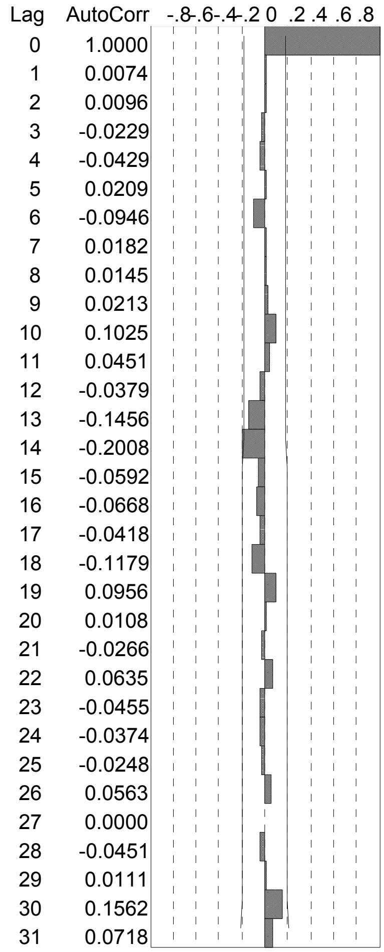

Figure IV-4. Autocorrelation plot for the gangsaw processing time dataset

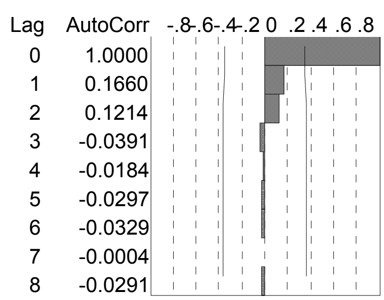

Figure IV-5. Autocorrelation plot for the debarker processing time dataset

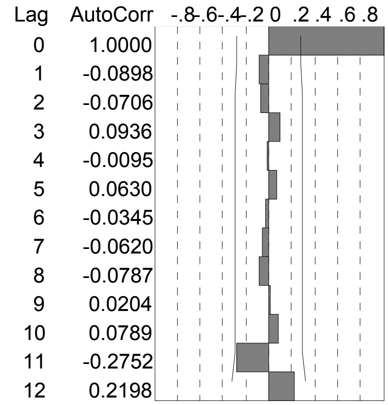

Figure IV-6. Autocorrelation plot for the edger processing time dataset

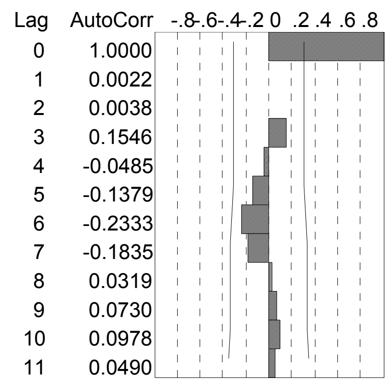

Figure IV-7. Autocorrelation plot for the log loading times dataset

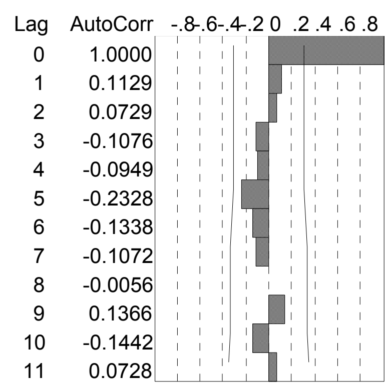

Figure IV-8. Autocorrelation plot for the log sawing times dataset

Lag	AutoCorr
0	1.0000
1	0.2091
2	-0.1553

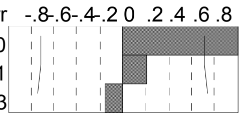

Figure IV-9. Autocorrelation plot for the log unloading times dataset

Lag	AutoCorr
0	1.0000
1	0.3113
2	0.1361
3	0.0567
4	0.3125
5	0.1974
6	0.1360
7	-0.0805
8	0.0477
9	0.2170
10	0.1705

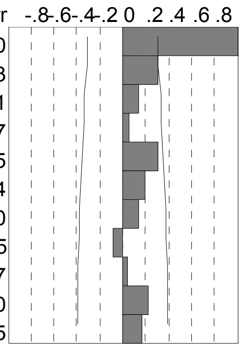

Figure IV-10. Autocorrelation plot for the return carriage from gangsaw times dataset

Lag	AutoCorr
0	1.0000
1	-0.0860
2	0.1410
3	-0.1205
4	-0.0093
5	-0.1060
6	-0.0627
7	0.1378
8	0.1157
9	0.0739
10	-0.1974

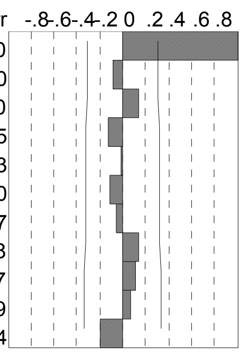

Figure IV-11. Autocorrelation plot for the return to original position times dataset

Lag	AutoCorr
0	1.0000
1	0.2989
2	0.1940
3	-0.0826
4	-0.0161
5	-0.0370
6	0.0184
7	0.1254
8	0.1819
9	0.0563
10	-0.1390
11	-0.0428

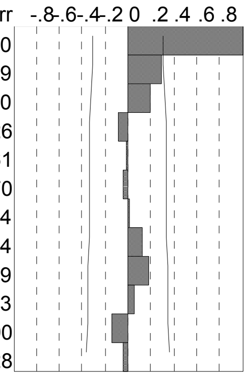

Figure IV-12. Autocorrelation plot for the return to short position times dataset

Lag	AutoCorr
0	1.0000
1	0.2615
2	0.0297
3	0.0865
4	-0.0477
5	0.0874
6	0.0253

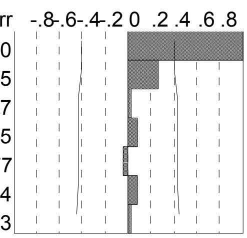

Figure IV-13. Autocorrelation plot for the trimmer processing times dataset

Lag	AutoCorr
0	1.0000
1	0.0863
2	0.0004
3	-0.0052
4	-0.0371
5	-0.1504

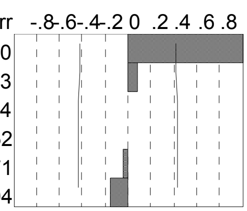

Figure IV-14. Autocorrelation plot for the lumber inspection processing times dataset

14.2. Comparison of simulation output data to actual system observations

14.2.1. Methods

Four production reports from days when red oak lumber was being sawn were able to be obtained from the sawmill. The volume of lumber produced per hour, and number of logs processed per hour values from the production reports were compared to output values from the simulation model. Validation of the model logic for the headrig machine center was also done by comparing cycle time values from the model to cycle time values measured at the sawmill.

Output values from the simulation model were obtained from ten replications, where each replication modeled a ten-hour workday. For each replication, a different random number stream was used so that the output values between each replication were statistically independent. Control of how entities were seized and released by resources when scheduled breaks and failures occurred followed the *Preempt* rule.

The input variable used for the validation process was fourteen different types of logs, with different grade, diameter, and length parameters. A discrete empirical distribution was used to control the proportion of each log type that was generated in the model. With the discrete empirical distribution, each log type had an equal probability of being input into the model. Statistical differences in the values of the production measurements between the actual system and the simulation model were examined using a two-sample Welch *t*-test.

14.2.2. Results

As was done with the validation process for the model of the large volume sawmill, the SAS `ttest` procedure was used to perform the two-sample Welch *t*-test at an alpha level of 0.05 (SAS Institute Inc. 2004). The null hypothesis, of each test, was the output from the simulation model was equal to the values from the production reports. The alternative hypothesis was that the values were not equal.

For the average volume of lumber produced per hour measurement, the null hypothesis was not rejected ($p = 0.49$). The values from the simulation model and the production reports were not significantly different as shown in Table IV-6. When the number of log processed per hour values were compared, the results also failed to reject the null hypothesis ($p = 0.17$). Results of the test are presented in Table IV-7.

For the headrig machine center data, the statistical test failed to reject the null hypothesis ($p = 0.92$), indicating that the headrig cycle times from the simulation were not significantly different from the values of the actual system (Table IV-8). The results of the three statistical tests illustrate that the simulation model properly represented the actual system.

Table IV-6. Two sample Welch t-test of the average volume of lumber produced per hour by the actual system and the output from model of the medium volume sawmill

		Range[B]		Two sample Welch *t*-test	
Variable	***n*** [A]	**Min**	**Max**	**95% Confidence intervals for μ**	***p*-value**[C]
System data	4	3,464	3,804	3,647 ± 246 (3,401 , 3,893)	0.49
Simulated data	10	3,670	3,781	3,708 ± 30 (3,678 , 3,738)	

[A]n = number of data points or replications
[B]Values are reported in units of board feet/hour
[C]$\alpha = 0.05$

Table IV-7. Two sample Welch t-test of the average number of logs processed per hour by the actual system and the output from model of the medium volume sawmill

		Range[B]		Two sample Welch *t*-test	
Variable	***n*** [A]	**Min**	**Max**	**95% Confidence intervals for μ**	***p*-value**[C]
System data	4	45	57	51 ± 8 (43 , 59)	0.17
Simulated data	10	45	48	46 ± 1 (45 , 47)	

[A]n = number of data points or replications
[B]Values are reported in the unit number of logs processed/hour
[C]$\alpha = 0.05$

Table IV-8. Two sample Welch t-test of the average headrig cycle time by the actual system and the output from model of the medium volume sawmill

Variable	***n*** [A]	**Range**[B] **Min**	**Max**	**Two sample Welch *t*-test 95% Confidence intervals for *μ***	***p-value***[C]
System data	51	19.14	180.00	71.74 ± 10.83 (60.91 , 82.57)	0.92
Simulated data	10	69.70	73.71	71.19 ± 0.94 (70.25 , 72.13)	

[A]*n* = number of data points or replications
[B]Values are reported in units of seconds
[C]$\alpha = 0.05$

14.3. Face validity

To examine the face validity of the model, the output values of the simulation model were examined from two different log input scenarios. The output values of interest were the number of logs processed, total volume of logs processed and total volume of lumber produced. These three production related measurements provided insight into how the simulation model responded to different inputs. The different inputs that were used to examine the face validity of the model was log diameter. In one scenario, only nineteen and twenty-one inch diameter logs were modeled as being sawn. For the second scenario, only thirteen-inch diameter logs were modeled as being sawn. Each scenario was replicated 10 times, where each replication modeled a ten-hour workday.

As shown in Table IV-9, when only thirteen-inch diameter logs were modeled as being sawn, the number of log processed, is twice the amount for the scenario when the log input is limited to only nineteen and twenty-one inch logs. The dissimilarity in the number of logs processed between the two scenarios is the response that would be expected to occur in the actual system, given that nineteen and twenty-one inch diameter logs are processed at the headrig differently than thirteen-inch diameter logs. At the headrig machine center, nineteen and twenty-one inch diameter logs have to be rotated three times and four sides of the log are required to be sawn in order to meet the dimensional specifications of the gangsaw. In comparison, thirteen-inch diameter logs are only rotated once and are sawn on two sides. Because fewer actions are needed to process thirteen-inch diameter logs in comparison to nineteen or twenty-inch diameter logs, more thirteen-inch diameter logs would be expected to be processed.

Table IV-9. Comparison of output values when only 19 and 21-inch or 13-inch diameter logs are sawn to the model output when all logs are sawn

Input scenario	**Number of logs processed**	**Total volume of logs processed (bd.ft.)** [A]	**Total volume of lumber produced (bd.ft.)**
	- - - - - - - - - - - - - 95% Confidence intervals for μ^B - - - - - - - - - - - - - -		
19 & 21-inch diameter logs	284 ± 2	54,549 ± 282	44,575 ± 250
13-inch diameter logs	550 ± 7	27,676 ± 414	33,364 ± 486
All available log diameters	450 ± 7	36,698 ± 503	37,083 ± 297

[A]The volume of logs processed values are reported in board feet from the Doyle log scale
[B]Confidence intervals were calculated using data from ten replications of the simulation model

The difference in the total volume of logs processed between the two scenarios relates to the fact that large diameter logs scale to a larger volume than small diameter logs. Because the total volume of logs processed value between the two scenarios was found to be different, the logic used to assign log volume attributes was further validated.

For the scenario where only thirteen-diameter logs were sawn, the total volume of lumber produced was greater than the total volume of logs that were input into the sawmill. This difference was expected based upon the lumber yield information for thirteen-inch diameter logs collected from the sawmill. Of the thirteen-inch diameter logs sampled, the volume of lumber produced exceeded the log volume. In the scenario where only nineteen and twenty-inch diameter logs were sawn, the total volume of lumber produced was less than the total volume of logs input into the sawmill. The lumber yield statistics, collected at the medium volume sawmill, for nineteen and twenty-one inch diameter logs also reflected this difference. In summary, the simulation model had high face validity as illustrated by how the output values of the simulation model changed as expected when different input variables were used.

15. References

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SECTION V. EVALUATION OF THE ACTIVITY-BASED COST ACCOUNTING SYSTEM

1. Introduction

One of the objectives of this research project was to compare the differences in product costs calculated from traditional accounting techniques, and the activity-based costing technique. With the use of discrete-event simulation, product costs were calculated using both the traditional and activity-based costing technique, with information that would have been difficult to measure in an actual sawmill system. The purpose of this section is to present how and to what degree the activity-based and traditional volume costing methods, differently allocated costs to the products.

2. Methodology

By using the output data from the models of the large and medium volume sawmill, the cost of manufacturing the lumber products was calculated, first with the traditional volume method and then with the activity-based method. Ten replications of each model were run so that confidence intervals could be calculated with the output values from the simulation models. Each simulation model was executed under terminating conditions, where the ending point of each run was when the model had simulated one complete workday. One complete workday constituted eleven hours for the model of the large volume sawmill and ten hours for the model of the medium volume sawmill.

2.1. Variance reduction

In an effort to reduce variance of the output values from the model, the common random number reduction technique was employed using the *Seeds* Element module. By using the *Seeds* Element, the random number streams for each variate; i.e. processing times, could be synchronized across replications. In the ARENA modeling environment, the synchronization is done by the software assigning the starting seed values for each successive replication 100,000 values apart within the random number stream (Kelton et al. 2004).

For the simulation experiment each machine center processing time distribution was assigned a different starting seed value. The random number stream used to assign the log type attribute values were also assigned starting seed values. In addition, the random number streams that controlled the frequency and duration for each of the machine center resources were assigned different starting seed values.

2.2. Input parameters

The number of logs generated by the models and their characteristics (grade, diameter, and length) was controlled using a Discrete distribution. Parameters of the Discrete distribution, allowed the probability of any log type value assigned to an entity to be equal across all of the possible values.

2.3. Definition of the cost categories

2.3.1. Direct labor costs

Direct labor costs encompassed the labor rates of personnel who operated or directly serviced machine centers where lumber was produced or processed. The line items for the direct labor cost category included the hourly labor rates of the:

1. Headrig machine operator
2. Sawfiler for the headrig
3. Gangsaw machine operator
4. Gangsaw tailman
5. Edger machine operator
6. Trimmer machine operator
7. Band resaw machine operator (relevant only to the large volume sawmill)
8. Sawfiler for the band resaw (relevant only to the large volume sawmill)

Since the debarker machine center does not produce lumber and all logs must be debarked, the labor cost of the debarker machine center was not included in the direct labor cost category.

Labor costs associated with lumber grading and stacking were also not included in the direct labor cost category. Because all of the lumber produced must be graded and stacked, there is little difference in how the cost structure would be different between the lumber grades. However, the labor rate of the trimmer operator was included in the direct labor cost category, even though every piece of lumber passes through the trimmer machine center. The labor cost of the trimmer operator was included because some pieces of lumber are routed directly to the trimmer machine center while others are first routed to the edger machine center. Because of this difference in material flow patterns, allocating the labor cost of the trimmer to the direct labor cost category is necessary to identify how individual pieces of lumber consume direct labor costs differently.

The hourly labor rates included in the direct labor cost category for the large volume and medium volume sawmill are presented in Table V-1 and Table V-2, respectively. Hourly labor rates for personnel at the large volume sawmill were able to be obtained, but the labor rates for the medium volume sawmill were not provided by the sawmill. As a result, the labor rates from the large volume sawmill were used for the labor rates of the medium size sawmill.

Table V-1. Components of the direct labor cost category for the large volume sawmill

Machine center	Associated employee(s)	Hourly wage ($/hr)	Quantity
Headrig	Head sawyer	17.16	1
	Saw filer #1	17.21	1
Band resaw	Band resaw operator	17.16	1
	Cant station operator	10.87	1
	Saw filer #2	17.21	1
Gangsaw	Gangsaw operator	10.87	1
	Gangsaw tailman	10.50	1
Trimmer	Trimmer operator	10.87	1
Edger	Edger operator	10.87	1

Table V-2. Components of the direct labor cost category for the medium volume sawmill

Machine center	Associated employee(s)	Hourly wage ($/hr)	Quantity
Headrig	Head sawyer	17.16	1
	Saw filer	17.21	1
Gangsaw	Gangsaw operator	10.87	1
	Gangsaw tailman	10.50	1
Trimmer	Trimmer operator	10.87	1
Edger	Edger operator	10.87	1

2.3.2. Indirect labor costs

The indirect labor cost category, consisted of the labor costs of personnel who work directly in the sawmill but do not perform a function that can be directly allocated to a specific lumber grade or can be differentiated between lumber grades. Costs for the indirect labor line item, included the hourly labor rate of:

1. Maintenance personnel
2. Employees who help maintain the flow of materials between machine centers; i.e. offbearers and floor personnel
3. Management personnel whose primary responsibility is to oversee sawmill activities
4. Lumber graders
5. Debarker operator
6. Lumber stackers on the green chain
7. Personnel who operate forklifts that remove lumber from the green chain
8. Personnel who operate log loaders that transport logs from the log yard to the sawmill

The indirect and direct labor rates used for this study only accounted for an hourly wage and did not include costs related to benefits or taxes that are incurred by the employer. The hourly labor rates included in the indirect labor cost category for the large volume and medium volume sawmill are presented Table V-3 and Table V-4, respectively.

Table V-3. Components of the indirect labor cost category for the large volume sawmill

Position	**Wage ($/hr)**	**Quantity**
Mill foreman	21.00	1
Debarker operator	10.87	1
Maintenance personnel	16.50	4
Floor personnel	10.50	1
Green chain workers	10.50	7
Lumber graders	15.25	2

Table V-4. Components of the indirect labor cost category for the medium volume sawmill

Position	Wage ($/hr)	Quantity
Mill foreman	21.00	1
Debarker operator	10.87	1
Maintenance personnel	16.50	1
Green chain workers	10.50	7
Lumber graders	15.25	1

2.3.3. Raw material costs

The raw material cost category encompassed the purchase price of logs. Prices paid for logs by grade, species, and volume were able to be obtained from the large and medium volume sawmill. Because log prices change over time, as a function of different market structures, the values presented in Table V-5 and Table V-6 may not be representative of current prices for red oak logs.

Table V-5. Prices that the large volume sawmill was willing to pay for delivered Prime and Select grade red oak logs (Effective October 2002)

Log grade	Price ($/MBF)[A]
Four clear faces (Prime)	650
Two clear faces (Select)	400

[A]MBF = 1,000 board feet

Table V-6. Prices that the medium volume sawmill was willing to pay for delivered Prime and Select grade red oak logs (Effective June 2003)

Log grade	Price ($/MBF)[A]
Four clear faces (Prime)	615
Two clear faces (Select)	360

[A]1 MBF = 1,000 board feet

2.3.4. Overhead costs

Information for the overhead costs of the large volume sawmill were provided by the management. For the medium size sawmill, the overhead costs values were based upon industry averages for hardwood sawmills that produce 7 million board feet (MMBF) or less of hardwood lumber annually. The industry average values were provided by the management of the large volume sawmill. The information regarding overhead costs was not very detailed as to what specific costs were included in the cost categories relating to overhead costs. Because of this, overhead costs could not be allocated to the machine centers.

Overhead costs, as they pertained to this research project, included fixed and variable overhead costs. The only fixed overhead cost used was depreciation on the sawmill equipment. Line items for the variable overhead cost category were supplies, and utilities. As defined by the information provided from the sawmill, the supplies cost category encompasses all maintenance supplies and other miscellaneous expenses not including log costs related to sawmill operations. Utility costs were defined as the electricity and other power generating expenses incurred by the sawmill operations. The overhead costs for the large volume and medium volume sawmill are presented Table V-7 and Table V-8, respectively.

Table V-7. Components of the overhead cost category for the large volume sawmill

Overhead cost category	Costs incurred over one year	Hourly rate
Fixed overhead cost		
Depreciation	$1,027,705	$117/hour[A]
Variable overhead costs		
Supplies	$1,644,328	$411/hour[B]
Utilities	$645,986	$161/hour[B]

[A]Calculated based upon 8,760 hours in one year
[B]Calculated based upon 4,000 operating hours in one year

Table V-8. Components of the overhead cost category for the medium volume sawmill

Overhead cost category	Costs incurred over one year	Hourly rate
Fixed overhead cost		
Depreciation	\$109,446	\$12/hour[A]
Variable overhead costs		
Supplies	\$140,675	\$70/hour[B]
Utilities	\$72,872	\$36/hour[B]

[A]Calculated based upon 8,760 hours in one year
[B]Calculated based upon 2,000 operating hours in one year

Figure V-1 and Figure V-2 give a perspective on the proportion of labor (direct and indirect), raw material, and overhead costs expenditures over one year for the large volume sawmill and sawmills that produce 7 MMBF or less of hardwood lumber annually. Both of these figures were created from the information provided from the management of the large volume sawmill.

Based upon Figure V-1 and Figure V-2, it is evident that annual expenditures for raw material costs are larger than overhead and labor costs. The traditional volume costing method allocates total raw material costs based upon the proportion of each lumber grade produced. It is one of the objectives of this work to illustrate how the values of product costs are different when raw material costs are allocated directly to the products that are produced from them.

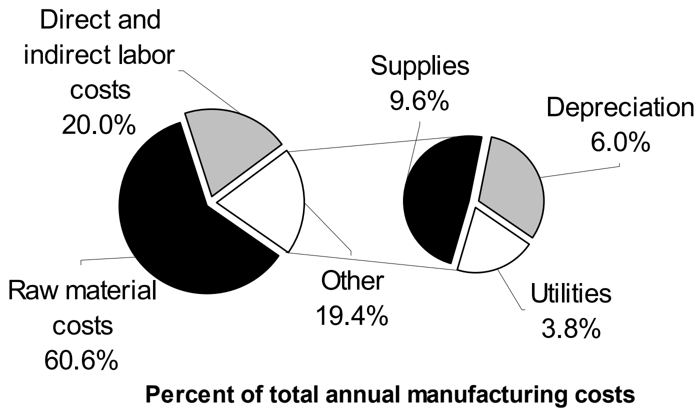


Figure V-1. Breakdown of annual manufacturing costs for the large volume sawmill

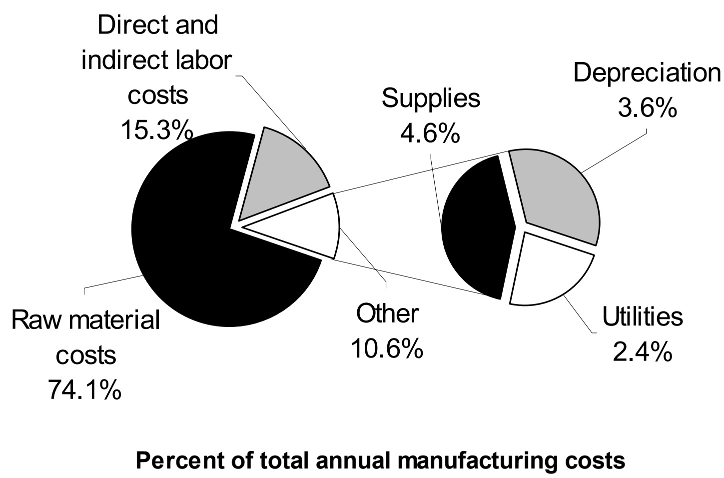


Figure V-2. Breakdown of annual manufacturing costs, on average, for hardwood sawmills producing 7 MMBF or less of hardwood lumber annually. Information provided by the management of the large volume sawmill

2.4. Allocation of the cost categories to the products with the activity-based costing method

The calculation method of applying the direct labor cost to each lumber grade is presented in Equation V-1. Essentially the calculation method in Equation V-1 allocates the total direct labor resource associated with a machine center to a specific lumber grade. The amount allocated is dependent upon the quantity of lumber grade i

produced or processed at machine center j in proportion to the total volume of lumber produced or processed at machine center j.

$$DLC_i = \frac{TVOL_{ij}}{TVOL_j} \times \sum_{j=1}^{m} \left(DLCR_{yj} \times TWH_y \right) \qquad \textbf{Equation V-1}$$

where:

DLC_i = the direct labor cost of lumber grade i
$TVOL_{ij}$ = total volume (bd.ft.) of lumber grade i produced or processed at machine center j
$TVOL_j$ = total volume (bd.ft.) of lumber produced or processed at machine center j
$DLCR_{yj}$ = the direct labor cost rate of the y^{th} equipment operator in the direct labor cost category of machine center j
TWH_y = total operating hours for the y^{th} equipment operator; including scheduled and unscheduled downtime
m = number of machine centers in the direct labor cost category used to produce or process entities of lumber grade i

The total raw material costs assigned to each lumber grade was derived by using the calculation method of Equation V-2. The term log group, used in Equation V-2 refers to logs that have the same scaling diameter, grade, and length parameters. The function of Equation V-2 is to allocate the cost of the raw material to only the products (different lumber grades) that are derived from the raw material, on an individual log basis. Allocation of the raw material cost to the different lumber grades depends upon the quantity of lumber grade i that originates from log group k in proportion to the total volume of lumber originating from log group k.

Equation V-2

$$TRMC_i = \sum_{i=1}^{f} \left(\frac{TVOL_{ik}}{TVOL_k} \right) \times TRMC_k$$

where:

$TRMC_i$ = total raw material cost of lumber grade i

$TVOL_i$ = total volume (bd.ft.) of lumber grade i produced, that originated from log group k

$TVOL_k$ = total volume (bd.ft.) of lumber produced from log group k

f = number of log groups

$TRMC_k$ = total raw material cost of log group k

$$= n_k \times \left(\frac{LC_k \times LVOL}{1{,}000\, bd.ft.} \right)$$

and:

n_k = number of logs processed from log group k

LC_k = purchase price of a single log per 1,000 bd.ft. for log group k

$LVOL$ = volume in board feet (Doyle log scale) of a single log

When the raw material costs were assigned to the lumber grades generated from the model of the large volume sawmill, Equation V-2 had to be slightly modified. The reason for the slight modification was to account for the logs present in the sawmill at startup and the logs that were not completely processed at the end of the simulation run. Allocation of raw material costs to the lumber grades from logs that had been partially processed during the current work shift or the previous shift would essentially be double billing raw material costs. To prevent double billing the raw material cost, each log entity generated was evaluated on an individual basis. The criteria for the evaluations was that the total raw material cost of an individual log, as calculated with Equation V-3, could not be greater than the purchase price of the individual log. Often the calculated raw material cost was greater than the purchase price of a log because the volume of lumber produced exceeded the estimated log volume. If the total raw material cost of an individual log, was calculated to be less than the purchase price, then the lesser value was used as the raw material cost for that log.

Equation V-3

$$TRMC_n = \left(\frac{TVOL_n}{LVOL_n}\right) \times LC_n$$

where:

$TRMC_n$ = total raw material cost of the n^{th} log

$TVOL_n$ = total volume of lumber in board feet produced by the n^{th} log

$LVOL_n$ = volume of the n^{th} log in board feet on the Doyle log scale

LC_n = the purchase price of the n^{th} log per 1,000 bd.ft.

This adjustment did not have to be applied when analyzing the raw material costs from the output of the medium volume sawmill because partially processed logs were not modeled as being present in the system at startup. In addition, the throughput rate of logs in the medium volume sawmill was greater than that of the large volume sawmill, so the number of logs that had not fully processed at the end of the simulation run was minimal.

In an actual sawmill system overhead costs are not equally consumed across all machine centers. However, of the sawmills modeled for this study, neither provided information as to how overhead costs are consumed differently between the machine centers. This is most likely due to the lack of an accounting system, used by the sawmills, that monitors the expenditures to the individual machine centers. These types of accounting systems are probably not in use because of the small percentage of total operating costs that fall into the overhead cost category. The disproportion of overhead costs to labor and raw material costs for the large and medium volume sawmill is illustrated in Figure V-1 and Figure V-2, respectively.

Because of the lack of specific overhead cost information for each machine center, overhead costs were allocated to the lumber grades based upon the volume of each grade produced. Consequently, overhead costs were allocated to the lumber products using the traditional volume costing method. Equation V-4 was the calculation technique used to allocate overhead costs to the lumber grades. A similar calculation (Equation V-5), based upon the principles of the traditional volume costing method, was used to assign indirect labor costs to the lumber grades.

$$OC_i = \frac{TVOL_i}{TVOL} \times \left(TOCR \times TWH\right)$$

Equation V-4

where:

OC_i = overhead cost for lumber grade i
$TVOL_i$ = total volume of lumber grade i produced
$TVOL$ = total volume of lumber produced across all grades
$TOCR$ = overhead cost rate per hour
TWH = total working hours

$$ILC_i = \frac{TVOL_i}{TVOL} \times \sum_{x=n+1}^{n} \left(ILCR_x \times TWH_x\right)$$

Equation V-5

where:

ILC_i = indirect labor cost for lumber grade i
$TVOL_i$ = total volume of lumber grade i produced
$TVOL$ = total volume of lumber produced across all grades
$ILCR_x$ = indirect labor cost rate for employee x
TWH_x = total working hours for employee x
n = number of employees in the indirect labor cost category

2.5. Allocation of the cost categories to the products with the traditional volume costing method

Calculation of the product costs for the lumber grades, with the traditional volume costing methodology, differed in two ways from the activity-based costing calculations defined in SECTION V.2.4. The first difference was that the allocation of total direct labor costs to the lumber grades was done based upon the total volume of each lumber grade produced. Mathematically the calculation technique is defined by Equation V-6. With the activity-based costing methodology, raw material costs were allocated to the lumber grades as a function of the log entity that each individual lumber entity had been replicated from.

$$DLC_i = \frac{TVOL_i}{TVOL} \times \left(DLCR_y \times TWH_y\right)$$ **Equation V-6**

where:

DLC_i = the direct labor cost of lumber grade i
$TVOL_i$ = total volume (bd.ft.) of lumber grade i produced during the simulated production run
$TVOL$ = total volume (bd.ft.) of lumber produced during the simulated production run
$DLCR_y$ = the direct labor cost rate of the y^{th} equipment operator
TWH_y = total operating hours for the y^{th} equipment operator; including scheduled and unscheduled downtime

The second calculation technique that was different from the procedures described in SECTION V.2.4 was that total raw material costs were allocated to the lumber grades based upon the total volume of each lumber grade produced (Equation V-7). In contrast, with the activity-based costing calculations, total direct labor cost was allocated to the lumber grades relative to the number of machine centers that were used to process each lumber entity of a particular grade.

Equation V-7

$$TRMC_i = \left(\frac{TVOL_i}{TVOL}\right) \times TRMC$$

where:

$TRMC_i$ = total raw material cost of lumber grade i
$TVOL_i$ = total volume (bd.ft.) of lumber grade i produced
$TVOL$ = total volume (bd.ft.) of lumber produced during the simulated production run
$TRMC$ = total raw material cost incurred during the simulated production run

$$= n_k \times \left(\frac{LC_k \times LVOL}{1{,}000\, bd.ft.}\right)$$

and:

n_k = number of logs processed from log group k
LC_k = purchase price of a single log per 1,000 bd.ft. for log group k
$LVOL$ = volume in board feet (Doyle log scale) of a single log

3. Results and discussion

From the output data generated by the model of the large volume sawmill, product costs were calculated, first with the traditional volume costing method and then with the activity-based costing method. The product cost values encompassed the total amount of raw material costs, indirect and direct labor costs, and overhead costs that were incurred, during the simulated eleven-hour workday.

As illustrated in Table V-9, most of the product cost values calculated with the activity-based costing method, were less than the values calculated with traditional volume costing method. The one exception being that the product cost of the FAS grade lumber was greater as calculated by the activity-based costing method. A graphical representation of the differences in product cost values, by calculation method is shown in Figure V-3.

Table V-9. Results from the analysis of the output data generated by the model of the large volume sawmill

Product	Average calculated product cost by method ($)[A] Traditional	Activity-based	Difference	% Difference
FAS	10,234.22 ± 264.90	11,228.63 ± 277.77	-994.41	-9.7
1C	9,089.24 ± 131.45	8,954.96 ± 134.12	134.29	1.5
2C	4,200.75 ± 103.61	3,971.20 ± 104.50	229.55	5.5
3A	726.30 ± 20.61	640.95 ± 19.14	85.34	11.8
3B	4,700.15 ± 106.61	4,378.76 ± 93.19	321.39	6.8
Pallet cant	5,360.16 ± 91.07	5,136.31 ± 90.40	223.85	4.2

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

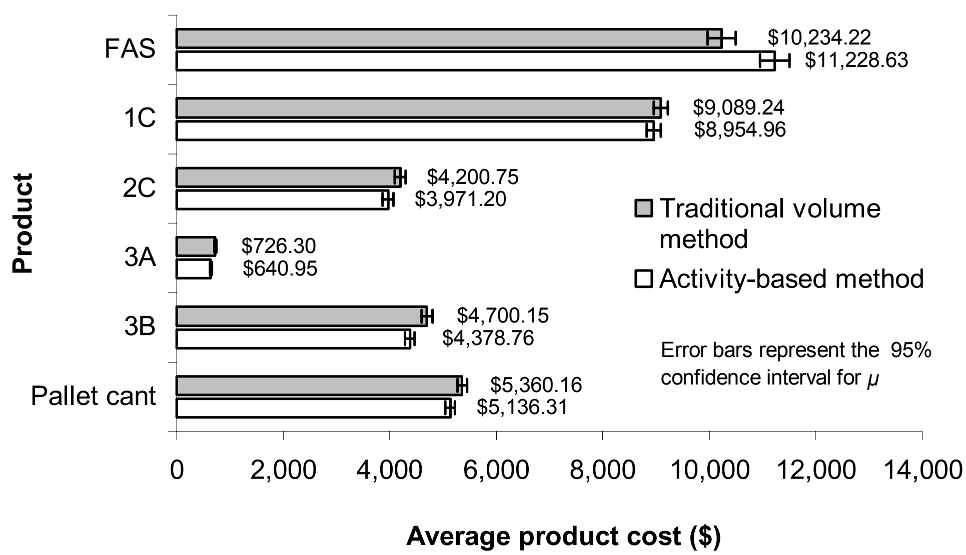


Figure V-3. Average product cost values as calculated using the activity-based costing method and the traditional volume costing method from the output data generated by the model of the large volume sawmill

Differences in the product cost values are due to the manner in which the raw material and direct labor costs were allocated to the lumber products between the two product costing methodologies. The practical significance of the differences between the two costing techniques is difficult to quantify because a $500 difference in manufacturing costs may be of importance to some sawmill managers, and of little consequence to others. A true subjective analysis of the insight that the activity-based costing method provides, in relation to cost estimation, would have to involve interviewing sawmill mangers to gauge their opinion of the differences.

It is also of interest to note the differences between the two calculation methods when the market prices of the individual lumber grades are subtracted from the product costs. Analysis of the estimated profits for the products, assumes that all of the products can be sold. As illustrated in Figure V-4, there is a $1,000 difference in the estimated profits of the FAS lumber between the two calculation methods. The market prices used for the various lumber grades were based upon information provided by the management of the sawmill.

Once again, the magnitude of the difference in relation to being practically significant is subjective. From the analysis of this dataset, it was also found that the profit loss for the low-grade lumber products (i.e. 3B, and pallet cants) was less, based upon the product cost values calculated with the activity-based methodology. This difference also illustrates that the two costing methodologies allocate manufacturing costs differently to the products manufactured.

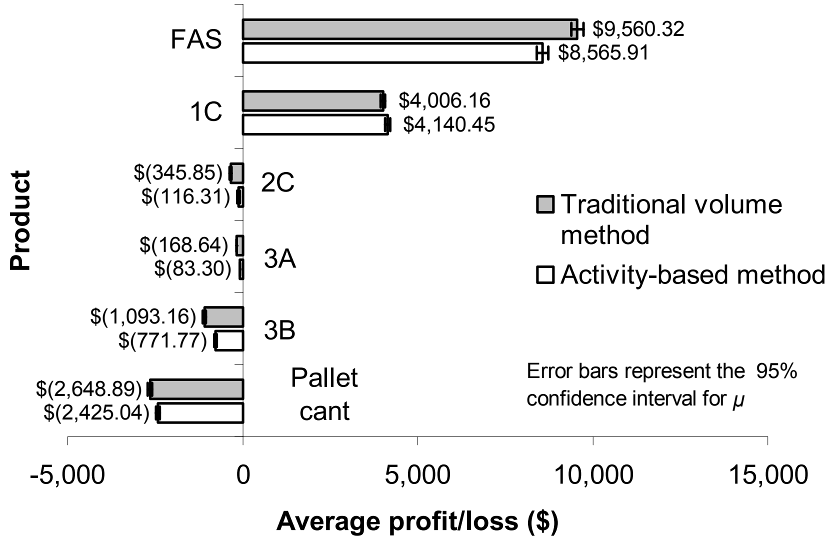
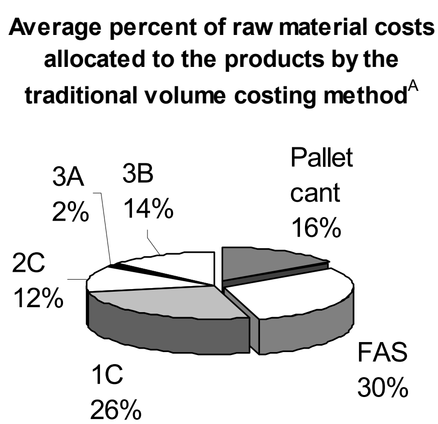


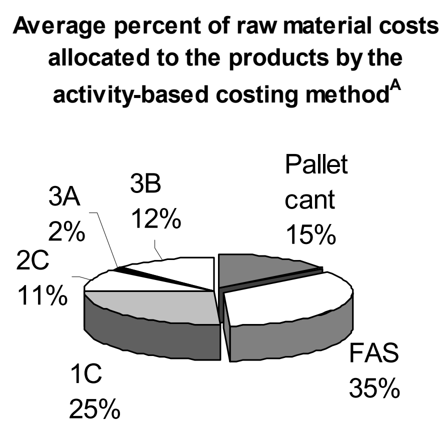
Figure V-4. Average profit levels based upon the calculated product cost values relevant to the model of the large volume sawmill

To better understand how the two cost accounting methodologies allocate costs differently, an analysis of the total raw material and direct labor costs allocated to the products, by calculation method, was performed. The allocation paths of the indirect and overhead costs to the products were not traced, since both of the calculation methods assign these two cost categories in an identical manner.

With the activity-based costing calculation method, the raw material costs were allocated to the products, based upon the raw material cost of the log that each lumber entity had been generated from. Because in the simulation models each log type entity had been assigned a unique number that was replicated to each lumber entity generated, the products could be traced back to the parent entity. Under the traditional volume costing method, the total raw material costs incurred during the production runs were allocated proportionally, based upon the total volume of each product manufactured. From which logs the lumber entities had originated was not considered in the process of calculating product cost with the traditional volume costing method.

Differences in the proportion of the total raw material costs that were allocated to the products, by calculation method, is presented in Figure V-5. A five percent difference in the percentage of total raw material costs allocated to the FAS product between costing methods, accounts for part of the reason why the FAS product cost values were higher by the activity-based calculation method. The percentage of raw material costs allocated to the 3B and pallet cant products were similar, across both calculation methods.

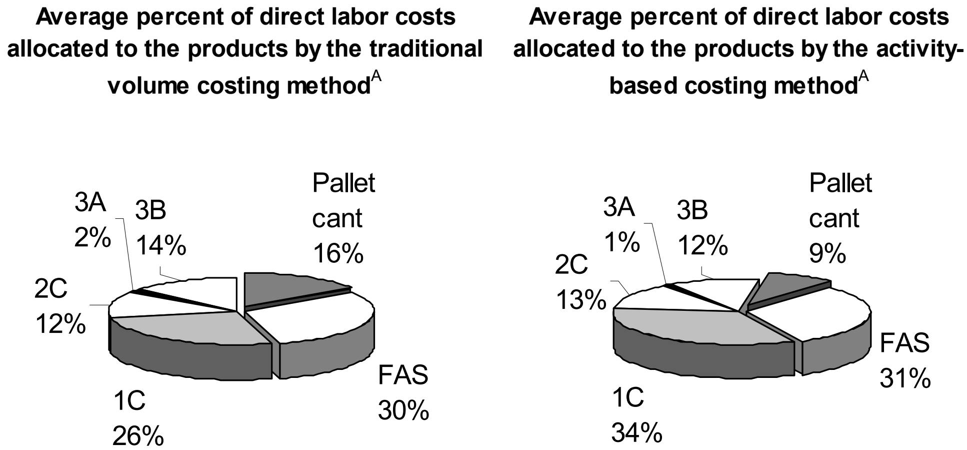




[A] Average values calculated from ten replications of the simulation model

Figure V-5. Proportion of the total raw material costs allocated to the lumber products by calculation method relevant to the output data generated from the model of the large volume sawmill

In examining the allocation of direct labor costs, a larger percent was allocated to the low-grade products by the traditional volume costing method in comparison to the percent allocated with the activity-based method. As illustrated in Figure V-6, there was a seven percent difference in the amount of direct labor costs allocated to the pallet cant products between the two costing techniques. For the FAS and 3B grade lumber products, the amount of direct labor cost allocated between costing techniques was similar.



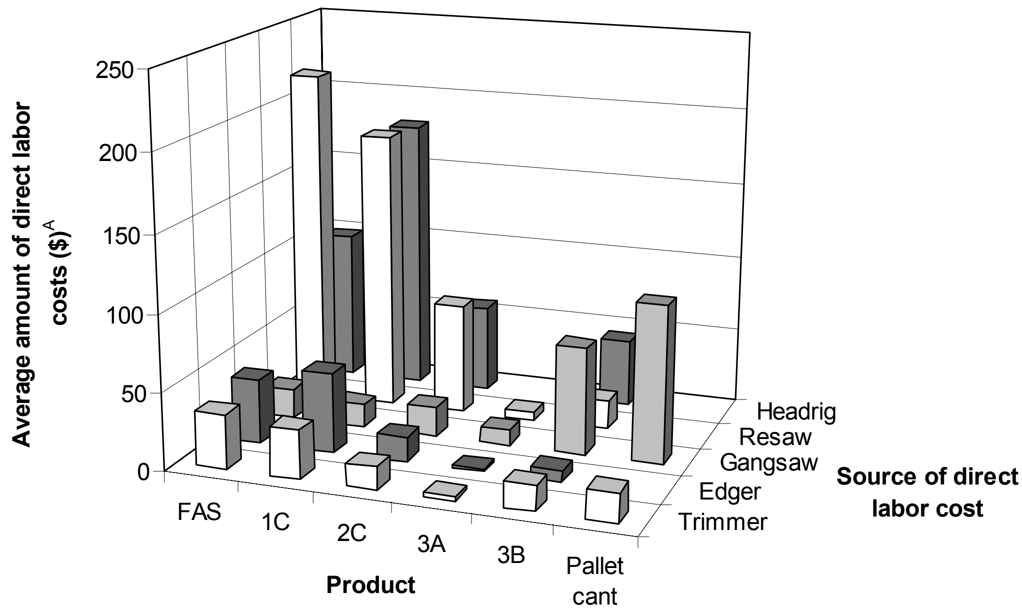
[A] Average values calculated from ten replications of the simulation

Figure V-6. Proportion of the total direct labor costs allocated to the lumber products by calculation method relevant to the output data generated from the model of the large volume sawmill

With the activity-based costing method, direct labor costs were allocated to the lumber products based upon the machine centers that were used to process or produce each of the lumber products. Since the pallet cant products were only processed at the gangsaw and trimmer machine centers, only the direct labor costs associated with these two machine centers were allocated to the pallet cant product, under the activity-based costing method. Figure V-7 illustrates the distribution of the direct labor costs across each of the lumber grades as calculated by the activity-based costing method. The principles of the traditional cost accounting method do not facilitate a similar breakdown of direct labor costs as shown in Figure V-7.

The traditional volume costing method allocated the total direct labor costs incurred during the production runs proportionally, based upon the total volume of each product that was manufactured. Collectively, Figure V-5, Figure V-6, and Figure

V-7 explain why the product cost values were different between the two cost accounting methods, for the simulation model of the large volume sawmill.



A Average values calculated from ten replications of the simulation model

Figure V-7. Average amount of direct labor costs used at each of the machine centers by lumber grade, as calculated with the activity-based costing method, using the output data from the model of the large volume sawmill

The traditional and activity-based cost accounting techniques were also used to calculate the product costs from the output data, generated by the model of the medium volume sawmill. Analysis of the differences in the product cost values calculated between the two costing methods illustrated the same trends realized from the analysis of the large volume sawmill.

As summarized in Table V-10, the activity-based costing methodology returned larger product cost values for the higher-grade lumber products (i.e. FAS and

1C) than the traditional costing method. For the lower-grade products, the product cost values calculated by the activity-based method were less in comparison to the values calculated with the traditional costing method. As illustrated in Figure V-8, the largest absolute dollar difference in product cost values between the two costing methods was for the 2C lumber grade product. The practical significance of the difference is realized when the profit levels of the 2C product are compared. Manufacturing the 2C product was calculated to be profitable with the activity-based product cost values, while a loss of \$107.80 was calculated using the traditional product cost values (Figure V-9). This difference in profit levels for the 2C product illustrates how the perception that little or no profit is realized from the low-grade lumber may not be true in some instances (Cumbo et al. 2003). The market prices used for the various lumber grades were based upon information provided by the management of the sawmill.

Table V-10. Results from the analysis of the output data generated by the model of the medium volume sawmill

Product	Average calculated product cost by method (\$)[A] Traditional	Activity-based	Difference	% difference
FAS	2,037.52 ± 76.58	2,221.50 ± 76.91	-183.98	-9.0
1C	5,955.68 ± 117.05	6,148.54 ± 117.01	-192.86	-3.2
2C and lower	7,187.44 ± 49.37	6,898.01 ± 60.21	289.44	4.0
Pallet cant	4,242.86 ± 47.97	4,155.45 ± 48.25	87.40	2.1

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

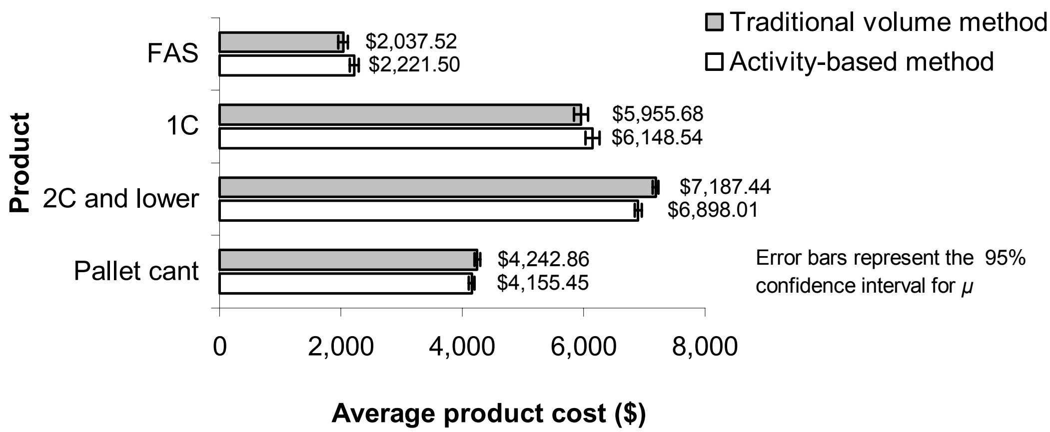


Figure V-8. Average product cost values as calculated using the activity-based costing method and the traditional volume costing method from the output data generated by the model of the medium volume sawmill

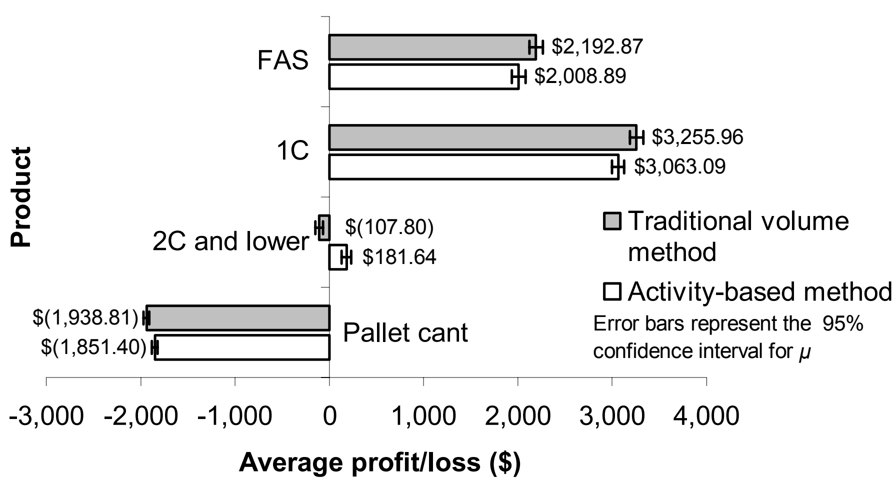


Figure V-9. Average profit levels based upon the calculated product cost values relevant to the model of the medium volume sawmill

Analysis of the allocation paths for the raw material and direct labor costs to the products generated by the model of medium volume sawmill, illustrated the same proportionalities realized from the analysis of the large volume sawmill. The first commonality was that in comparison to the traditional volume costing method, the activity-based costing method allocated a larger percentage of the raw material costs to the FAS lumber grade. In addition, the percent of raw material costs allocated to the pallet cant product was similar between the two costing methods as illustrated in Figure V-10. The second commonality identified between the two simulation models was that the percentage of the direct labor costs assigned to the pallet cant products was less when calculated with the activity-based costing method (Figure V-11). Moreover, as illustrated in Figure V-12, the reason for the disproportionality between the two costing methods in allocating direct labor costs to the products is that with the activity-based costing technique, labor costs are able to be segregated by machine center.

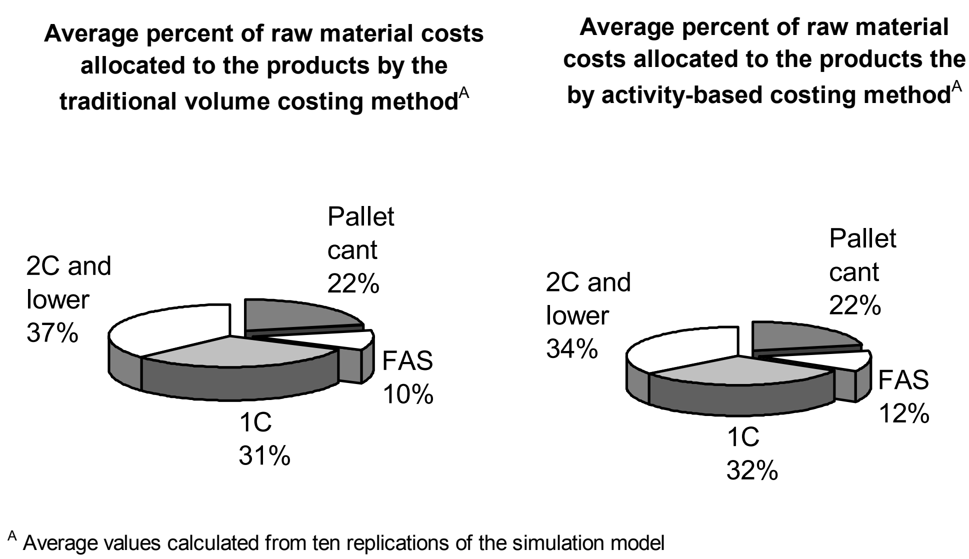
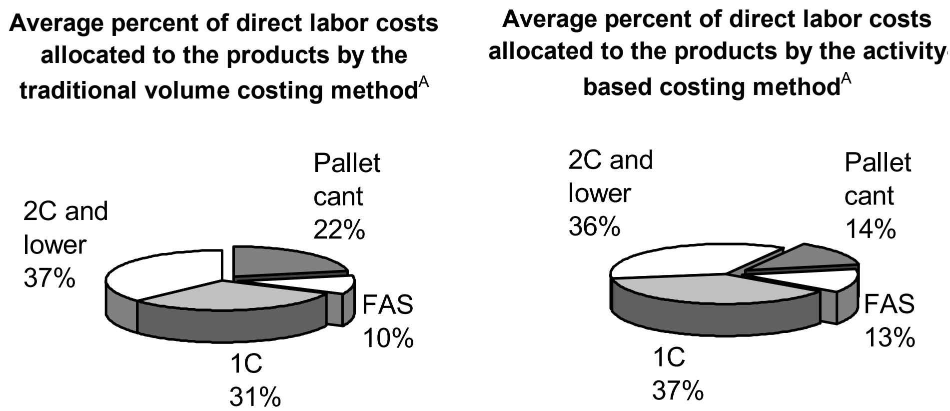
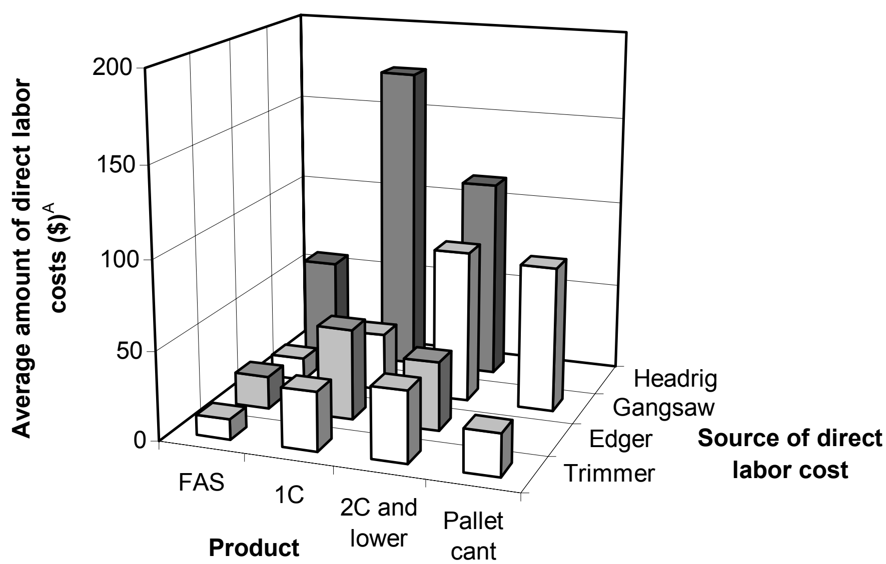


Figure V-10. Proportion of the total raw material costs allocated to the lumber products by calculation method relevant to the output data generated from the model of the medium volume sawmill



[A] Average values calculated from ten replications of the simulation model

Figure V-11. Proportion of the total direct labor costs allocated to the lumber products by calculation method relevant to the output data generated from the model of the medium volume sawmill



[A] Average values calculated from ten replications of the simulation model

Figure V-12. Average amount of direct labor costs used at each of the machine centers by lumber grade, as calculated with the activity-based costing method, using the output data from the model of the medium volume sawmill

4. Summary

The output data from the two simulation models was used to demonstrate how the traditional and activity-based cost accounting methods allocate manufacturing costs differently to products. With the activity-based costing method, the product costs for the FAS grade lumber were greater in comparison to the values calculated with the traditional costing method. In addition, the product costs for the pallet cants were less under the activity-based costing method in comparison to the values calculated with traditional costing method.

An analysis of how the raw material costs and direct labor were allocated to the products by the two methods demonstrated why the product cost values for the FAS and pallet cant material was consistently different. The analysis illustrated that with the activity-based costing method, raw material and direct labor costs are able to be allocated to products as a function of the material from which the products originated and the machines used to process the products. In contrast, the traditional volume costing method allocated raw material and direct labor costs proportionally to the total volume of material produced.

5. References

Cumbo, D., R. Smith, and P. Araman. 2003. Low-grade hardwood lumber production, markets and issues. Forest Prod. J. 53(9):17-24.

Kelton, W.D., R.P. Sadowski, and D.T. Sturrock. 2004. Simulation with ARENA - 3rd edition. McGraw-Hill; Boston, MA. 668 pgs.

SECTION VI. QUANITIFICATION OF THE EFFECT OF LOG PARAMETERS ON PRODUCT COSTS

1. Introduction

The overall purpose of this research was to quantify the impact of different log variables, i.e. length, log grade, and diameter, on product costs by using activity-based costing techniques. Using discrete-event simulation, the changes in the dynamics of two sawmill systems were examined as a function of different log parameters that were input into the models. The activity-based costing methodology was then used to quantify how the differing log inputs affected the total cost to manufacture the products.

2. Methodology

2.1. Experimental design

The logs from which lumber volume and grade yield had been measured were grouped into classes based upon diameter class, log length, and log grade, by the sawmill from which they were sampled (Table VI-1). Each of the different log groupings served as the treatment combinations for the simulation experiments. Diameter class, log length, and log grade served as the experimental factors of the treatment combinations. Levels of the experimental factors, by sawmill, are presented in Table VI-1. The treatment combinations were systematically applied to the simulation models, to identify how the sawmill systems would respond when only logs with only the parameters related to each of the experimental factors were modeled as being sawn. The system response to the treatment combinations was quantified by using the activity-based costing method to calculate total manufacturing costs and the product cost of the 1C grade lumber.

Table VI-1. Treatment combinations by sawmill

Treatment combinations for the model of the large volume sawmill				**Treatment combinations for the model of the medium volume sawmill**		
Log grade[A]	Length (ft.)	Diameter class (in.)		Log grade[A]	Length (ft.)	Diameter class [B] (in.)
Select	8	12-15		Prime	8	13-15
Select	8	18-19		Select	8	13-15
Prime	12	13-15		Prime	12	13-15
Prime	12	18-20		Select	12	13-15
Select	12	12-15		Select	12	19-21
Select	12	18-20				

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces
[B]The 12-15 inch diameter class and the 13-15 diameter class experimental factors were considered to be in the same level of the experimental design

Between the two sawmills, the log groupings were not equal, primarily because the time constraints associated with the lumber yield sampling process did not facilitate an equal sampling of logs. The diameter class parameters of the treatment combinations were also not equal between the two sawmills due to the different log grade specifications used by the two sawmills. In addition, the diameter class parameters of the treatment combinations were not equal within the experimental matrix of the large volume sawmill because of changes in the manufacturing process made at the sawmill, halfway through the completion of this study. The net effect of not having an equal sampling across all of the log parameters was that a full factorial design could not be performed.

Instead, a basic sensitivity test was performed where the main effects of log diameter, log grade, and log length experimental factors were compared between the treatment combinations. Based upon the average values of the main effects, the log parameter that had the greatest effect on the cost to manufacture the products was able to be identified, for each of the two sawmills.

2.2. Parameters of the simulation models

For each treatment combination, ten replications of the model were run using common random numbers that were synchronized between replications. Ten replications of each model were run so that confidence intervals could be calculated with the output values from the simulation models. Each simulation was run under terminating conditions, where the ending point of each run was when the model had generated two thousand board feet of 1C lumber. The output data from the simulation models essentially provided a snapshot of the operating and raw material costs that had been incurred up to the point in time when the model had generated two thousand board feet of 1C lumber.

For this simulation experiment, the end of a normal workday was not chosen as the terminating condition for the models, because the total values for the direct labor costs, indirect labor costs and overhead costs would have been the same between the treatment combinations. Since the yield of 1C grade lumber differed between the treatment combinations, the time it takes to reach the terminating parameters changed dynamically based upon the treatment combination. Therefore, because direct labor, indirect labor, and overhead costs were time dependent, the values of these costs fluctuated between the treatment combinations.

The ending point of the simulation models was controlled using the *Statistic* data module. Information on the current generated volume of 1C lumber, during the simulation runs, was relayed to the *Statistic* module by means of a *Record* flowchart module, positioned at an area in the models that represented the trimmer machine center.

The two thousand board foot figure was chosen based upon target monthly red oak production goals for the medium volume sawmill. Target production values for red oak lumber on a monthly or annual basis was not obtained from the large volume sawmill. The 1C lumber grade terminating parameter was used because some of the logs sampled from the actual sawmill systems did not yield FAS grade lumber.

2.3. Collection of total simulated work time information

Since the terminating condition of the simulation models in this experiment was not the end of a full workday, the total simulated work time changed dynamically as a function of the yield of 1C lumber from logs in the treatment combinations. Because the total simulated work time differed between the treatment combinations, the total direct labor costs, indirect labor costs, and overhead costs incurred during the simulation runs were also different between the treatment combinations.

Collection of the total simulated work time values for each of the simulation runs was done by means of an *Assign* flowchart module positioned in an area of the simulation models that represented the trimmer machine center. As an entity passed through the *Assign* module, the current simulation time was added as an attribute value. Identification of the total work time required to generate two thousand board feet of 1C lumber was done by sorting through the output data and finding the maximum current simulation time attribute value. The maximum current simulation time value from the output of the models was rounded down to the nearest quarter of the hour and was used as the total working hours (TWH_y) variable of Equation V-1 to allocate the direct labor costs to the lumber grades. The maximum simulation time value was also used as the total working hours (TWH) variable of Equation V-4, for overhead cost allocation, and as the TWH_x variable in Equation V-5, for the allocation of indirect labor costs to the lumber grades.

3. Results and discussion

For each treatment combination, product cost values for the lumber grades were calculated, from the output data, by means of the activity-based costing method, were added together. Total manufacturing costs were calculated by adding together the individual product costs for each lumber grade, by treatment combination. Summary statistics, which included sample means and half-width values at the 95% confidence level, were calculated from the ten replications of each treatment combination. A graphical representation of the summary statistics calculated using the activity-based costing method, from the output generated by the model of the large volume sawmill is presented in Figure VI-1.

Based upon the values presented in Figure VI-1, the largest manufacturing costs were incurred by the two treatment combinations that contained Prime grade logs. The cost of producing two thousand board feet of 1C lumber was also the greatest for the treatment combinations with the Prime grade logs. In comparison, total manufacturing costs and 1C product costs were less for the treatment combinations that contained Select grade logs.

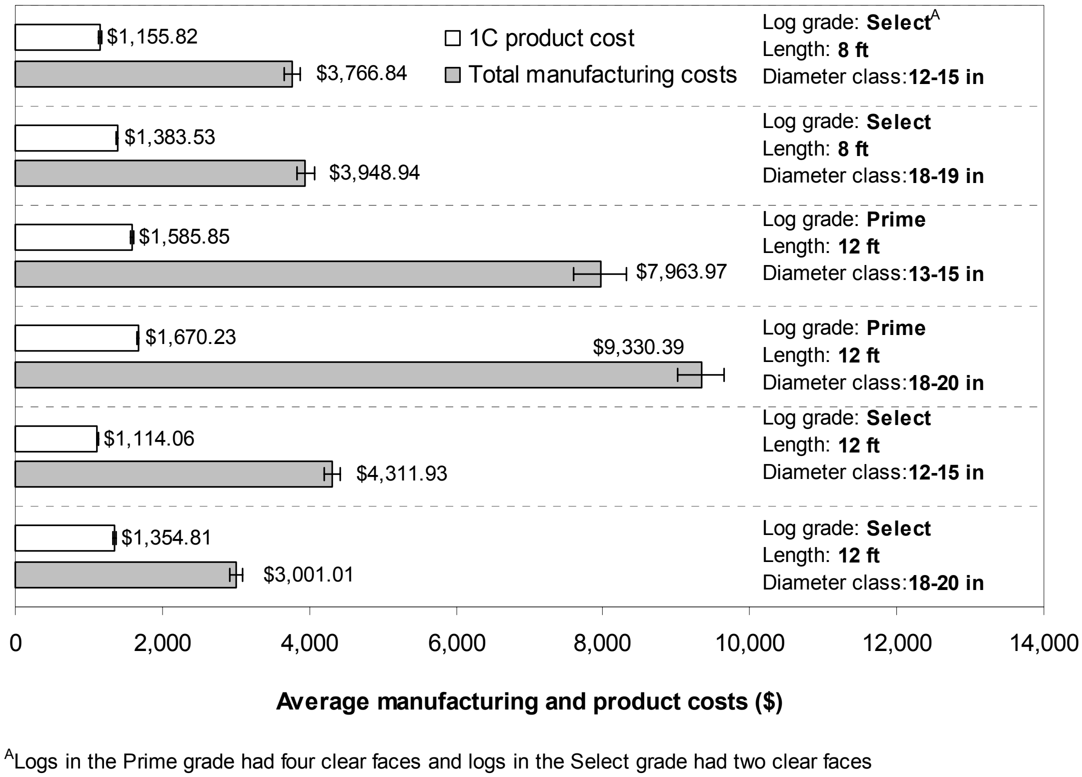
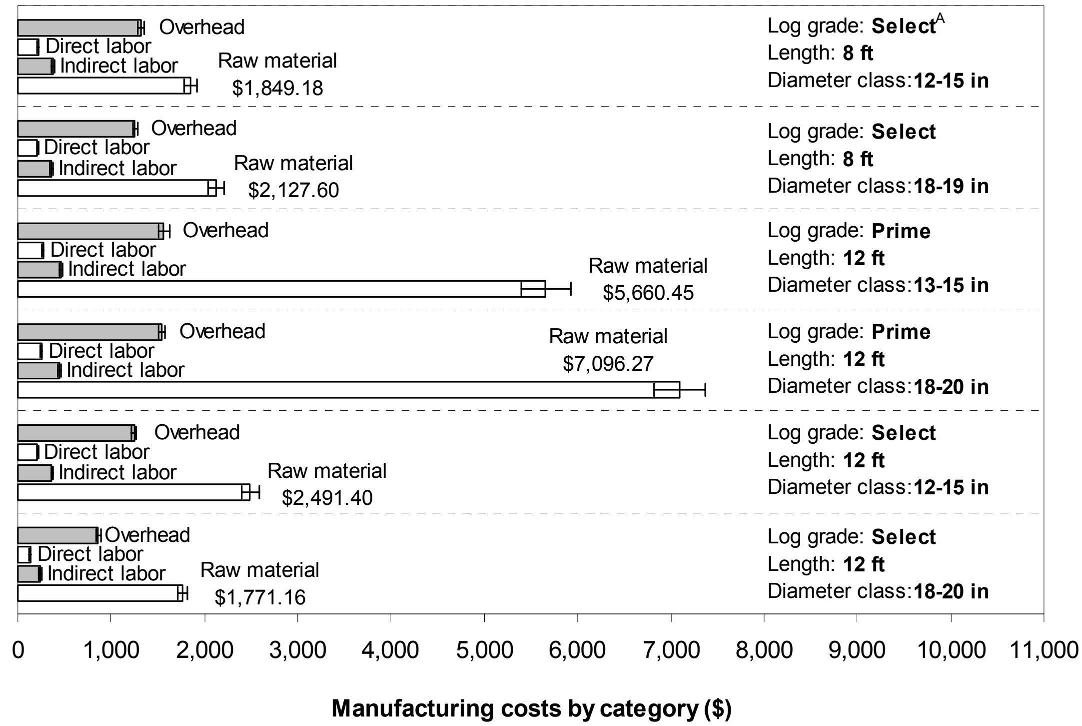


Figure VI-1. Total manufacturing cost and 1C product costs, by treatment combination, as calculated from the output data generated by the model of the large volume sawmill

An examination of the total manufacturing costs by category, illustrates why the product cost values between the treatment combinations were different. As shown in Figure VI-2, total raw material costs accounted for the largest difference between the different treatment combinations. The overhead and indirect labor costs were also different between the treatment combinations. Differences in the overhead and direct labor costs, indicates that the amount of time required to produce two thousand board feet of 1C lumber was not equal between the treatment combinations.



[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces

Figure VI-2. Total manufacturing costs allocated to each cost category as calculated by the activity-based costing method with the output from the model of the large volume sawmill

The cause of the differences in raw material costs between the treatment combinations relates to the lumber yield and the purchase price of the logs in each treatment combination. The treatment combination where the largest raw material costs were incurred was the group that contained high-grade, large volume logs. The specific characteristics of the logs assigned to the treatment combination, with the greatest resulting total raw material costs, was that the logs ranged in diameters between eighteen and twenty inches, had four clear faces (Prime grade) and were twelve feet long. Logs with these characteristics are large in volume and typically yield proportionally more high-grade lumber than low-grade lumber. Because of these log characteristics it would be expected that the total raw materials cost for this treatment combination would be relatively low since it would not require many logs to produce two thousand board feet of 1C lumber. However, when the lumber grade and volume yield information was collected at the large volume sawmill from the logs in this treatment combination, only 20 percent of the total volume of lumber produced was of the 1C grade. Most of the lumber produced from logs of this type, was graded as FAS.

The cost inefficiency of processing high volume, high-grade logs is that they have an elevated purchase price, in comparison to logs of the same volume but lower grade. As an example, the raw material costs for the treatment combination that contained logs with diameters between eighteen and twenty inches, were twelve feet long, but only had two clear faces (Select grade) was substantially less. For this treatment combination, log grade was the only log characteristic different from the treatment combination that had the largest manufacturing and raw material costs. The measured yield of 1C grade lumber from logs of this type was 39 percent, in comparison to 20 percent from the Prime grade logs. To produce two thousand board feet of 1C lumber, only 31 of the Select grade logs had to be sawn, while 49 Prime logs had to be sawn to meet the terminating conditions of the simulation model. In addition, the simulated working time required to meet the terminating conditions was an hour longer for the Prime grade logs than the Select grade logs.

Collectively, the number of logs sawn and the time required to meet the terminating conditions accounts for the differences in manufacturing costs between these two treatment combinations, where the logs were similar in volume, but differed only in log grade. Given that the large volume Prime logs yielded mostly FAS, the raw material costs for these logs probably would have been less if, the terminating parameter of the simulation models had been the generation of two thousand board feet of FAS lumber.

To quantify which log parameter (log grade, scaling diameter, or length) had the greatest impact on total manufacturing costs, the average main effect of the different experimental factors were compared. To calculate average main effect, Equation VI-1 was used, which is based upon a technique described by Law and Kelton (1991) to calculate the main effects for factorial designs.

Equation VI-1

$$e_k = \frac{\sum_{i=1,2,..n}^{k} (\overline{\mu}_{ikl} - \overline{\mu}_{ikl+1})}{n}$$

where:

e_k = average main effect of the k^{th} experimental factor, i.e. log length, log diameter, log grade

$\overline{\mu}_{ikl}$ = average manufacturing cost of the i^{th} treatment combination where the l^{th} level of k^{th} experimental factor was represented

n = number of comparisons made between treatment combinations at different levels of k^{th} experimental factor

In comparing the average main effects between the experimental factors, log grade was found to have the largest influence on manufacturing costs. As presented in Table VI-2, Table VI-3, and Table VI-4, the average main effect calculated for the log grade experimental factor was 80 percent greater than the main effect calculated for the log diameter factor and 85 percent greater the main effect due to log length. Overall, log length had the smallest impact on manufacturing costs. The limitation of this analysis is that the experimental factors were not equally represented in each of the treatment combinations.

Table VI-2. Average main effect of log length as calculated from the model of the large volume sawmill for Select grade logs of two diameter classes

Treatment combination	Average manufacturing cost ($)[A]	Main effect	Average main effect
Select 8 ft 12-15 in	3,766.84 ± 111.48	545.08	746.50
Select 12 ft 12-15 in	4,311.93 ± 113.15		
Select 8 ft 18-19 in	3,948.94 ± 119.66	947.93	
Select 12 ft 18-20 in	3,001.01 ± 84.29		

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

Table VI-3. Average main effect of log diameter as calculated from the model of the large volume sawmill for Select grade logs of two length classes and Prime grade logs of one length class

Treatment combination	Average manufacturing cost ($)[A]	Main effect	Average main effect
Select 8 ft 12-15 in	3,766.84 ± 111.48	256.32	1,022.39
Select 8 ft 18-19 in	3,948.94 ± 119.66		
Select 12 ft 12-15 in	4,311.93 ± 113.15	1,310.92	
Select 12 ft 18-20 in	3,001.01 ± 84.29		
Prime 12 ft 13-15 in	7,963.97 ± 355.05	1,499.93	
Prime 12 ft 18-20 in	9,330.39 ± 317.50		

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

Table VI-4. Average main effect of log grade as calculated from the model of the large volume sawmill for twelve foot logs of two diameter classes

Treatment combination	Average manufacturing cost ($)[A]	Main effect	Average main effect
Prime 12 ft 13-15 in	7,963.97 ± 355.05	3,652.04	4,990.71
Select 12 ft 12-15 in	4,311.93 ± 113.15		
Prime 12 ft 18-20 in	9,330.39 ± 317.50	6,329.39	
Select 12 ft 18-20 in	3,001.01 ± 84.29		

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

For the model of the medium volume sawmill, the same terminating parameter of two thousand board feet of 1C lumber was used to examine how product costs change as a function of log input parameters. A graphical representation of the summary statistics calculated using the activity-based costing method, from the output generated by the model of the medium volume sawmill is presented in Figure VI-3. In comparison to the results from the model of the large volume sawmill the total manufacturing costs and 1C lumber product costs were less. The smaller manufacturing costs in some part, reflects upon the medium volume sawmill utilizing fewer machine centers and employees than the large volume sawmill.

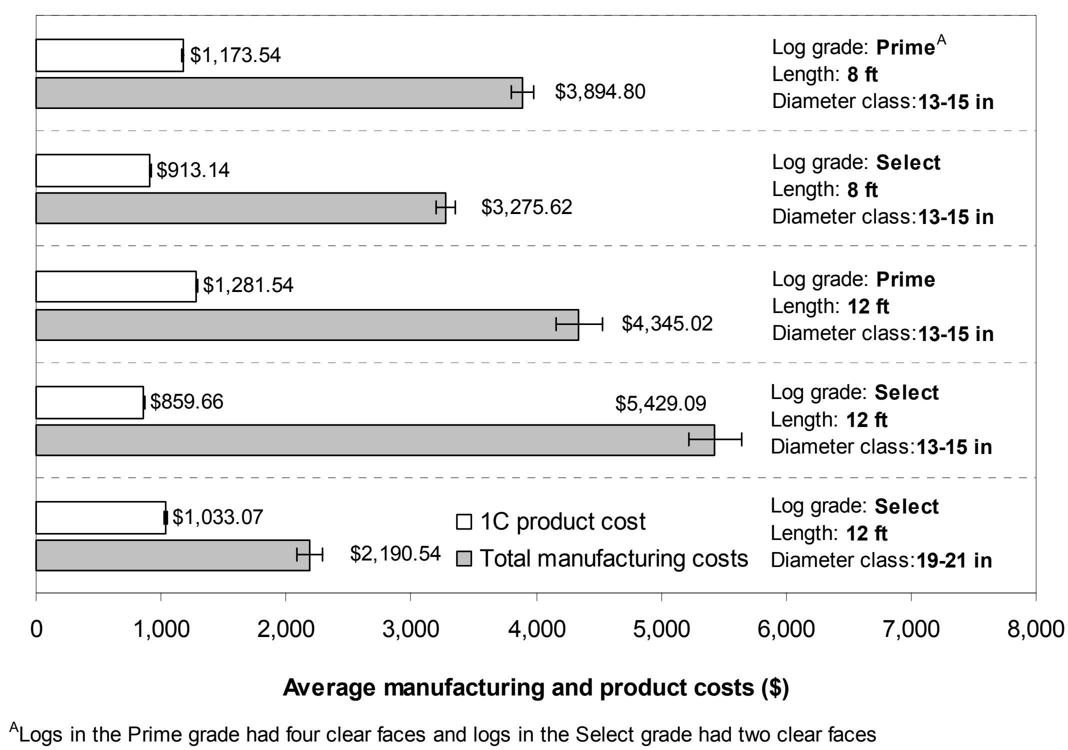
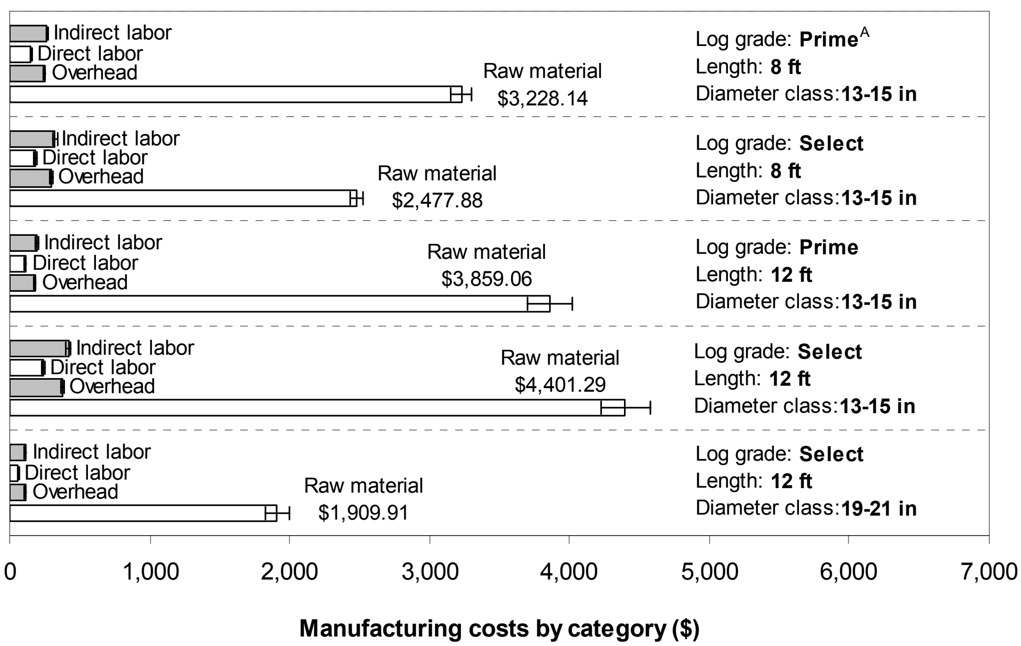


Figure VI-3. Total manufacturing cost and 1C product costs, by treatment combination, as calculated from the output data generated by the model of the medium volume sawmill

Unlike the results from the model of the large volume sawmill, the treatment combination with the Select grade logs had the highest calculated manufacturing costs. More precisely the treatment combination that had the highest manufacturing costs contained Select grade logs that were 12-feet long with scaling diameters ranging from 13-15 inches. For logs in this treatment combination, only 22 percent of the total volume of lumber produced was of the 1C lumber grade. In comparison, the treatment combination that had Select grade logs, 12-foot in length and scaling diameters between 19 and 21-inches, on average yielded 20 percent more 1C grade lumber. The effect of the differences in the yield of 1C lumber on raw material and direct labor costs, between the two treatment combinations as a function of different levels of the scaling diameter factor, is illustrated in Figure VI-4.



[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces

Figure VI-4. Total manufacturing costs allocated to each cost category as calculated by the activity-based costing method with the output from the model of the medium volume sawmill

Because the 1C yield values were different between the two treatment combinations that had 12-foot Select grade logs, the number of logs that had to be processed in order to meet the terminating conditions of the simulation model was also different. For the treatment combination that had logs of the 19-21 inch scaling diameter, only 28 logs had to be processed. In comparison, 145 logs that were 13-15 inches in diameter had to be processed to meet the terminating conditions of the simulation model. In addition, the simulated working time required to meet the terminating conditions was two hours longer for the 13-15 inch diameter logs than the 19-21 inch diameter logs.

Despite the larger raw material costs and longer working time, the product cost value for the 1C lumber grade was less for the 13-15 inch diameter logs than the 19-21 inch diameter logs (Figure VI-3). The reason for this unexpected disparity is also related to the difference in the yield of 1C lumber between the treatment combinations with the Select 12 foot logs. Because in the treatment combination with the 19-21 inch diameter logs, the majority of the lumber produced was of the 1C grade, more of the raw material costs were allocated to 1C product. The difference in the amount of raw material cost allocated to the 1C product between the two treatment combinations is illustrated in Figure VI-5. In instances, such as the experiments described in this section, where the population of logs is similar in price and volume, the percentage of raw material costs allocated to the products is comparable between the activity-based and traditional costing method.

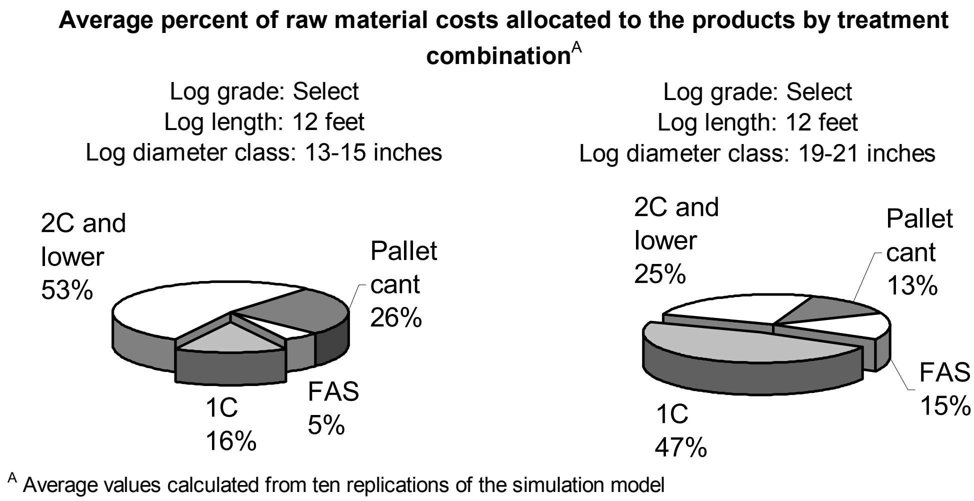


Figure VI-5. Proportion of the total raw material costs allocated to the lumber products by treatment combination relevant to the output data generated from the model of the medium volume sawmill

When the main effects of the experimental factors were compared, log diameter was found to have the greatest influence on manufacturing costs. In contrast to the results from the large volume sawmill, log grade was shown to have the least amount of impact on manufacturing costs. This could be because no large volume logs of Prime grade could be put into the model because of a lack of information pertaining to the yield and material flow patterns of these logs, relative to the medium volume sawmill.

Table VI-5. Average main effect of log length as calculated from the model of the medium volume sawmill for Prime and Select grade logs of two diameter classes

Treatment combination	Average manufacturing cost ($)[A]	Main effect	Average main effect
Prime 8 ft 13-15 in	3,894.80 ± 88.73	466.13	1,309.80
Prime 12 ft 13-15 in	4,345.02 ± 182.11		
Select 8 ft 13-15 in	3,275.62 ± 80.05	2,153.47	
Select 12 ft 13-15 in	5,429.09 ± 211.80		

[A]Half-widths of the mean are reported at the 95% confidence level
and were calculated using data from ten replications of the simulation model

Table VI-6. Main effect of log diameter as calculated from the model of the medium volume sawmill for Select grade 12-foot logs

Treatment combination	Average manufacturing cost (\$)[A]	Main effect
Select 12 ft 13-15 in	5,429.09 ± 211.80	3,238.55
Select 12 ft 19-21 in	2,190.54 ± 101.92	

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

Table VI-7. Average main effect of log grade as calculated from the model of the medium volume sawmill for 8 and 12-foot logs of one diameter class

Treatment combination	Average manufacturing cost (\$)[A]	Main effect	Average main effect
Prime 8 ft 13-15 in	3,894.80 ± 88.73	619.18	851.63
Select 8 ft 13-15 in	3,275.62 ± 80.05		
Prime 12 ft 13-15 in	4,345.02 ± 182.11	1,084.08	
Select 12 ft 13-15 in	5,429.09 ± 211.80		

[A]Half-widths of the mean are reported at the 95% confidence level and were calculated using data from ten replications of the simulation model

4. Summary

To quantify the effect of log parameters on product costs, the logs that had been sampled from the large and medium volume sawmill were grouped into treatment combinations based upon scaling diameter, length, and grade. Scaling diameter, length, and log grade served as the experimental factors. The simulation models of the large and medium sawmill were used to examine how the different levels of the experimental factors influenced manufacturing costs. For both of the simulation models the terminating condition of a simulation run was when two thousand board feet of 1C grade lumber was produced.

The results from both of the simulation models illustrated that raw material costs were a larger factor than indirect labor, direct labor, and overhead costs, in affecting the total cost of the manufactured products. Despite the differences in the amount of time required to saw two thousand board feet of 1C lumber between the treatment combinations, the indirect labor, direct labor, and overhead costs incurred were disproportionately small in comparison to the total raw material costs.

Results from the model of the large volume sawmill illustrated that log grade was found to have the largest impact on manufacturing costs. The log parameter that had the least affect on manufacturing costs was shown to be log length. Differences in the purchase price between high-grade and low-grade logs along with differences in the yield of 1C lumber between the treatment combinations were identified as the reason that log grade had the greatest affect on manufacturing costs.

For the model of the medium volume sawmill, manufacturing costs were shown to be strongly affected by log diameter. In contrast to the results from the large volume sawmill, log grade had the least impact on manufacturing costs. Since the levels of the experimental factors were not equal between the two sawmills, definitive comparisons between the two sawmills could not be made. However, for the model of the medium volume sawmill, differences in the yield of 1C grade lumber between the treatment combinations was also identified as the reason that log diameter had the greatest influence on manufacturing costs.

5. References

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SECTION VII. PROPOSED METHODOLOGY FOR APPLYING THE ACTIVITY-BASED COSTING METHOD TO THE INDUSTRIAL SETTING

1. Introduction

Results from the previous experiments with the two simulation models, demonstrated that raw material costs account for more than half of the manufacturing costs in a hardwood sawmill environment. The principles of the activity-based costing methodology, allow for the allocation of raw material costs directly to the products based upon the raw material cost of the log from which the products originated. Tracing each piece of lumber back to the log from which it was sawn is easily done in a simulation model, but would not be practical in an actual hardwood sawmill system.

In this section, a technique is presented that would enable sawmill managers to estimate how raw material costs are distributed among the different lumber grades using the principles of activity-based costing. Under the traditional volume costing method, total raw material costs are allocated based upon the total volume of each lumber grade produced. Results from the simulation experiments illustrate that the traditional volume costing method underestimates the raw material cost of producing FAS grade lumber and overestimates the raw material cost of producing the pallet cant products. Consequently, when the value of the lumber is subtracted from raw material costs, profit from the FAS grade lumber is overestimated and profit from the pallet cant product is underestimated.

2. Methodology

To illustrate how the technique would be implemented, the simulation models of both sawmills were used to generate the information needed to execute the technique. Ten replications of each simulation model were run under terminating conditions where the ending condition was a full workday. Common random numbers synchronized between replications were also used to reduce the variance of the output data. The pertinent information that is required for the proposed methodology to be applied at an actual sawmill is:

1. Lumber volume and grade yield statistics from logs with similar log grade, scaling diameter, and length parameters
2. The log grade, scaling diameter, and length information for every log that was used to produce the lumber for which product costing information is desired

In regards to the number of logs that should be sampled, to accurately estimate lumber volume and grade yield, a minimum of ten is recommended for each log parameter or combination of parameters. The minimum value of ten logs is based upon guidelines published by Mayer and Wiedenbeck (2005) to ensure that an accurate distribution of the lumber yield from the logs is collected.

From the output data generated by simulation models, lumber volume and grade yield statistics were calculated from ten randomly selected logs, for each of the log parameter combinations. The variables defined in Equation VII-1 were used to calculate the lumber volume and grade yield statistics from the output of the simulation models. Lumber volume and grade yield statistics for the model of the large volume sawmill and the medium volume sawmill are presented in Table VII-1 and Table VII-2 respectively.

Equation VII-1

$$ELY_{ik} = \left(\frac{Vol_{ik}}{Vol_k}\right) \times 100$$

where:

ELY_{ik} = estimated yield, in percent, of the i^{th} product from the k^{th} log parameter or set of log parameter combinations

Vol_{ik} = volume in board feet of the i^{th} product from the k^{th} log parameter or set of log parameter combinations

Vol_k = volume in board feet of the products (i.e. grade lumber and pallet cants) produced from k^{th} log parameter or set of log parameter combinations

Table VII-1. Lumber yield statistics calculated from the output generated by the model of the large volume sawmill

Log parameter combinations			**Average yield (%)[B]**					
Log grade[A]	Length (ft.)	Diameter (in.)	FAS	1C	2C	3A	3B	Pallet cant
Prime	8	14	47	12	5	0	16	21
Select	8	12	19	17	9	7	15	23
Select	8	13	17	24	6	0	38	16
Select	8	14	12	25	30	7	8	18
Select	8	18	17	23	32	6	9	12
Select	8	19	22	41	12	3	12	10
Prime	12	13	36	13	14	0	15	22
Prime	12	14	44	25	5	0	4	22
Prime	12	18	62	9	3	0	14	12
Prime	12	19	41	26	16	1	5	11
Select	12	12	16	23	18	5	15	22
Select	12	13	5	26	26	0	18	25
Select	12	14	21	36	16	0	8	20
Select	12	15	11	19	13	0	38	18
Select	12	18	32	42	8	1	5	13
Select	12	20	28	43	1	6	12	10

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces
[B]Average yield is reported in percent of total lumber volume produced from each log group

Table VII-2. Lumber yield statistics calculated from the output generated by the model of the medium volume sawmill

Log parameter combinations			**Average yield (%)**[B]			
Log grade[A]	Length (ft.)	Diameter (in.)	FAS	1C	2C and lower	Pallet cant
Prime	8	13	0	13	61	27
Prime	8	14	25	22	30	22
Prime	8	15	0	43	40	18
Select	8	13	2	25	42	31
Select	8	14	0	23	55	22
Select	8	15	0	33	41	26
Prime	12	13	18	31	20	31
Prime	12	14	14	40	22	24
Prime	12	15	23	20	34	23
Select	12	13	5	17	52	26
Select	12	14	4	7	61	28
Select	12	15	7	20	48	24
Select	12	19	27	31	28	15
Select	12	21	3	59	25	12

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces
[B]Average yield is reported in percent of total lumber volume produced from each log group

Recording the log grade, scaling diameter, and length information, for every log processed is necessary in order to calculate total raw material cost values for each of the log groups. For this study, the output from the simulation models provided the necessary information. In Figure VII-1, two methods are presented, of how one hardwood sawmill collects information on the grade, scaling diameter, and the lengths of logs as they enter the sawmill.

Figure VII-1. Example of the manual method and barcode method used to monitor the volume and grade of logs sawn at a hardwood sawmill

One method is to manually write the gross volume and grade of a log on one of its ends with a waterproof lumber crayon. The procedure of marking the logs can be done in the log yard, as logs are being scaled and inventoried. In reference to Figure VII-1, the gross volume of the log in the photograph was measured to be 126 board feet with the Doyle scale and the grade of the log was identified with the “m” symbol. At the sawmill where the photograph was taken, the operator of the debarker machine center will visually estimates a log’s length, and with log volume value marked on the end of the log, interpolate scaling diameter from a Doyle log volume table. The sawmill where this procedure was observed, uses the information recorded by the debarker operator to calculate overrun statistics from the production runs. Log information collected by the debarker operator is also used to update the inventory statistics for the log yard. This method of collecting log input information appeared to be fairly easy to implement and did not seem to require much additional effort on the part of the sawmill employees.

Another method of recording information on the material entering a sawmill is with barcode tags (Figure VII-1). The barcode tag enables the gathering of information for individual logs from a database stored on a personal computer. In addition to just log grade, diameter, length, and volume information, the database may also contain the date the log was scaled and the price that was paid for the log. Using barcodes as a system for recording log information does require purchasing equipment that is needed to read the barcodes and transfer information to and from the database that contains the log information. In addition, computer software needed to create and manage the database may have to be purchased and updated as necessary. However, the computer software may reduce the time required to analyze the log information. Regardless of what method is used, the overall need is to identify the total raw material cost for each log parameter group or set of log parameter combinations so that it can be allocated to the lumber products. The raw material costs calculated from the output generated by the model of the large volume sawmill are presented in Table VII-3 and the raw material costs for the model of the medium volume sawmill are presented in Table VII-4.

Table VII-3. Average total raw material costs for each of the log parameter combinations as calculated with the output data from the model of the large volume sawmill

Log parameter combinations			Average total raw material cost ($)[B]	Half-width[C]
Log grade[A]	Length (ft.)	Diameter (in.)		
Prime	8	14	1,071.79	106.74
Select	8	12	416.24	24.35
Select	8	13	540.72	43.69
Select	8	14	677.72	92.63
Select	8	18	1,184.56	131.26
Select	8	19	1,311.44	116.22
Prime	12	13	1,325.22	70.14
Prime	12	14	1,722.50	163.28
Prime	12	18	3,473.54	263.81
Prime	12	19	3,368.42	427.09
Select	12	12	638.96	53.57
Select	12	13	800.80	91.02
Select	12	14	945.00	110.01
Select	12	15	1,127.20	99.17
Select	12	18	1,953.00	127.78
Select	12	20	2,493.40	156.58
		Total	23,050.50	441.77

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces
[B]Average total raw material costs calculated from ten replications of the simulation model
[C] Half-widths of the mean are reported at the 95% confidence level

Table VII-4. Average total raw material costs for each of the log parameter combinations as calculated with the output data from the model of the medium volume sawmill

Log parameter combinations			Average total raw material cost ($)[B]	Half-width[C]
Log grade[A]	Length (ft.)	Diameter (in.)		
Prime	8	13	797.04	79.13
Prime	8	14	934.80	45.10
Prime	8	15	1,136.52	128.83
Select	8	13	447.84	62.47
Select	8	14	496.80	42.79
Select	8	15	727.92	48.90
Prime	12	13	1,260.67	75.31
Prime	12	14	1,623.78	170.38
Prime	12	15	1,796.64	181.69
Select	12	13	685.15	67.84
Select	12	14	850.50	47.50
Select	12	15	950.04	89.28
Select	12	19	1,952.96	158.44
Select	12	21	2,437.34	130.72
		Total	16,098.01	201.83

[A]Logs in the Prime grade had four clear faces and logs in the Select grade had two clear faces
[B]Average total raw material costs calculated from ten replications of the simulation model
[C] Half-widths of the mean are reported at the 95% confidence level

Calculation of the raw material costs for each set of log parameters, from the output from the model of the medium volume sawmill was done by multiplying the number of logs processed by the purchase price of each log. The purchase price values used for the logs were based upon reported values from both of the sawmills, which were previously defined in Table V-5 and Table V-6 of SECTION V.2.3.3.

To calculate the raw material costs of the log entities generated from the model of the large volume sawmill, each log entity had to be individually evaluated to determine if the log had been modeled as being partially processed during the current work shift or the previous shift. The procedure used for evaluating the log entities and assigning raw material costs to the partially processed logs was presented in SECTION V.2.4. In the actual system, that the model of the large volume sawmill is based upon, the information pertaining to the number of logs processed per shift, is controlled by the debarker operator. At approximately forty-five minutes, before the end of each shift, all logs entering the sawmill are credited to the next shift's production report. This is done by the management of the sawmill for the purpose of being able to calculate accurate lumber overrun values for each shift. Because the sawmill system is not purged of logs at the end of each shift, it is difficult to calculate exact lumber overrun values.

Since being able to trace each lumber product back to the log from which it originated is not realistic in an actual hardwood sawmill, the lumber volume and grade yield statistics from the logs sampled could be used to estimate what log group the lumber products originated from. Mathematically this allocation technique is defined by Equation VII-2, and is subsequently referred to as the lumber yield method.

$$TRMC_i = TRMC_k \times \left(\frac{ELY_{ik}}{100}\right)$$ **Equation VII-2**

where:

$TRMC_i$ = total raw material cost used to make the i^{th} product

$TRMC_k$ = total raw material cost for the k^{th} log parameter or set of log parameter combinations that was incurred during a production run

ELY_{ik} = estimated yield, in percent, of the i^{th} product from the k^{th} log parameter or set of log parameter combinations

The lumber yield method enables the ability to estimate how much raw material costs each product consumed, based upon lumber yield values from logs with similar characteristics. Through the lumber yield method, the total volume of lumber produced is not used to allocate raw material costs to the lumber grades, as with the traditional volume costing method. Because of this, the amount of raw material costs allocated to each product should be similar to the values calculated with the activity-based costing methodology. To examine the differences in amount of raw material costs allocated to the products, by the three costing methods a multiple comparison test was performed using the output values from the simulation models.

3. Results and discussion

For the multiple comparison tests, the average raw material cost values allocated to the products by the lumber yield method were compared to the values calculated by the activity-based costing method and the traditional volume costing method. Confidence intervals for the differences between the average product cost values of the costing methods were calculated using a form of the Bonferroni inequality (Equation VII-3), that is valid for analyzing the output of simulation models when the common random number variance reduction technique is used (Banks et al. 2001).

$$\overline{D}_i \pm t_{(\alpha_E/K-1)/2,R-1} * \frac{S_{D_i}}{\sqrt{R_i}}$$ **Equation VII-3**

where:

$R_i =$ number of replications or simulation runs that were made for the i^{th} treatment effect

$K =$ number of confidence intervals that will be compared

$\overline{D}_i =$ average difference between the i^{th} treatment effect and the standard

$= \frac{1}{R}\sum_{r=1}^{R} D_{ri}$ for $i = 2, \ldots, K$

$S_{D_i} =$ standard deviation of the average difference average difference between the i^{th} treatment effect and the standard

$= \frac{1}{R-1}\sum_{r=1}^{R}\left[D_{ri} - D_{\bullet i}\right]^2$ for $i = 2, \ldots, K$

$\alpha_E =$ target overall error probability

The Bonferroni inequality enables the construction of confidence intervals, for multiple comparison purposes, while maintaining a desired error probability (Banks et al. 2001). With the Bonferroni inequality, the probability of accepting a false conclusion is adjusted to compensate for the number of confidence intervals to be compared.

Results from the multiple comparison tests found that the differences in the amount of raw material costs allocated to the products by the lumber yield method were not significantly different from the activity-based costing method. The differences of the values between the lumber yield method and the traditional volume costing method were however found to be significantly different.

These results were true for both simulation models as illustrated in Table VII-5 and Table VII-6. A visual illustration of the amount of raw material costs allocated to each product, by costing method, relevant to the output data from the model of the large volume sawmill is presented in Figure VII-2. In Figure VII-3, the raw material cost of each product generated from the model of the medium volume sawmill is shown. Additional statistics from the multiple comparison test of the output from the model of the large volume is presented in Appendix A, consecutively from Table IX-3 to Table IX-8. In Appendix B, the statistics for the multiple comparison test of the output from model of the medium volume sawmill is presented in Table IX-8 to Table IX-14.

Table VII-5. Results of the multiple comparison tests for the amount of raw material costs allocated to the products between costing methods using the output data generated by the model of the large volume sawmill

Product	**Average raw material cost ($)**[A]	**95% confidence intervals for the difference between the average raw material cost value calculated with the lumber yield method**[B]	
	Lumber yield method	ABC method	Traditional volume method
FAS	7,817.22	(-148.44 , 67.40)	(844.39 , 1,039.86)
1C	5,888.29	(-77.53 , 115.36)	(-305.73 , -127.31)
2C	2,608.99	(-50.90 , 113.19)	(-288.16 , -136.06)
3A	405.62	(-21.97 , 10.33)	(-95.43 , -68.53)
3B	2,850.68	(-74.45 , 49.67)	(-379.97 , -232.28)
Pallet cant	3,479.71	(-33.27 , 59.97)	(-165.72 , -75.70)

[A]Average raw material cost value calculated from ten replications of the simulation model
[B]Confidence intervals of the ABC and traditional methods that lie completely above or below zero are significantly different from the lumber yield method

Table VII-6. Results of the multiple comparison tests for the amount of raw material costs allocated to the products between costing methods using the output data generated by the model of the medium volume sawmill

Product	Average raw material cost ($)[A]	95% confidence intervals for the difference between the average raw material cost value calculated with the lumber yield method[B]	
	Lumber yield method	ABC method	Traditional volume method
FAS	1,835.38	(-56.80 , 17.73)	(108.53 , 184.75)
1C	5,075.36	(-83.27 , 85.19)	(57.15 , 221.64)
2C and lower	5,692.73	(-65.47 , 99.06)	(-339.17 , -188.35)
Pallet cant	3,494.53	(-12.83 , 17.41)	(-39.50 , -4.05)

[A]Average raw material cost value calculated from ten replications of the simulation model
[B]Confidence intervals of the ABC and traditional methods that lie completely above or below zero are significantly different from the lumber yield method

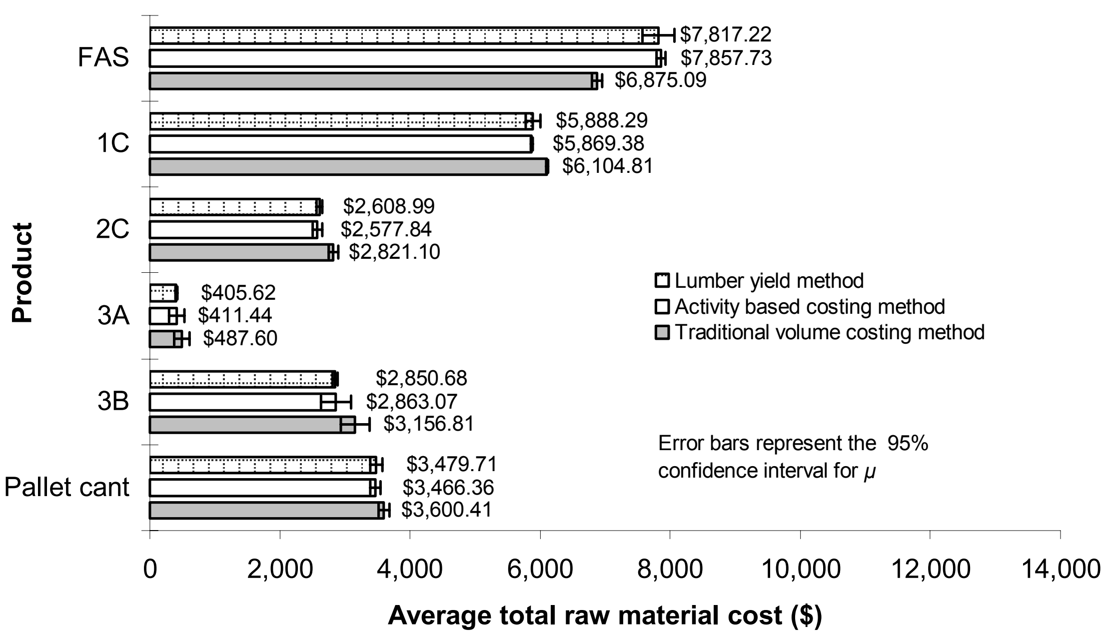

Figure VII-2. Comparison of how raw material costs were allocated to the different products between the three cost accounting methods as calculated with output data from the model of the large volume sawmill

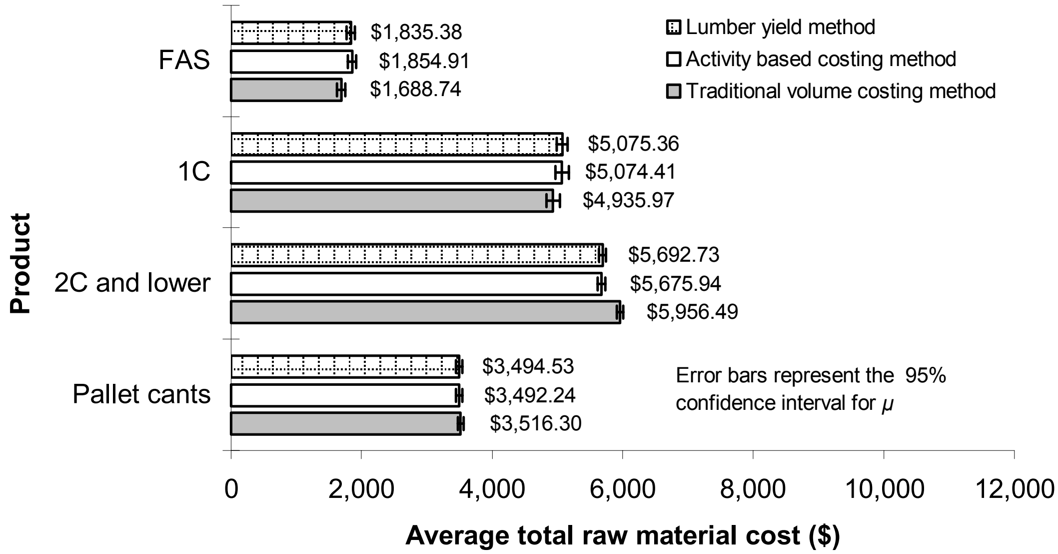

Figure VII-3. Comparison of how raw material costs were allocated to the different products between the three cost accounting methods as calculated with output data from the model of the medium volume sawmill

It should be noted that since the lumber yield information was generated from a simulation model, the variability of the yield values was limited to the input parameters. In an actual sawmill system; the variability of the lumber yield from logs is probably larger than was generated by the models due to the limited number of logs sampled. Because of this, it is not known how close in value the raw material costs of the products as calculated with the lumber yield method would be to the values calculated by the activity-based costing methodology, in a real world setting.

4. Summary

A method of allocating raw material costs to lumber products, based upon the principles of activity-based costing, was presented. The proposed methodology, termed the lumber yield method, allocates raw material costs to the lumber products as a function of the estimated lumber yield from the individual logs. To put into practice the lumber yield method requires recording the characteristics of the logs sawn and an estimation of the lumber yield from logs with similar characteristics. The requirements to implement the lumber yield methodology are not greatly different from the required information, described by Mayer and Wiedenbeck (2005), that is needed to perform standard sawmill efficiency studies.

Analysis of the output from the simulation models illustrated that with the lumber yield method, the amount of raw material costs allocated to the products was not significantly different that the amounts allocated by the activity-based costing method. The raw material costs of the products were found to significantly different between the lumber yield method and the traditional volume costing method.

5. References

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SECTION VIII. DISSERTATION SUMMARY

1. Background and scope of the study

In a typical hardwood sawmill, a number of different machine centers work collectively to process logs into lumber products. However, because logs are not naturally uniform in dimension or quality, the number of machine centers used to process a log will vary between logs. In addition, the quantity and quality of the products that are processed from a log will differ not only between logs but also within a log. Because of the variability of hardwood logs and the nature of the manufacturing process it is difficult to precisely assign manufacturing costs to the products as a function of the resources that were used to manufacture the product.

The purpose of this research was to quantify the impact of the log variables, length, grade, and scaling diameter, on hardwood lumber product costs using activity-based costing techniques. Two discrete-event simulation models were developed, based upon manufacturing information collected from a hardwood sawmill that produces approximately 35 MMBF of hardwood lumber annually, and from a second sawmill producing 7 MMBF of hardwood lumber per year. With the discrete-event simulation models, experiments were performed that demonstrated how the differences in the calculated product cost values between the traditional and activity-based cost accounting techniques were a function of how manufacturing costs are allocated to the products. It was also examined how the product costs and manufacturing costs changed based upon different log characteristics.

2. The value of activity-based product costing in a hardwood sawmill

Since hardwood lumber is a commodity product, the managers of hardwood sawmills have minimal control over setting the price at which they can sell their products. While quality and service can be used to some extent for product differentiation, the selling price of hardwood lumber is typically governed by market averages. The profits that sawmill managers calculate on the sales of their products are typically based on the traditional cost accounting method, which allocates manufacturing costs to the products based upon the volume manufactured.

In this research, it was found that in comparison to the activity based costing method; product cost values calculated with the traditional volume method were smaller for high-grade products and larger for the low-grade products. Consequently, when the value of the lumber is subtracted from product cost calculated by the traditional method, profit from the high-grade products is overestimated and profit from the low-grade products is underestimated.

An analysis of how the raw material costs and direct labor were allocated to the products by the two calculation methods demonstrated why the product cost values for the high-grade and pallet cant material was consistently different. The analysis illustrated that with the activity-based costing method, raw material and direct labor costs can be allocated to products as a function of the material from which the products originated and the machines used to process the products. In contrast, the traditional volume costing method allocated raw material and direct labor costs proportionally to the total volume of material produced.

In terms of allocating manufacturing costs to the products manufactured, the activity-based method takes into account more variables than the traditional costing technique. With the activity-based costing method, direct labor costs were able to segregated between the lumber products, based upon the amount of direct labor used to manufacture the individual products. This type of analysis is not possible under the principles of the traditional cost accounting method. However due to the nature of the manufacturing environment of a hardwood sawmill, calculation of product costs with the activity-based is not practical because it is difficult to track individual boards through the system.

3. The impact of log parameters on product costs and manufacturing costs

The quality and quantity of the estimated lumber that can be produced from a log are the criteria used when buying or selling hardwood logs. Consideration of how the particular parameters of a log will affect the cost to saw the lumber from the log is typically not accounted for. Because hardwood sawmills are designed to process logs of different lengths, diameters, and grades simultaneously, it is difficult to quantify how the cost to manufacture the products is affected by different log parameters. By using the two simulation models, changes in the cost to manufacture two thousand board feet of 1C grade lumber was quantified as a function of different log parameters.

For the model of the sawmill that produces 35 MMBF of hardwood lumber annually, log grade was identified as having the greatest influence on determining product costs and total manufacturing costs. Results from the model of the sawmill that produces 7 MMBF of hardwood lumber annually however demonstrated that log diameter had a greater impact on determining product costs and total manufacturing costs. The commonality of the results from the two simulation models was that the differences in the volume of lumber produced, between the logs that were studied, was a critical component in determining which log parameter had the most effect on changing the dynamics of the sawmill system.

4. An experimental method for more precisely allocating raw material costs in a hardwood sawmill environment

Based upon the principles of activity-based accounting, a methodology was proposed that could be used by the hardwood sawmill industry to more closely estimate how raw material costs can be more appropriately allocated to each lumber grade. The proposed methodology, termed the lumber yield method, uses lumber yield values from logs with similar characteristics to allocate raw material costs to the lumber products. Analysis of the output from the simulation models illustrated that with the lumber yield method, the amount of raw material costs allocated to the products was not significantly different that the amount allocated by the activity-based costing method. The raw material costs of the products were found to significantly different between the lumber yield method and the traditional volume costing method.

5. Recommendations for future research

One of the limitations for both of the simulation models that were built for this research project, was that they were only able to model lumber yield based upon the data collected from the sawmill. An analysis of how changing the sequence of machine centers used to process a log affects lumber volume and grade yield could not be done with the existing models. The models developed for this research project are only able to predict lumber yield when logs are processed through a fixed sequence of machine centers. With a more dynamic simulation model, studies could be performed that examined how lumber volume and grade yield changed by altering the sequence of machine centers used to process a log.

Previous research done by Meimban (1991) has demonstrated that lumber volume and grade yield can be generated for any size and grade of log, by using geometric algebra to predict volume yield, and U.S.D.A. Forest Service grade recovery data to predict grade yield. The procedure used by Meimban (1991) was not implemented in this research study because incorporating this information into the simulation model would have been cost prohibitive in terms of time and money budgeted for this project.

Another area of study that could be explored is the application of the activity-based costing methodology to help identify the cost inefficiencies of removing and processing underutilized small-diameter trees from the forest. The removal of small-diameter trees from forests in the Western United States has been identified as a key element in helping to reduce forest fire hazards and also improving wildlife habitat (LeVan-Green and Livingston 2001). However, because the trees are of low quality and yield products with relatively low market value, the harvesting and processing of small-diameter timber under the traditional cost accounting methodology has been determined to be cost inefficient. An analysis of the costs that accumulate as the trees move from the forest to the factory, with the activity-based costing methodology, may help to identify areas in the supply chain where the traditional costing technique does not accurately allocate costs to the products or activities.

An important topic, not addressed by this research is the application of just-in-time manufacturing strategies that could be implemented by the hardwood sawmill industry. Previous research (Leonard 2005) has shown that the potential exists for softwood sawmills to financially benefit from reducing lead-time and inventory levels. Typically, neither hardwood nor softwood sawmills actively manage the quality or quantity of logs sawn for the purpose of optimizing the production rates. As illustrated by this research, different log parameters do have an effect on overall processing time and manufacturing costs. However, the limited number of logs available for this research prevented an in-depth optimization study that could quantitatively identify the cost benefits of implementing just-in-time manufacturing strategies. A more dynamic simulation model of a hardwood sawmill, as developed by Meimban (1991), would be an effective tool in performing such a study.

6. References

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SECTION IX. APPENDICES

Appendix A. Information regarding the model of the large volume sawmill

Table IX-1. Time distributions and statistical results of the K-S goodness of fit tests for activities by machine center utilized in the large volume sawmill

Machine center / Activity(s)	Time distribution (sec.)[A]	n[B]	Square error	p – value[C]
Debarker				
Debark logs	21 + ERLA(5.97, 3)	62	0.011	> 0.15
Headrig				
Log loading and rotating	1 + LOGN(2.89, 1.59)	145	0.008	> 0.15
Rotating log	0.11 + LOGN(2.18, 0.913)	124	0.316	0.118
Sawing	NORM(3.57, 0.703	26	0.212	> 0.15
Log unloading times	TRIA(0.53, 0.688, 1.21)	20	0.007	> 0.15
Returning carriage to original log loading position	2.12 + ERLA(0.211, 4)	20	0.124	> 0.15
Returning carriage to set up a cut without rotating log	1.31 + 1.63*BETA(1.26, 2.34)	20	0.008	> 0.15
Move carriage forward towards saw	0.75 + GAMM(0.1, 8.38)	168	0.003	> 0.15
Return carriage to original position after unloading cant on the headrig conveyor	0.04 + WEIB(3.8, 4.56)	65	0.017	0.04
Band resaw				
Sawing	NORM(3.57, 0.703)	26	0.021	> 0.15
Cant positioner				
Set up cant for band resaw	0.19 + LOGN(0.523, 0.278)	105	0.019	0.149
Gangsaw				
Cant setup and sawing	26 + GAMM(2.37, 3.28)	146	0.013	> 0.15
Edger				
Sawing	TRIA(5, 6.38, 7.75)	24	0.012	> 0.15
Trimmer				
Lumber handling	9*BETA(0.889, 3.3)	75	0.003	< 0.01
Lumber grader(s)				
Grade lumber	0.14 + LOGN(2.33, 1.52)	22	0.027	> 0.15

[A]Time distributions were generated using Input Analyzer Ver. 7.01.00 by Rockwell Software Inc.
[B]Number of data points
[C]*p* - values from Kolmogorov-Smirnov test as calculated by the Input Analyzer software

Table IX-2. Frequency of unscheduled downtimes, time distributions and statistical results of the K-S goodness of fit tests by machine center for the large volume sawmill

Machine center	Frequency of unscheduled downtime distribution (count)	Duration of unscheduled downtime distribution (sec.)[A]	n[B]	Square error	p – value[C]
Debarker	UNIF(25, 30)	UNIF(48, 126)	5	0.320	> 0.15
Headrig	POIS(49)	6 + 42 * BETA(0.303, 0.456)	4	0.038	> 0.15
Band resaw	POIS(96)	5 + WEIB(15.8, 0.716)	15	0.015	> 0.15
Cant positioner	POIS(89)	UNIF(10, 21)	5	0.000	> 0.15
Gangsaw	POIS(49)	6 + 42 * BETA(0.303, 0.456)	4	0.038	> 0.15
Edger	POIS(51)	3 + LOGN(34.6, 88)	16	0.007	> 0.15
Trimmer	POIS(200)	8 + 46 * BETA(0.392, 0.65)	8	0.060	> 0.15

[A]Time distributions were generated using Input Analyzer Ver. 7.01.00 by Rockwell Software Inc.
[B]Number of data points
[C]p - values from Kolmogorov-Smirnov test as calculated by the Input Analyzer software

Table IX-3. Multiple comparison analysis of the difference from the amount raw material cost allocated to the FAS product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	Raw material cost ($)	Difference from the amount of raw material cost allocated to the FAS product by the lumber yield method[A]	
	Lumber yield method	Activity-based method	Traditional volume method
1	7,653.65	-72.02	954.88
2	7,564.36	-98.36	936.56
3	7,614.74	-27.30	932.14
4	7,823.41	-158.26	796.48
5	7,526.95	-132.14	864.47
6	8,441.10	234.67	1,206.75
7	8,583.54	-146.30	910.15
8	7,920.57	126.96	1,054.93
9	7,653.76	-96.12	868.97
10	7,390.08	-36.31	895.92
Sample mean		-40.52	942.13
Standard deviation		126.86	114.89
Variance		16,094.40	13,199.55
Standard error		40.12	36.33
Half-width		107.92	97.73
95% LCL		-148.44	844.39
95% UCL		67.40	1,039.86

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-4. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 1C product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)**	**Difference from the amount of raw material cost allocated to the 1C product by the lumber yield method**[A]	
	Lumber yield method	Activity-based method	Traditional volume method
1	5,579.86	14.17	-258.91
2	5,737.08	-69.96	-324.56
3	5,821.10	4.69	-159.89
4	6,032.22	229.69	-12.14
5	5,858.65	65.89	-215.42
6	6,148.02	-114.81	-375.18
7	6,111.43	93.04	-186.80
8	5,984.03	20.56	-160.21
9	5,827.53	-156.15	-308.66
10	5,782.98	102.02	-163.43
Sample mean		18.91	-216.52
Standard deviation		113.38	104.87
Variance		12,854.21	10,998.46
Standard error		35.85	33.16
Half-width		96.44	89.21
95% LCL		-77.53	-305.73
95% UCL		115.36	-127.31

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-5. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 2C product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)** Lumber yield method	**Difference from the amount of raw material cost allocated to the 2C product by the lumber yield method**[A] Activity-based method	Traditional volume method
1	2,485.14	85.69	-164.20
2	2,586.25	83.51	-168.17
3	2,618.71	44.23	-239.07
4	2,654.75	34.07	-236.38
5	2,468.51	-19.58	-245.17
6	2,672.85	48.78	-188.39
7	2,690.77	41.34	-175.70
8	2,649.08	-44.67	-242.00
9	2,634.25	204.51	-55.23
10	2,629.60	-166.41	-406.79
Sample mean		31.15	-212.11
Standard deviation		96.45	89.40
Variance		9,301.84	7,992.02
Standard error		30.50	28.27
Half-width		82.04	76.05
95% LCL		-50.90	-288.16
95% UCL		113.19	-136.06

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-6. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 3A product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	Raw material cost ($)	Difference from the amount of raw material cost allocated to the 3A product by the lumber yield method[A]	
	Lumber yield method	Activity-based method	Traditional volume method
1	393.99	-20.49	-101.00
2	401.81	-13.11	-72.34
3	404.27	-28.78	-104.54
4	410.76	3.54	-71.87
5	405.20	2.95	-90.66
6	429.34	38.35	-52.69
7	382.70	-11.02	-82.30
8	366.30	-22.57	-88.93
9	426.42	-6.20	-86.89
10	435.38	-0.89	-68.61
Sample mean		-5.82	-81.98
Standard deviation		18.98	15.81
Variance		360.34	250.04
Standard error		6.00	5.00
Half-width		16.15	13.45
95% LCL		-21.97	-95.43
95% UCL		10.33	-68.53

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-7. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 3B product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	Raw material cost ($)	Difference from the amount of raw material cost allocated to the 3B product by the lumber yield method[A]	
	Lumber yield method	Activity-based method	Traditional volume method
1	2,860.91	-104.66	-399.03
2	2,892.47	37.74	-296.40
3	2,839.58	5.13	-286.29
4	2,765.29	-46.11	-307.50
5	2,747.54	72.60	-180.59
6	2,955.87	-126.10	-377.09
7	2,908.39	29.19	-305.74
8	2,837.20	-85.82	-430.83
9	2,884.22	23.76	-320.52
10	2,815.36	70.40	-157.28
Sample mean		-12.39	-306.12
Standard deviation		72.96	86.81
Variance		5,322.97	7,536.68
Standard error		23.07	27.45
Half-width		62.06	73.85
95% LCL		-74.45	-379.97
95% UCL		49.67	-232.28

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-8. Multiple comparison analysis of the difference from the amount raw material cost allocated to the pallet cant product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	Raw material cost ($)	Difference from the amount of raw material cost allocated to the pallet cant product by the lumber yield method[A]	
	Lumber yield method	Activity-based method	Traditional volume method
1	3,467.74	97.32	-31.73
2	3,473.78	60.18	-75.10
3	3,437.96	2.03	-142.35
4	3,492.67	-62.92	-168.59
5	3,332.50	57.09	-85.83
6	3,585.33	-80.89	-213.40
7	3,617.02	-6.24	-159.62
8	3,590.68	5.54	-132.97
9	3,379.18	30.20	-97.67
10	3,420.20	31.19	-99.81
Sample mean		13.35	-120.71
Standard deviation		54.80	52.91
Variance		3,003.42	2,799.71
Standard error		17.33	16.73
Half-width		46.62	45.01
95% LCL		-33.27	-165.72
95% UCL		59.97	-75.70

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Appendix B. Information regarding the model logic of the medium volume sawmill

Table IX-9. Time distributions and statistical results of the K-S goodness of fit tests for activities by machine center utilized in the medium volume sawmill

Machine center / Activity(s)	Time distribution (sec.)[A]	*n*[B]	Square error	*p* – value[C]
Debarker				
Debark logs	12 + LOGN(17.3, 28.5)	33	0.005	> 0.15
Headrig				
Log loading and rotating	1 + LOGN(2.78, 2)	44	0.008	> 0.15
Rotating log	1 + ERLA(0.267, 6)	44	0.008	> 0.15
Sawing	2 + GAMM(0.419, 3.48)	44	0.019	> 0.15
Log unloading times	0.57 + LOGN(0.446, 0.344)	8	0.056	> 0.15
Returning carriage to original log loading position	1.81 + LOGN(0.75, 0.378)	42	0.005	> 0.15
Returning carriage to set up a cut without rotating log	1 + GAMM(0.136, 6.18)	44	0.003	> 0.15
Move carriage forward towards saw[D]	1.81 + LOGN(0.75, 0.378)	42	0.005	> 0.15
Return carriage to original position after unloading log onto the headrig conveyor	2.12 + WEIB(1.86, 3.16)	42	0.004	> 0.15
Gangsaw				
Cant setup and sawing	28 + LOGN(5.7, 3.89)	127	0.006	> 0.15
Edger				
Sawing	4.42 + GAMM(0.366, 4.31)	49	0.002	> 0.15
Trimmer				
Lumber handling	0.6 + LOGN(0.876, 0.534)	24	0.002	> 0.15
Lumber grader				
Grade lumber	1 + 4.77*BETA(0.879, 1.55)	22	0.004	> 0.15

[A]Time distributions were generated using Input Analyzer Ver. 7.01.00 by Rockwell Software Inc.
[B]Number of data points
[C]*p* - values from Kolmogorov-Smirnov test as calculated by the Input Analyzer software
[D]*Move carriage forward towards saw* and *returning carriage to original log loading position* time distributions were derived from the same dataset

Table IX-10. Frequency of unscheduled downtimes, time distributions and statistical results of the K-S goodness of fit tests by machine center for the medium volume sawmill

Machine center	**Frequency of unscheduled downtime distribution (count)**	**Duration of unscheduled downtime distribution (sec.)**[A]	***n***[B]	**Square error**	***p* – value**[C]
Debarker	POIS(9)	16 + WEIB(42.5, 0.69)	5	0.073	> 0.15
Headrig	POIS(17)	UNIF(6, 37)	4	0.050	> 0.15
Gangsaw	POIS(21)	7 + LOGN(62.5, 178)	10	0.035	> 0.15
Edger	POIS(17)	UNIF(6, 37)	4	0.050	> 0.15
Trimmer	POIS(28)	1 + LOGN(5.01, 8.53)	15	0.008	> 0.15

[A]Time distributions were generated using Input Analyzer Ver. 7.01.00 by Rockwell Software Inc.
[B]Number of data points
[C]*p* - values from Kolmogorov-Smirnov test as calculated by the Input Analyzer software

Table IX-11. Multiple comparison analysis of the difference from the amount raw material cost allocated to the FAS product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)** Lumber yield method	**Difference from the amount of raw material cost allocated to the FAS product by the lumber yield method**[A] Activity-based method	Traditional volume method
1	1,745.25	-45.19	115.39
2	1,742.79	-86.92	76.35
3	1,804.16	-95.70	82.04
4	1,730.51	3.30	185.00
5	1,906.45	-17.63	121.25
6	1,961.17	17.63	189.02
7	2,033.08	-6.00	164.98
8	1,889.55	-12.47	153.34
9	1,805.35	10.12	191.20
10	1,735.49	37.51	187.82
Sample mean		-19.54	146.64
Standard deviation		43.81	44.80
Variance		1,919.31	2,007.07
Standard error		13.85	14.17
Half-width		37.27	38.11
95% LCL		-56.80	108.53
95% UCL		17.73	184.75

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-12. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 1C product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)** Lumber yield method	**Difference from the amount of raw material cost allocated to the 1C product by the lumber yield method**[A] Activity-based method	Traditional volume method
1	5,125.39	9.86	182.67
2	4,959.23	-44.48	89.34
3	4,960.20	100.59	273.79
4	4,956.32	-168.44	-15.49
5	5,307.83	41.97	157.83
6	5,138.67	153.73	266.94
7	5,221.17	-73.67	53.15
8	4,924.65	69.77	149.17
9	5,175.45	-106.27	38.67
10	4,984.72	26.51	197.87
Sample mean		0.96	139.39
Standard deviation		99.02	96.69
Variance		9,804.63	9,348.71
Standard error		31.31	30.58
Half-width		84.23	82.25
95% LCL		-83.27	57.15
95% UCL		85.19	221.64

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-13. Multiple comparison analysis of the difference from the amount raw material cost allocated to the 2C product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)** Lumber yield method	**Difference from the amount of raw material cost allocated to the 2C product by the lumber yield method**[A] Activity-based method	Traditional volume method
1	5,785.02	56.67	-242.36
2	5,663.53	127.23	-161.30
3	5,575.80	-32.55	-351.89
4	5,731.62	151.60	-147.20
5	5,782.85	-45.27	-284.50
6	5,547.18	-157.90	-421.33
7	5,782.53	66.74	-219.81
8	5,772.38	-34.53	-270.39
9	5,704.29	89.65	-194.82
10	5,582.15	-53.70	-343.99
Sample mean		16.80	-263.76
Standard deviation		96.71	88.65
Variance		9,352.48	7,859.21
Standard error		30.58	28.03
Half-width		82.27	75.41
95% LCL		-65.47	-339.17
95% UCL		99.06	-188.35

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Table IX-14. Multiple comparison analysis of the difference from the amount raw material cost allocated to the pallet cant product by the lumber yield method between the amount allocated by the activity-based method and the traditional volume method

Replication	**Raw material cost ($)** Lumber yield method	**Difference from the amount of raw material cost allocated to the pallet cant product by the lumber yield method**[A] Activity-based method	Traditional volume method
1	3,587.65	-20.81	-55.17
2	3,438.16	4.64	-3.93
3	3,435.56	28.15	-3.46
4	3,454.12	14.00	-21.85
5	3,567.93	21.45	5.94
6	3,433.92	-12.92	-34.10
7	3,623.68	13.52	2.28
8	3,494.88	-22.28	-31.63
9	3,500.12	7.00	-34.53
10	3,409.29	-9.88	-41.26
Sample mean		2.29	-21.77
Standard deviation		17.77	20.84
Variance		315.930	434.193
Standard error		5.621	6.589
Half-width		15.12	17.73
95% LCL		-12.83	-39.50
95% UCL		17.41	-4.05

[A]Confidence intervals of the costing methods that lie completely above or below zero are significantly different from the lumber yield method

Appendix C: Vita

Patrick Matthew Rappold earned an A.A.S. degree in Forest Technology from the New York State Ranger School and went on to complete a B.S. and M.S. degree in Wood Products Engineering at the College of Environmental Science and Forestry. At Virginia Polytechnic Institute and State University, Mr. Rappold continued graduate work in the area of wood science and completed the requirements for the degree of Doctor of Philosophy in July of 2006.