DEVELOPMENTS OF AN ADAPTIVE SAWMILL - FLOW SIMULATOR TEMPLATE FOR PREDICTING RESULTS OF CHANGES AT SMALL- LOG SAWMILLS.

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ABSTRACT
Managing or designing sawmills can be an extremely difficult and sawmill managers and designers face a multitude of decisions each day with regard to management of sawmill operations and productivity. Sawmill managers therefore must be skilled enough at balancing the variables that determine sawmill production including: raw materials, personnel, equipment, product mix, product quality, orders and money in order to make profits. Changing any of these variables in one part of the mill can have unforeseen and sometimes detrimental impact upon other parts of the mill. Extreme heterogeneity in raw materials adds significantly to the complexity of sawmill systems. Simulation is one of the most common methods for constructing models that include random behaviour of a large number and a wide variety of components in sawmilling such as reduced availability of large-diameter logs with increased wood demands which may result into smaller-diameter logs entering sawmills. The design and operation of a modern small-log sawmill requires skills different from those needed in a large-log sawmill. Because the log size is small and lumber production per log is low, production must be high. Profitable sawing of small diameter logs requires high speed processing, use of curve sawing, and careful log-geometry and orientation considerations before sawing. Although numerous simulation studies have investigated sawing process of large-diameter logs, only a limited number of simulators have addressed processing of small-diameter logs. Further, these latter simulators concentrated on improving either the lumber volume yield or the lumber grade/value from logs. The modeling of entire sawmill operations has been far less extensive. The sawmill-flow simulator template (SFST) and a simulation template end–user interface designed on Excel spreadsheets in this study is a unique modeling package that can be used to predict results of changes in production at a small-log sawmills. The SFST encompasses log–sawing and sawmill-flow logics designed to facilitate flexibility in modeling different sawmill configurations and production scenarios. These may include predicting the impact on sawmill performance measures due to changes in mill layout, raw material and product specifications, sawing solutions, and queue sizes which can greatly help the saw miller to make well-informed decisions.

Key words: Sawmill flow simulator – modular approach – discrete event simulation

INTRODUCTION
Reduced availability of large-diameter logs and increased wood demands have resulted in smaller-diameter logs entering sawmills over the last couple of decades. This has been true for North America, Western Europe, Scandinavia, the Soviet Union (Williston 1981), and in developing countries (Guzman 1981, Baharuddin 1984, Oliver 2000). However, previous research has indicated that making profits from converting small-diameter logs into lumber can be a real challenge for sawmill managers. For example, a study by Wagner *et al.* (2000) pointed out that the conversion of small-diameter timber of less than 22.86 cm diameter at breast height (dbh) into lumber may not recover the cost of sawlog harvest and delivery to conventional stud sawmills in the western US. This was true even at a low level of return on investment of 10%. The design and operation of a modern small-log sawmill requires skills different from those needed in a large-log sawmill (Williston 1981).

Since the log size is small and lumber production per log is low, production must be high. High production implies the need to increase both the piece count and lumber recovery. To achieve both higher lumber recovery and higher lumber production, sawmill managers must be skilled at balancing interdependent variables including raw materials, personnel, equipment, machine layout and material flow, product mix, product quality, orders and capital. Changing any of these variables in one part of the mill can have unforeseen and sometimes detrimental impacts upon other parts of the mill. Put another way, studying only one component of such a broad system in isolation from other components may not produce the best overall results (Kline et al. 1992). Managers need timely and comprehensive information on which to base important decisions. Simulation provides a method to rapidly conduct experiments that predict results of alternative manufacturing decisions (Banks *et al.*, 2003).

One of the largest application areas for simulation modelling is that of manufacturing systems (Rogers 2002). Modelling and simulation have been cited as emerging key technologies to support manufacturing in the 21st Century. It has been stated that no other technology offers more than a fraction of the potential that modelling and simulation offer for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing product realization costs (IMTR 1998). Although simulation modelling has gained wide acceptance in many fields, its use by the sawmill industry has been limited (Wagner and Taylor 1983, Meimban 1991, Wagner et al. 1996). Major factors that have deterred the sawmill industry from adopting modelling and simulation techniques include: 1) simulation requires considerable investment of time and money, 2) lack of adequately-trained personnel to conduct simulation procedures, and 3) lack of awareness of the potential benefits of the technique (Aune 1982, Kline *et al.*1992, Wagner et al. 1996). Therefore, a sawmill simulation program is needed that could overcome these factors.

Uses of simulation modelling in the sawmill industry can be categorized into two groups: 1) log-sawing programs used to investigate the log sawing process at headrigs and resaws, and 2) sawmill simulation-flow programs used to model the entire sawmill operations. Numerous studies investigated the log sawing process (McAdoo1969, Tsolakides 1969, Hallock and Lewis 1971, Cummins and Culbertson 1972, Airth and Calvert 1973, Richards 1973, Pnevmaticos *et al,* 1974, Wagner and Taylor 1975, Richards 1977, Pnevmaticos and Mouland 1978, Richards, *et al.* 1979, Adkins *et al.*, 1980, Steele *et al.,* 1993, and Steele *et al.*, 1994). These log-sawing programs concentrated on improving either the lumber volume yield or the lumber grade/value from logs (Aune 1982). The modelling of entire sawmill operations has been far less extensive than the modelling of the log-sawing process (Aune 1982, Wagner and Taylor 1983, Meimban 1991, Zhang 1993).

Investigators at MacMillan Bloedel Ltd. developed and used another simulation program (MILLSIM) to evaluate a number of production parameters within existing and planned sawmill operations (Aune 1982). A comprehensive design and evaluation simulation modelling program (DESIM) for hardwood sawmills was also described by Adams (1988). Additionally, Wagner and Taylor (1983), developed the SPSM sawmill model to demonstrate the potential for simulation techniques in the softwood sawmill industry. Although these simulation programs complemented log-sawing programs, they had some real limitations. Both SPSM and Micro-MSUSP programs incorporated Best Opening Face (BOF), a DOS-based program for log breakdown in which logs were considered to be straight, uniform in taper, and circular in cross section, which led to critically over-estimation of models' outputs. In addition, both SPSM and Micro-MSUSP lacked animation, which is an important tool in model debugging and adding face-validity to the model. Another weakness associated with the two programs was the limited number of concurrent entities that could be handled. DESIM and MILLSIM programmes assumed a truncated cone as the log model. While this satisfied the need for a brief analysis, this log model assumption reduced their productive value particularly when sweep was present. The DESIM program was also limited to the lumber sizes that it could produce from a log. The DESIM program could simulate the production of one lumber thickness from each individual log as opposed to up to three different thicknesses that may be processed from small logs. The SPSM, Micro-MSUSP, DESIM, and MILLSIM programmes were mainly designed to process large-diameter logs.

The creation of a simulator capable of modelling any log shape and portraying the dynamic, discrete, and stochastic nature of small-log sawmill operations has never before been accomplished. Therefore, the main objective of this research was to develop a sawmill-flow simulator template (SFST) for use at small-log sawmills. An adaptive simulation template would provide the necessary framework in which details could be added to accurately depict specific processes. A sawmill simulation template would significantly reduce model development time and provide valuable insight into appropriate inputs to be considered when analyzing a given process. Specific objectives of the study were to 1) to describe the log-sawing logic for small-diameter logs using SAWSIM (a log-sawing program), 2) to describe a sawmill-flow logic model for small-log sawmills using Arena software 3) to design a template in Excel spreadsheets for user-data entry 4) to integrate Arena and Excel Application using Visual Basic for Application (VBA) programming interface, and 5) to validate the model. The scope of the SFST was limited to the green end of the sawmill, i.e. everything from the log yard to green lumber-sorting.

Model Development

The sawmill-flow simulator template (SFST) is made up of two main components: 1) the log–sawing logic, and 2) the sawmill-flow logic. The log-sawing logic, also known as log breakdown, is a key to predicting lumber recovery. The sawmill-flow logic analyzes machine utilization, material flow in sawmills, and production. Low machine-utilization levels and poor material flow negatively impact throughput, safety of workers, lead times, and the amount of "pile-ups" in the sawmill (Cedarleaf 1994). Therefore, a combination of the log-sawing and sawmill-flow logics provides a wide range of options for mill analysis.

The SFST development process conformed to a model development paradigm suggested by Sargent (2003). The model development paradigm stressed the need to have a thorough description of the system and the type and format of data to be used in the model. Other equally important aspects included model verification and validation. Subsequent sections will articulate these issues. Data collected from one small-log sawmill in the Northwest US, hereafter referred to as the study mill, were used to illustrate the SFST development process and validation of the model.

Log-sawing logic and SAWSIM

In the SFST program, log-sawing logic is performed by a log-sawing simulator (SAWSIM). SAWSIM has been used at literally hundreds of sawmills across North America, Europe, New Zealand, South Africa, and Australia (Leach 1994). The program has several advantages. Unlike BOF, DESIM, and MILLSIM which applied truncated cones as log models, SAWSIM uses real log-shapes. The program is capable of simulating the breakdown of saw logs with crook, sweep and variable taper, and is capable of handling complicated sawing patterns. The program can orient and align sawlogs in any position prior to sawing. The program provides various “loss factors” that may be applied to allow for defect and real operating conditions experienced in a sawmill (Leach 1994). Therefore, this program was found appropriate for enhancing log breakdown solutions in small-log sawmills.

In the SFST program, the SAWSIM program generates outputs from logs (lumber, chips, and sawdust). These SAWSIM outputs are written to Excel spreadsheets. As logs and cants reach headrigs and resaws in a simulation, the appropriate lumber pieces generated from sawn logs and their attributes are read from the spreadsheets and enter the simulation. Excel spreadsheets also serve as an input interface for SAWSIM. Inputs include detailed information on saw logs (i.e. saw log diameter, length, sweep and taper), lumber thickness groups (2.54 cm, 5 cm etc), lumber description (i.e. lumber widths, lengths, wane allowances), sawmill machines, saw kerfs, and product prices. The SAWSIM program requires that cutting patterns for logs, cants, flitches, boards, and slabs be specified in detail. The program considers each alternative pattern and selects one that generates maximum yield or value.

Sawmill-flow logic and Arena®

The sawmill-flow logic for the SFST was developed with Arena® 8.01 software (2004), produced and marketed by 2000 Rockwell Software Inc. in Milwaukee, Wisconsin, USA. It is general-purpose simulation-modelling software that provides an integrated framework for building and animating simulation models. The software provides a user with modelling modules (queues, resources, entities, etc.) necessary to simulate any manufacturing environment. In addition, Arena® uses the SIMAN modelling framework which stresses distinction between the system model and the experimental frame. The system model defines the static and dynamic characteristics of the system. The experimental frame defines the experimental conditions under which the model is run to generate specific output data (Sturrock and Pedgen 1990). By separating the model structure and experimental frame into two separate components, different simulation experiments can be performed by changing only the experimental frame. The SFST experimental frame was created in Excel workbook-spreadsheets. Using Visual Basic for Application (VBA) subroutines, these data were read into the SFST. Arena® provides a graphical interface that uses windows and modules. However, building a sawmill simulation model with these modules was difficult. Unlike most manufacturing systems that assemble components into products, sawmills disassemble logs into lumber and other products, customization of modules was therefore necessary. In this SFST, modules were identified and configured into sub-models germane to the sawmill industry. These sub-models formed the model-building blocks that were pulled together to form a small-log sawmill-simulation model (the SFST).

Small-log sawmill data and data format

Small-log sawmill data were collected at the study mill to allow model building and testing. The types of data collected included log descriptions, distributions and breakdowns, lumber sizes and prices, equipment types and configurations, machine-material processing times, types of material handling mechanisms and speeds, log arrival rates (inter-arrival times), failure patterns of machines, working schedules, i.e., number of shifts, shift and break-lengths. Of the data collected at the study mill, material processing times, log arrival rates, and machine-failure patterns were random variables. These variables are better represented by probability distributions than by their mean values (Biller and Nelson 2002, Law and Kelton 2000, Kelton *et al.* 2002). Simulation models rely on the accurate specification of these distributions and their associated parameters that serve as inputs to the models (Henderson 2003). Therefore, raw data on these variables were collected and fit with probability distributions. The *"Input Analyzer for Arena®"*, a package that comes with *Arena®* software, was used to fit continuous theoretical distributions to empirical data, estimate their parameters, and measure how well they fit the data. For example, Figure 1 shows a Weibull distribution that was the best fit distribution to empirical processing times collected from a headrig machine.

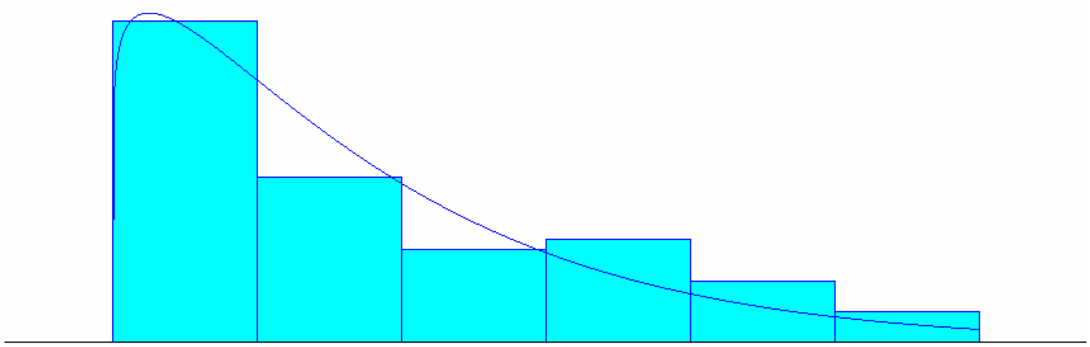


Figure 1 A function density distribution fitted to the data

Expression: 5 + WEIB (2.18, 1.12)
Chi Square Test
Corresponding p-value < 0.005
Kolmogorov-Smirnov Test
Corresponding p-value = 0.1481

Two criteria were used in the *Input Analyzer* to select the best fit distribution (Kelton *et al.* 2002: 1) the mean squared error which measures quality of the distribution's match to the empirical data (the smaller the better fit), and 2) *p-values* from the chi-square and Kolmogorov-Smirnov (K-S) goodness-of-fit hypothesis tests. Large *p-values* support the fit of the distribution and *p-values* greater than 0.1 are typically considered to be large (Kelton *et al.* 2002, Biller and Nelson 2002). *P-values* less that 0.05 indicate that the distribution is not a very good fit (Kelton *et al*. 2004).

Computerized model development: The modular approach, ActiveX® technology and VBA subroutines

When developing small-log sawmill models, a good approach is to simplify the model building process by modularization (Sturrock and Pegden 1990, Diamond *et al.* 2002, Banks, *et.al.* 2003, Kelton *et al.* 2004). The modularization-concept assumes that the entire system is made up of a set of smaller manageable components (building blocks) that can be linked together to form a complete system model. In the application of this approach to the modelling of small-log sawmills, sawmills were considered to be systems made up of smaller manageable components. The smaller manageable components were modelled separately and tested before being used in the entire small-log sawmill model. These components included log input distributions, machine centres, surge decks/queues (as part of machine centres), and conveyors. In the SFST, these components were modelled as submodels. The modularization approach utilized Arena® modules archived in the Arena® library. These modules were identified and logically grouped into submodels representing various components of a sawmill system. Using this approach, time used on final model verification and validation was spared since much was addressed during the submodel development (Webster and Goulet 1978, Kelton *at el.*

2004). The overall planning and programming effort needed to develop an appropriate package and the requirement that the developed package include all functional activities of the problem entity added complexity to the modular approach. Configuration of submodels and solving these modularization shortcomings formed much of the work of this study.

Automation of Applications

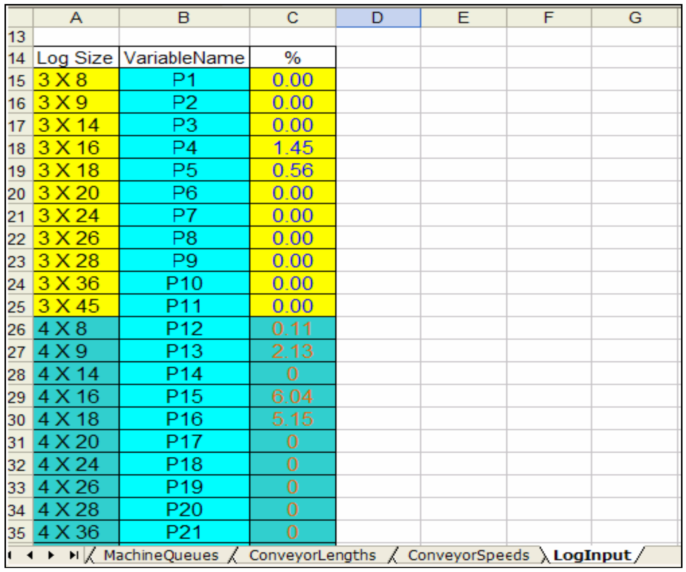
In a computer program involving a number of applications such as the SFST where Arena®, Excel and VBA applications are involved, there should be a way to organize and control (automation) the applications so that set goals are met. The Arena program exploits two window technologies that are designed to enhance the integration of desktop applications (Kelton et al 2004). These technologies are ActiveX® and Visual Basic for Application (VBA). Visual Basic for Application provided an interface on which automation subroutines were written.

The SFST VBA-Subroutines

The programmed VBA subroutines in the SFST performed two main functions: 1) declaration and 2) interaction of VBA and Arena®. The declaration entailed notifying VBA of the kinds of data (type and format) that were to be handled and how much space was needed for each type of data. The declaration also notified VBA where to hold or keep each data type. The interaction of VBA and Arena® was through model logic subroutines and functions that were automatically executed on the occurrence of specific events.

Simulation workbook and Excel user interface

A single simulation Excel workbook with several worksheets was created and served as the SFST experimental frame "the template". The data stored in this simulation workbook included the log input distributions, log-sawing solutions, machine down times, prices, conveyor speeds and lengths, surge deck capacities, lumber sorter-batch sizes, etc. The user may change data in this workbook for each modelling situation. The VBA subroutines were used to read data from the simulation workbook and update respective data in the SFST. The VBA subroutines allow the SFST users to maintain and modify the experiment frame without knowing the details of Arena® software. Figure 2 presents a snapshot of a simulation workbook.



Log Size	VariableName	%
3 X 8	P1	0.00
3 X 9	P2	0.00
3 X 14	P3	0.00
3 X 16	P4	1.45
3 X 18	P5	0.56
3 X 20	P6	0.00
3 X 24	P7	0.00
3 X 26	P8	0.00
3 X 28	P9	0.00
3 X 36	P10	0.00
3 X 45	P11	0.00
4 X 8	P12	0.11
4 X 9	P13	2.13
4 X 14	P14	0
4 X 16	P15	6.04
4 X 18	P16	5.15
4 X 20	P17	0
4 X 24	P18	0
4 X 26	P19	0
4 X 28	P20	0
4 X 36	P21	0

MachineQueues / ConveyorLengths / ConveyorSpeeds / LogInput

Figure 2 A snapshot of a simulation workbook.

Generation and distribution of computerized saw logs sub model

A "Create" module in Arena® was used to generate computerized logs at a specified-time interval. Since saw logs arrived at the study mill at random rate, it was imperative to define the rate as a distribution function. Therefore, arrivals of 368 saw logs at the study mill were timed. The time-intervals were determined and the *Input Analyzer* for Arena® was used to find a best-fit distribution to the data. The logs inter-arrival rate (seconds) was found to follow a 2.5+GAMMA (0.9, 3.39) distribution. Then a two dimensional matrix of log diameters with 1.27 cm increments and length in 0.3 increments intervals was made in an Excel spreadsheet representing the sawlog distribution pattern (Table 1). A cell (log diameter and length combination) in the matrix represented a quantity (percentage) of a particular log size to be processed in simulation run. Since the SFST was designed for multiple uses, each of these percentages was represented by a variable name as opposed to numerical values.

Table 1 Part of the simulation workbook showing distribution of sawlogs supplied to the sawmill

Log Size- Diameter (cm) and length (m)	Variable Name	Variable value (%)
7.62 X 1.8	P_i	0.00
7.62 X 2.1	P_{i+1}	0.00
7.62 X 2.4	.	10.00
7.62 X 2.7	.	1.45
8.89 x 3.08	.	.
.	P_n	20.00
Total		100

Where: P_i = variable name representing percent composition of a particular saw log size in a simulation run, 'i' = 1 and 'n' = log size sorts supplied to the sawmill

The last column of Table 1 shows where the user could enter the sawlog composition in percent. Users must ensure that the total percentage of the sawlogs in a simulation run is equal to 100 percent.

```
Public ArenaFolder As String
Public ModelFolder As String
Public Sub ModelLogic_RunBeginSimulation()
End sub
Public SimanModel As Arena.Model
Public Siman As Arena.Siman
Const sheetName1 As String = "LogInput" 'the sheet that contains the data
Const SheetColumnStart1 As Long = 2 'column start for log distribution
Const SheetRowStart1 As Long = 15 'row start for log distribution
Public ModelFileName As String
Public FileNumber As Long
```

VBA code to read log input distribution

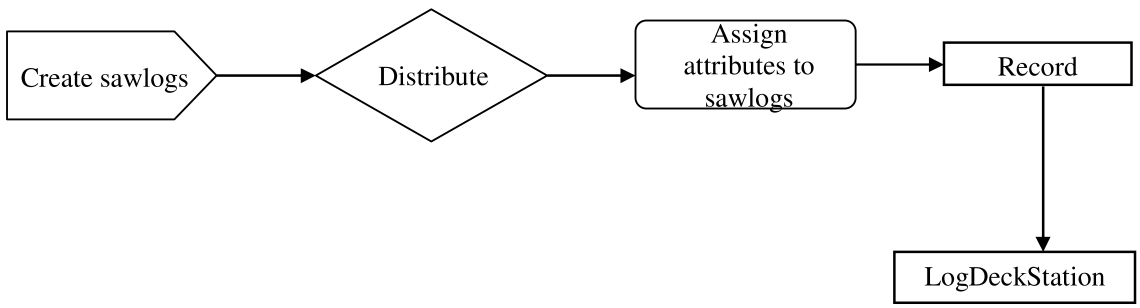


Figure 3. Saw logs generation and distribution sub model

Once the sawlogs are generated, distributed, and read in the SFST, "Assign" and "Record" modules are utilized. The "Assign" modules assign dimensions and processing-time attributes to sawlogs. The "Record" modules record the count of logs processed from each sawlog size. The log input distribution submodel ends with the Log Deck-station module to which a link to the next station may be implemented (Figure 3).

Stations and Station transfers

Arena® uses S*tations* and *Station transfers* to model material transfer times and show movement of the materials in the mill. *Stations* may be viewed as physical places in a system where some process or activity occurs (Kelton *et al.* 2004). These may be a log deck (for log arrival), a headrig, a resaw, a cut off saw, or areas of log/lumber departures, etc. Stations also appear as entry points for entities from upstream in the model. Therefore, each machine centre was preceded by a station. To distinguish stations from each other, each station in the SFST was given a unique name.

Station transfers allow movement of entities from one station to another and routing of materials in the mill. Arena® has different *Station* and *Station transfers* that could be used to model the transfer of materials in the sawmill. In this SFST, "Enter" and "Station" modules represented stations while "Route" and "Leave" modules represented *station transfers*.

Conveyors sub-model

Most small-log sawmills use conveyors to move materials between machine centres. In this, SFST, uni-directional endless (looping) conveyors were applied. Arena® "conveyor" and "segment" data modules were utilized. The conveyor data module defines the starting and ending stations, and the speed of the conveyor. The "segment" module defines the length of a conveyor. Each conveyor was given a unique identifier (tag name) to distinguish it from other conveyors. To populate conveyor and segment data modules with conveyor speeds and lengths values, VBA variables and subroutines were used. The variables carry values of conveyor speed and length defined by the user in the simulation workbook. Then, a VBA subroutine locates a specific conveyor using its identifier, the operand name in the conveyor module, and updates the operand value using the variable value.

VBA code to read conveyor speed and length

```
With
smXL.Workbooks(FileNumber).Worksheets(
sheetName2)
SheetRow = SheetRowStart2
ConveyorName=Trim(.Cells(SheetRow,
SheetColumnStart2).Value)
' Get the speed Value from value-column
LogDeckDebarkerConveyorSpeed          =
.Cells(SheetRow,SheetColumnStart2+
1).Value
End With
Private Sub locateConveyorModule()
Dim m As Model
Dim mymod As Module
Dim index As Long
Set m = ThisDocument.Model
index=m.Modules.Find(smFindTag,
"LogDeckDebarker")
   Set mymod = m.Modules.Item(index)
   mymod.Data("Vel")=
LogDeckDebarkerConveyorSpeed
   mymod.UpdateShapes
End Sub
```

Sawmill machine centres submodels

Sawmill machine centres may include single or multiples of debarkers, cut-off saws, headrigs, resaws, edgers and trim saws. These centres were modelled as resources in Arena®. A resource in Arena® is an object with a constraint. Constraints may include equipment capacity, number of people, resource state, etc. Most of the machine centre sub-models consisted of the "Enter" station, a surge deck, a machine centre "Process", and Leave station-transfer modules. The "Enter" station module receives logs from the log deck. The important inputs in the Process module include defining the processing time variable and time units. If the machine centre was busy, then the conveyor supplying sawlogs would be blocked. If the centre was idle and a sawlog (entity) seized it, the machine centre would be released after the process was completed. The Leave station-transfer then would route the entity to the next station downstream.

Headrig submodel

The main task of a headrig at a small-log sawmill is to break down logs into cants and/or lumber. At the study mill, the headrig converts sawlogs into lumber, sawdust, and chips. Upon leaving the headrig (Figure 4), sawlogs are converted into lumber. Thus upon leaving the headrig (Figure 4) entities receive lumber attributes. An "Assign" module was used to assign lumber attributes (i.e. width, thickness, and length) to all pieces coming out of the headrig. Also, an attribute named "quantity" was assigned to hold the number of pieces for each size of lumber produced from each sawlog processed. The lumber attributes and quantity were determined by the SAWSIM program which was run before the SFST. Excel ranges in the simulation workbook were used to store SAWSIM lumber-attributes information for all logs in the log sample.

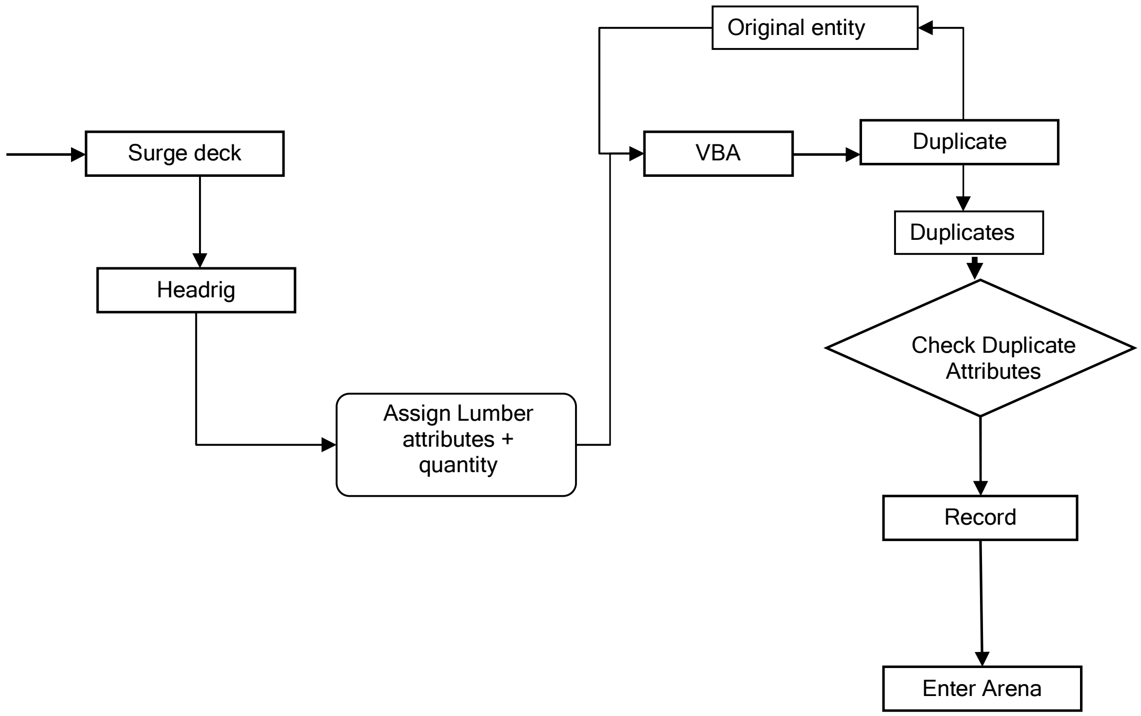


Figure 4. Reading SAWSIM output from simulation workbook

Lumber sorting and stacking sub-models
Lumber sorting and stacking sub-models are almost identical in operation. Both group lumber either by dimension or species. Arena® provides a "Batch" module which allows grouping entities either permanently or temporarily by attribute. Also, one can specify the batch size in the module (i.e., the number of lumber pieces in a batch). Batch size, is a user-defined variable whose value may be entered in an Excel spreadsheet and read into Arena®. The "Batch" module was incorporated into the SFST for lumber sorting and stacking.

Surge decks sub-models
Surge decks are part of machine centres sub-models. In the SFST, surge decks were modelled as queues and/or as detached parallel queues. If a queue is detached, it means that the queue is not directly linked to a downstream module. To populate queue modules with their respective capacities, VBA variables and subroutines were used.

Resource schedules and failures sub-models
Schedules are intended to model the planned variation in the availability of resources such as shift changes, breaks, meetings, changes of saw blades, and other maintenance activities. Failures are intended to model random events that cause resources to become unavailable (Kelton *et al.* 2004) e.g. machine breakdown, blockage, and lack of material to process. Schedules are necessary interruptions to allow proper mill operations. In practice, these are planned ahead of time in such a way that the production process is little impacted. Consequently, schedules are of less interest in this study. On the other hand, resource failures are unpredictable both in time and location. They interrupt the on-going processes and sometimes destroy the material being processed (Zhang 1993). Therefore, failures were modelled in this SFST. Since resource failures are random in nature, the best way of modelling these failures was through distribution functions. Data on machine up- and down-times were collected and used in the *Input Analyzer* for Arena®.

Also, a probabilistic branching approach was used. The basic assumption of the branching approach was that each entity arriving at a resource has a chance of causing a resource breakdown. The probability of an entity causing a breakdown could be estimated by recording the number of times a machine goes down per shift, the number of entities processed per shift, and the average length of the resource repair. In a shift for example, the branch module (Figure 5) can route entities through the repair route only two percent of the time. When this branch is taken by an entity, it is delayed for resource repair time before it proceeds to the resource. The "Delay" module delays the arrival of other entities to the resource rendering the resource operationally idle. Machine utilization statistics will reflect the impact of machine breakdown as total idle time.

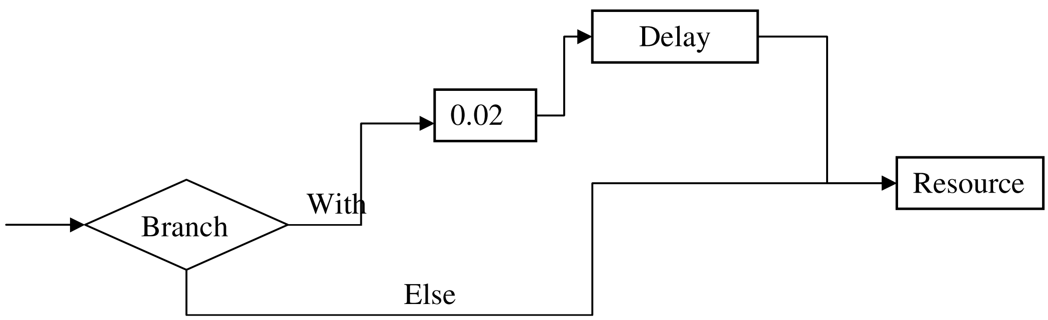


Figure 5 Modelling of failure of a resource

Model verification ("debugging")
Model verification is defined as ensuring that the computer program and its implementation are "correct" (Robinson 1997). The main objective in model verification is to obtain high confidence that a "correct" model has been developed (Sargent *et al.* 1997). The following approaches were used for both verification and debugging in the SFST:

Performance estimation - This is a technique in which the user defines a set of conditions for the simulation, estimates results, makes a run and looks at the summary data to see if the model produced the expected results (Kelton *et al.* 2004).

Check model - This is an Arena® function which checks for errors in the model while it is in the edit mode (i.e. not in a run mode). If an error is present, Arena® notifies the user about the presence of an error and provides suggestions on how to fix it.

Trace – This is an important verification tool available in Arena®. A trace is a way of exploring whether entity flow is incorrect and/or the function performed at a specific module is incorrect (Pegden *et al.* 1990). The trace feature may examine detailed movement of entities through the system. The trace consists of compiling a detailed history of all entity movements through the block model.

Animation - The model operational behaviour is displayed graphically as the model moves through time. These techniques were utilized to check and debug errors in the model.

SFST validation
Model validation is done to measure and assess the quality of the model (Balci 1997). Model validation is the substantiation that the model behaves with satisfactory accuracy within the scope of applicability (i.e., building the right model) (Robinson 1997). Validation was done through statistical comparison/testing of the performance measures of the model and the

actual system. Therefore, the main objective of model validation in this study was to determine how well the SFST simulated the lumber manufacturing process at the study mill. To test the SFST, data were collected at the study mill and used in the validation procedure. Computer-generated shift-outputs were also collected from the mill to augment the manually collected data. Some of these data were used to describe the study mill in the SAWSIM program. The SAWSIM programme was run before the SFST, and the SAWSIM-sawing solutions for a log-sample were saved in a spreadsheet of the simulation workbook and read into the SFST. Similarly, other data required to drive the SFST were entered in spreadsheets of the simulation workbook. Then, thirty three simulation replications of the SFST were run. The Arena® "Statistic" module was used to collect data on measures of performance and others as specified. For each test factor, actual values from a shift at the study mill are also shown (Table 2).

Table 2 Simulation results of 33 replication runs compared to the actual performance of the study mill.

		Simulated results (33 runs)		
Factors	**Actual value**	**Mean**	**SD**	**Percent difference**
Log processed	7,973	8,004	41.7	0.39
Total log volume(m^3)	540.85	598.87	141	9.69
Lumber tally (m^3)	393.78	394	1200	0.002
LRF	8.72	7.88	0.02	-10.66
2 x 3 x 6 (pieces)	258	235	11.7	- 20.56
2 x 3 x 7 (pieces)	192	179	17.8	- 7.2
2 x 3 x 8 (pieces)	90	114	19	21
2 x 3 x 9 (pieces)	39	47	9.5	17
2 x 4 x 6 (pieces)	221	225	19.7	1.78
2 x 4 x 7 (pieces)	174	178	15.8	2.25
2 x 4 x 8 (pieces)	5,384	5,340	122	- 0.82
2 x 4 x 9 (pieces)	7,739	7,690	103	- 0.64
2 x 6 x 6 (pieces)	202	240	21.8	15.8
2 x 6 x 7 (pieces)	18	15	4.12	- 20
2 x 6 x 8 (pieces)	3,960	4,000	102	1
2 x 6 x 9 (pieces)	5,332	5,320	67.4	- 0.23

During the actual 8-hour shift, 7,973 real logs were processed compared to 8004 simulated logs. The number of real logs processed fell within one standard deviation of the simulated mean. The simulated volume of lumber produced was 394 m^3 compared to 393.78 m^3 of real lumber produced during the shift. The real lumber production during the shift was within one standard deviation of the simulated mean. However, there was considerable difference between the simulated-log volume (m^3) and the real log volume. This difference resulted in a large difference between the real and simulated Lumber Recovery Factors (LRFs). The log volume difference may have been attributed to different log-diameters that were used in calculation of the log volumes. While in the SFST log volumes were calculated using diameter and length classes (constant taper), the study mill used a scanner to more precisely measure diameter over the entire length of the log (variable taper). Use of these different diameter inputs in the volume expression may have contributed to the observed difference. However, from the lumber volume produced, it is evident that the sawing solutions applied in both cases were similar.

The primary mill products (i.e. 2 x 4 x 8, 2 x 4 x 9, 2 x 6 x 8, and 2 x 6 x 9) were captured well by the SFST. The real numbers of these products were within one standard deviation of the simulated means. However, it is evident in Table 4 that the SFST was less accurate in simulating numbers of narrow and/or short lengths which were produced in low quantities by the study mill. Nevertheless, the 2 x 3 x 8, 2 x 6 x 6, 2 x 6 x 7, and 2 x 3 x 9 values fell within one standard deviation of the simulated values, and the real value for 2 x 3 x 6 fell within two standard deviations. Most of the simulated means of these products were higher than what was actually produced. The difference may have been due to the SAWSIM program producing shorter and narrower pieces in an attempt to improve lumber recovery. Results from Table 4 show that most of the test factors fell within one standard deviation of the corresponding mean of the simulated variable. Thus the SFST satisfactorily simulated the study mill.

CONCLUSIONS

The SFST developed in this study take a unique approach to the modelling of small-log sawmills, and it addresses several lumber manufacturing processes prevalent in small-log sawmills. These areas include log debarking, log cross-cutting, log sawing, lumber edging and trimming, lumber sorting, lumber stacking, and material handling. The SFST may be utilized for a variety of uses. These include predicting the impact of change in mill layout, raw material and product specifications, sawing solutions, and queue sizes on numerous performance measures of small-log sawmills. This helps the sawmiller to make well-informed decisions.

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